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PROCEEDINGS OF THE I.R.E.

INSTITUTE NEWS AND RADIO NOTES

E. R. Piore

Board of Directors, 1951

E. R. Piore is a graduate of the University of Wisconsin, where he received the B.A. and Ph.D. degrees in physics in 1930 and 1936, respectively. He remained there from 1936 to 1938 as an assistant instructor in physics.

From 1938 to 1942 Dr. Piore was engineer in charge of the television laboratories of the Columbia Broadcasting System, and was instrumental in the development of color television. In 1942 he joined the civilian staff of the United States Navy's Bureau of Ships as senior physicist. In 1944 he was called to active duty in the Naval Reserve as a Lieutenant Commander attached to the office of the Deputy Chief of Naval Air Operations.

Dr. Piore joined the Office of Research and Inventions (which later became the Office of Naval Research) in 1946 as head of the electronics branch. Since then, his service with ONR has been continuous except for the year 1948–1949, when he was a guest scientist in electronics at the research laboratory of the Massachusetts Institute of Technology. In 1949 Dr. Piore became Deputy for Natural Sciences, and in April, 1951, he was appointed Deputy and Chief Scientist of the Office of Naval Research.

Dr. Piore joined the Institute of Radio Engineers as an Associate in 1938. He became a Member in 1942 and a Senior Member in 1943. In 1950 he received the award of Fellow for his "many contributions in the fields of engineering and physical sciences, and for outstanding service in enhancing the national effort in basic research."

He is also a Fellow of the American Physical Society, a member of Sigma Xi, a member of the American Society of Naval Engineers, and a member of the Association for Computing Machinery.

The Color-Television Issue

From the beginning, it has been the aim of the PROCEEDINGS OF THE I.R.E. to meet the major technical-information needs of its readers. One of its functions has therefore been to present papers describing advanced research and development projects, thus providing basic information for future use and preparing the engineer to take practical advantage of new and powerful tools. Another of its functions has been, in timely fashion, to publish papers describing the current status of certain divisions of engineering and to give analyses of important accomplishments in these fields.

The present is an appropriate time to fulfill both these functions by offering to the IRE membership an unusual and valuable group of papers on color television, specially selected for the purpose. Their publication as a group in this greatly expanded issue of the PROCEEDINGS was proposed by the Editorial Department and approved by the IRE Executive Committee. They are exceptional contributions to a field in which basic progress has recently been made, and one which should be carefully studied and well understood by the communications-engineering fraternity.

The recent techniques in color television are also of special interest to others besides engineers in that they offer a whole new series of instrumentalities for the control of color. It is now possible to control the brightness, hue, and chroma of light-emissive sources by purely electronic means. These methods and instruments should be helpful to scientists in a number of fields (including physiologists, psychologists, colorimetrists, and ophthalmologists), to color-photographic investigators, and to certain industries (such as printing, dyeing, and the like). Manifestly, these techniques will find many valuable applications, as yet partly unforeseen.

The IRE is gratified to be able to place this issue of its PROCEEDINGS before a large group of workers who can profit from it. It is thought that this issue, like certain earlier issues, will be found in the coming years to have been a classical contribution to the subject of which it treats. It is believed that it will thus advance the art of color television.—*The Editor.*

Alternative Approaches to Color Television*

DONALD G. FINK†, FELLOW, IRE

ENGINEERS and administrators concerned with establishing standards for color television have been divided for several years into two camps of opinion. In the first camp, it has been argued that a system based on simple apparatus (the field-sequential system) should be adopted, despite certain difficulties imposed on the system by the nature of human vision. In the second, it is argued that a system based on more complicated apparatus (the color-subcarrier system) should be adopted to take advantage of certain characteristics of human vision and thus to provide higher quality of transmission.

This schism has been greatly intensified by the public investment in over 13 million receivers, designed for the 525-line, 60-field black-and-white scanning standards and incapable of operating on other standards without extensive modification. Unfortunately the field-sequential method of color reproduction leads inevitably to scanning standards well outside the range of these receivers. The field-sequential system is, therefore, incompatible with the existing television broadcast structure and must operate under a heavy economic handicap during the early stages of its introduction to the public. The color-subcarrier system, on the other hand, is inherently more flexible in the choice of scanning standards. This makes it possible to adopt values identical to the black-and-white standards and thus achieve a compatible color system.

While the desire for a compatible color system is without doubt the principal motivating force behind the development of the color-subcarrier system, there is doubt that compatibility should be the controlling factor in the choice of a system. Compatibility has important economic consequences only during the early stages of the introduction of color service. Thereafter, the normal processes of competition and obsolescence can be expected to bridge the gap between the systems, so far as scanning standards are concerned. After this transitional stage, the important and enduring questions are the quality of the television service (in color and in black-and-white) and the cost of rendering and utilizing the service. Since the life of the television standards is presumably longer than the transition period, it would appear that principal importance should be attached to the quality and cost factors, and that compatibility should be considered only to the extent that it affects the initial acceptance by the public of the color service.

This philosophy was adopted by the Federal Communications Commission in its recent action in adopting the field-sequential system for public service. In effect, the Commission ruled that a satisfactory color system should not be retarded merely because it was incompatible, whereas an inferior color system should not be adopted merely because it was compatible. Viewed from the perspective of the past year, it now appears to many observers that this decision was a correct one at the time it was made. At that time, the quality and cost factors weighed on the side of the field-sequential system and the compatibility argument was used only as a reason for making the decision at once, to ease the introduction of the field-sequential service.

The error which may properly be attributed to the Commission is its judgment that the quality of the color-subcarrier system could not be improved, nor its costs reduced, in a period comparable to the time required to introduce the field-sequential system. This error now appears to be one of excessive conservatism, always a danger in assessing the future course of technical development.

Fortunately judgments of this sort are subject to review in a free society and the Commission has in fact "left the door open" for such a review as soon as the facts of technical development warrant it. The future procedure with respect to administration of color television service thus appears to involve a continuing assessment of the quality and cost factors until such time as the public acceptance of one or another system precludes further discussion.

In endeavoring thus to assess the relative merits of the field-sequential and the color-subcarrier systems from the standpoint of quality and cost, the technical worker is confronted with a rapid change in the state of knowledge, more rapid perhaps than at any previous stage in the history of television development. The rate of change applies not only to the development of apparatus, but also to our appreciation of the role of the human eye as an element in the television system. Concurrently a revolution has occurred in many traditional concepts in transmission theory. Methods of transmission which, five years ago, seemed impossible in principle to the majority of television workers, have now been further analyzed, proved sound and, in fact, demonstrated.

It is not surprising, therefore, that much confusion exists among radio engineers, even among those whose specialty is television systems development. One result of the confusion is the tendency to take sides in the controversy, and thus to intensify it, based on partial knowledge of the facts. Qualified engineers can be heard

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† *Electronics* Magazine, McGraw-Hill Publishing Co., New York, N. Y.

to denounce the color-subcarrier system as a "paper system," while others, equally qualified, denounce the field-sequential system on the score of "mechanical complexity." In point of fact, neither judgment is valid, let alone necessary and sufficient cause for argument.

Within recent months certain clarifying concepts have been advanced and certain crucial demonstrations have taken place which permit the whole field of television, including the two principal systems of color television, to be viewed in better perspective than has been possible since the end of the war. It is the purpose of this paper to review these concepts and demonstrations as an introduction to the more specialized papers which follow in this issue of the PROCEEDINGS OF THE I.R.E.

Subjective Requirements in Television

From the standpoint of systems engineering, the phrase "quality of television service" implies just one attribute of the system: the degree to which the television image satisfies observers as a *pleasing reproduction* of the events which occur before the camera. The important word in this definition is "pleasing.[1]" Ten years ago, "accurate" reproduction would have been the criterion among television engineers. Today, largely as a result of the influx of knowledge from the field of photography, it is recognized that the reproduction should not be accurate in the technical sense. From the standpoint of system economics the system should not perform better than is necessary to please typical observers with what they see.

Full recognition of this criterion has come with the development of color television, not only because of the many compromises involved in color transmissions, but also because television engineers have availed themselves of the experience of photographic technicians in color reproduction. In color photography it is a truism that an accurate reproduction is usually less satisfactory than a distorted reproduction carefully contrived to impress the viewer as being "natural," "bright," "warm," or "cold," depending on the context of the material represented.

A color television system must be flexible enough to convey these intentional distortions of image quality. *But a television system should never be called upon to reproduce an image that is "more than pleasing."* This seemingly trivial limit on the required excellence of a television system has profound influence on the cost of rendering the service and the amount of radio spectrum space required. It implies that the system should not have capabilities beyond the reproduction of a satisfactory (pleasing) image, since such capabilities cost dear, in money and in spectrum resources.

Television system design thus properly starts with a statistical study of what constitutes a pleasing image. The statistics must be based on a suitably large sample of experienced (but preferably technically untrained) viewers who are asked to state a preference or discern a difference as one variable in image quality is changed.

Many such tests have been conducted in past years. One crucial series of tests by Baldwin[2] in 1939–40 on the subjective sharpness of television images had an important bearing on the choice (by the National Television System Committee, in 1940) of the 525-line image in preference to the 441-line standard then in vogue. Tests of flicker have been conducted extensively by motion picture engineers and, in the television field, by RMA Committee TS 2.3 in 1946,[3] and in 1950 by Study Group 11 of the CCIR. These tests confirm the logarithmic form of the Ferry-Porter law and establish absolute levels of brightness at which flicker becomes perceptible and intolerable, under given conditions of apparatus and observation.

In addition to subjective tests of resolution and flicker, tests are necessary to establish the allowable or desirable distortions in the tonal gradation of television images. Here again, extensive tests have been conducted in the motion picture field, and preferred values of negative and positive gamma, contrast range, and limits on halation and flare have been established. In television this subject is less perfectly developed, partly because the standards of tonal gradation are independent of the scanning standards and hence are not so material a factor in transmitter and receiver design. The FCC standard on gradation (the input-light versus carrier-level-output curve of the transmitter) is written in vague terms and is, in point of fact, not enforced at the present time.

Despite the unsatisfactory state of tonal gradation standards, it may safely be said that the presently available subjective data on resolution, flicker and gradation are sufficient to form a sound basis for the choice of black-and-white standards. To a certain extent the same data are useful in the choice of standards for a color-television system. But in a number of essential respects they are deficient. The brightness level at which flicker becomes perceptible is known to be a function of the color of the image, and the tonal gradations of primary-color images must be related in a specific manner. But, so far as the writer is aware, no definitive tests of subjective tolerances of these effects, directly applicable to color-television system design, have been conducted.

[1] The word "pleasing" is here used in its psychometric sense of "giving pleasure in general"; it does not refer to the emotional reaction to particular program material. "Convincing" and "having the appearance of reality" are implied. "Realistic" is *not* meant, since this means a characterization of things "as they really are."

[2] M. W. Baldwin, "The subjective sharpness of simulated television images," PROC. I.R.E., vol. 28, p. 548; October, 1940.

[3] RMA Television Systems Committee, "UHF Television Systems," RMA Data Bureau Report 2146; November, 1946.

The major deficiency has been, until very recently, the lack of detailed knowledge on the required subjective sharpness (resolution of the image) as a function of color. This problem has not figured importantly in the development of color photography, so the pertinent data lay hidden for years in the records of physiological optics. References to visual acuity for colored light can be found as far back as 1865, but it was not until 1940 that the facts were rediscovered by television engineers. In that year, Alfred N. Goldsmith applied for a patent[4] on a television system having low resolution in the blue primary; in 1945 this proposal was applied by Bedford in the "mixed-highs" method of transmission.[5]

The lack of suitable information on the subjective aspects of color television has now been fully realized and has led to an extensive series of tests at the Bell Telephone Laboratories, the first of which, having to do with the subjective sharpness of simulated color television images, is reported by Baldwin in this issue of the PROCEEDINGS.[6] Other tests have been reported by Panels 2 and 11 of the NTSC. The time is not far off, therefore, when the performance of competing color systems can be judged in terms of the basic factors in a pleasing color reproduction. Meanwhile, the judgments expressed herein must be considered as subject to refinement.

Whatever the final outcome of these subjective tests, one principle of system design may be accepted: the color television image, as a whole and in all its constituent parts, should not display an excess of quality with respect to resolution or flicker. Such excesses, measured against a proper standard of pleasing reproduction, have three effects: they add unnecessarily to the cost of transmitters and receivers; they add unnecessarily to the radio spectrum occupied; or, if the spectrum space is fixed, an excess in one quantity (flicker performance) leads to a deficiency in another (resolution). This criterion (a restatement of the "not-more-than-pleasing" rule) thus serves to delineate the quality-cost ratio of a given system. In addition, the tonal gradation, the color gamut covered, and the freedom of the image from extraneous disturbances, such as transients, interference and noise, must also satisfy the "pleasing, but not-more-than-pleasing" rule. In what follows, the field-sequential and color-subcarrier systems are compared on the basis of these requirements.

Development of the Field-Sequential System

In the field-sequential color system, successive fields are scanned individually in one of the three primary colors, the color fields following in the order red, green, blue, red, green, blue, and so on. The rate of scanning the fields is so rapid that the sensation produced by one field persists in the mind of the observer during the scanning of the next two fields. Consequently, the image appears as if all three primary colors were present simultaneously and the sensations add, producing mixtures of the primaries which reproduce the variegated colors of the scene before the camera.

This method of color reproduction has had a long history in motion pictures and television. In one of the early color-movie systems, the frames of the film were exposed successively through two color filters (red-orange and blue-green) carried on a filter wheel rotating before the camera lens. The film was projected through a similar rotating filter wheel so synchronized with the film that red-orange light was projected by the frames corresponding to those exposed through the red-orange filter, and similarly for the other color. In the course of these experiments it became clear that, to keep flicker within acceptable limits, approximately twice as many frames had to be projected in a given time for color reproduction as for black-and-white reproduction. The resulting high consumption of film, and the strain put on the film by the rapid intermittent actions of camera and projector, forced abandonment of the system. Successful commercial color motion pictures were produced only when it became possible to include all three primary colors in each film frame, first by the additive methods of Dufaycolor and Kodacolor, and later by the subtractive processes of Technicolor, Agfacolor and Kodachrome.

The first color television demonstration in the United States[7] was given to the press by the Bell Telephone Laboratories on June 27, 1929. The equipment operated on the simultaneous-color basis. The head and shoulders of the subject were scanned in white light by a mechanical flying-spot scanner, and the light was picked up by three phototubes fitted with color filters (blue, red and green). Three separate transmission channels were used to actuate three glow lamps in the respective colors. Those were viewed through mirrors which superimposed the primary-color images. The images were scanned at 50 lines per picture, 17.7 pictures per second.

The start of experimental color-television broadcasting did not come until 11 years later when P. C. Goldmark gave his first demonstration to the press on September 4, 1940, over the facilities of the Columbia Broadcasting System. These early images were highly impressive and provided the initial impetus on which the subsequent development of the art has largely depended. The images were scanned by the field-sequential

[4] Alfred N. Goldsmith, U.S. Patent 2,335,180, issued November 23, 1943.

[5] A. V. Bedford, "Mixed highs in color television," PROC. I.R.E., vol. 38, p. 1003; September, 1950.

[6] M. W. Baldwin, "Subjective sharpness of additive color pictures," PROC. I.R.E., pp. 1173–1176; this issue.

[7] H. E. Ives and A. L. Johnsrud, "Television in colors by a beam scanning method," *Jour. Opt. Soc. Amer.*, vol. 20, p. 11; January, 1930.

method at 343 lines per frame and 120 fields per second, and were transmitted over the standard 6-mc channel then occupied by the CBS black-and-white station W2XAX.

Subsequently, papers[8,9] by Goldmark and his associates revealed that the CBS color system, even in its early form, had reached a high state of development with respect to camera taking characteristics, receiver primary filters, and control of color balance and gradation, all of which contributed to the excellent color rendition of the system. In other respects, the images were limited by the scanning standards adopted to fit the signal into the 6-mc channel. The 343-line resolution was considered unsatisfactory, and the 120-per second field rate produced severe flicker when the image brightness was increased above a few foot-lamberts. In 1941, work on the system was suspended as a result of the war.

At the end of the war, in 1945, television engineers were in accord that a channel wider than 6 mc was required for a satisfactory color image, and that any color system must therefore be incompatible (on a frequency assignment basis) with the black-and-white system which had been in commercial operation since July, 1941. Since this conflict was considered inevitable, all eyes turned toward the ultra-high-frequency spectrum reserved for television (then 480–920 mc) as the eventual home of the color service. There was some conflict of opinion as to the preferred method of transmission, but the field-sequential method was in general favor. The majority of the RTPB Television Panel favored a field rate of 180 per second to achieve flicker performance equal under all circumstances to that of the black-and-white system, and 525 lines per frame to provide equal resolution. These figures implied a channel width of the order of 15 mc, and this requirement was viewed with understandable misgiving by all concerned.

At the FCC color-television hearing which began December 9, 1946, the Columbia Broadcasting System petitioned for immediate commercialization of color television, proposing a compromise which would permit field-sequential color transmissions on channels 12 mc wide. The proposed scanning standards were 525 lines per frame, 144 fields per second. These values were in line with the majority opinion concerning resolution; the compromise was the field rate of 144 per second which limited the brightness of the image, for tolerable flicker, to about 25 foot-lamberts. This compared with over 100 foot-lamberts for the black-and-white system.

At this hearing the compatibility argument was heard for the first time. It was argued that the demand for television channels would soon exceed the supply and that channels devoted to color transmissions should also be capable of serving the existing black-and-white receivers when tuned to the color transmissions. Laboratory demonstrations of a simultaneous color system, designed to meet this requirement, were given by the Radio Corporation of America to the FCC during the hearing. In this system, described in greater detail below, three separate signals, devoted respectively to the primary colors, were transmitted on separate carriers. The proposed scanning standards were identical to the black-and-white standards, so existing black-and-white receivers could be operated by tuning to one of the carriers, i.e., that carrying the green image. By reducing the bandwidth devoted to the blue and red images (mixed-highs transmission) it was believed possible to confine the transmissions to a 12-mc channel. Those opposing the CBS petition argued that it was unwise to decide on any color system until the relative merits of the field-sequential and simultaneous systems could be explored, and until further information was available on uhf propagation, since both systems were then envisaged as occupying the uhf channels. In March 1947, the FCC denied the CBS petition.

The subsequent development of the field-sequential system has been conditioned by the phenomenal acceptance by the American public of television broadcasting. In 1948 it became clear that the channel demand had already outrun the supply. By September in that year, the FCC had issued 107 construction permits or licenses to tv stations and had 310 applications for permits on its books. It was evident that this large number of stations could not be accommodated in the 12 channels of the vhf band, particularly since numerous reports of excessive cochannel and adjacent-channel interference had been received. Accordingly, in that month the Commission called a halt on further expansion of television broadcasting, pending further study of interference as affected by channel assignments. The pressure for additional channels was so great that the requirement of 12-mc channels for color television, essential as it then seemed from the standpoint of satisfactory service, was wholly impractical in view of the public demand for television service. Accordingly in 1949, the Commission adopted the position that the proponents of color television must reconcile themselves to 6-mc channels, and asked for information on the practicability of instituting color service in the near future, using such channels.

Meanwhile the CBS field-sequential system had been demonstrated on a closed-circuit basis before the American Medical Association at Atlantic City, on June 6, 1949, using scanning standards suitable for a 6-mc channel. This demonstration, the first since 1940 on a 6-mc basis, convinced the majority of those who observed it that field-sequential color television was indeed practical on 6-mc channels so far as the quality of reproduction was concerned, provided that care was

[8] P. C. Goldmark, J. N. Dyer, E. R. Piore, and J. M. Hollywood, "Color television—Part I," Proc. I.R.E., vol. 30, p. 162; April, 1942.

[9] P. C. Goldmark, E. R. Piore, J. M. Hollywood, T. H. Chambers, and J. J. Reeves, "Color television—Part II," Proc. I.R.E., vol. 31, p. 465; September, 1943.

taken to minimize the effects of limited resolution. Accordingly, at the FCC color-television hearing which began on September 26, 1949, the Columbia Broadcasting System proposed that commercial color broadcasting begin at once on the basis of 405-line images, scanned field-sequentially at 144 fields per second.

It should be noted that these standards exceeded the 1940 values both in number of lines (405 versus 343) and in fields per second (144 versus 120). Two factors underly these changes. First, the CBS engineers decided to utilize a large number of lines, and thus to augment the vertical resolution at the expense of horizontal resolution, in the expectation that a new technique ("crispening," see paper[10] on this subject by Goldmark and Hollywood in this issue of the PROCEEDINGS) would permit improved horizontal resolution. Second, it had been conclusively demonstrated that 144 fields per second was the minimum field rate for acceptable freedom from flicker.

At this hearing, the compatibility issue came into sharp focus. The incompatibility of frequency assignments was resolved, since the location of carriers for field-sequential color was to be the same as for black-and-white, but the scanning standards differed materially. The number of lines scanned per second in field-sequential color is 29,160 per second ($405 \times 144/2$), against 15,750 ($525 \times 60/2$) in black-and-white. The number of fields scanned per second in color is 144 as against 60 in black-and-white. All attempts to reduce these wide discrepancies had failed; the field-sequential system and the black-and-white system were unavoidably incompatible in scanning standards.

The simultaneous system, brought to the attention of the Commission in 1946–47, was not suitable in its original form because the three carriers could not be squeezed side-by-side into the 6-mc channel without complete loss of compatibility in the frequency sense. Another form of compatible system, similar to the earlier simultaneous system in many respects, was brought forward by RCA. This system (described below) used only one color subcarrier so modulated and demodulated that the colors appeared to be laid down as dots along each line. Accordingly it was christened the "dot-sequential system."

After 62 days of taking testimony from 53 witnesses, the transcript of which totalled nearly 10,000 pages, the FCC decided on October 10, 1950 that immediate commercialization of the field-sequential color system was in the public interest. After an interval, during which the decision was reviewed and upheld by the Supreme Court, the Commission's order became effective early in 1951. Public color broadcasts, the first in the history of the art, were inaugurated by CBS in New York on June 25, 1951.

[10] P. C. Goldmark and J. M. Hollywood, "A new technique for improving the sharpness of television pictures," PROC. I.R.E., pp. 1314–1322; this issue.

Capabilities and Limitations of Field-Sequential Color

The principal strength of the field-sequential color system, from the technical standpoint, is that it offers the equipment designer a wide range of choice of terminal equipment (cameras and picture reproducers). The salient fact is that the primary colors, being presented in successive scanning fields, succeed one another at intervals of the order of a hundredth of a second (actually 1/144th second). This is a sufficiently long time to permit the color change to be introduced mechanically by the rotation of a disk (or cone or drum) carrying filter segments. When this mechanical method is used, a single sensitive surface in the camera, and a single light-producing area in the picture tube, suffice to reproduce the image. Several advantages accrue from this arrangement, among them being uniformity of color gradation over the area of the image, and freedom from misregistration[11] among the primary colors.

Several disadvantages also appear in the mechanical method. Among them are the perfection of dynamic balance, the large amount of mechanical power and the precision of synchronization required in rotating a disk, cone or drum of sufficient size to encompass the large images demanded by the public. If these drawbacks dismay the designer, the alternative of purely electronic color reproduction, using a tricolor picture tube, can be adopted.

In any event, wide latitude is available to the designer, including designs displaying a rockbottom simplicity (for example, a mechanical receiver synchronized by connection to the power line with manual control of color phase) that cannot, it now appears, be matched by any other proposed system of color television.

Whether these simple receivers will find favor with the public, particularly if the picture size is limited, only time will tell. If they do not, the advantage of receiver simplicity may prove, to that extent, to be illusory. But even in that event, the simplicity of the camera remains and with it the advantages of uniform color balance and accurate registration.

The limitations of the field-sequential system are found in two characteristics of the human eye: its aversion to excessive discontinuity of light and to excessive discontinuity of motion. If the eye were generously tolerant of such discontinuities, it would be feasible to adopt for the field-sequential system the same scanning standards as are used in the black-and-white system.[12] The compatibility difficulty would then evaporate, and the flicker performance and resolution of the systems

[11] Misregistration can occur, however, due to the effects of hum and stray fields, since the field-scanning rate is not integrally related to the power-supply frequency.

[12] On the same assumption of flicker tolerance, however, the field rate for black-and-white pictures would have been chosen at a lower value. In that case, the flicker tolerance would presumably not extend sufficiently to permit field-sequential color to operate at the same field rate as black-and-white.

would roughly coincide. Under such circumstances, it is doubtful if any serious opposition to the field-sequential system would have arisen.

But natural vision is not so constituted. The eye rebels when light flashes are presented to it at an effective flicker rate lower than about 40 per second, unless the image is so dim that eyestrain results from continued observation of the image. This flicker limit corresponds, as explained below, to the 120-per-second field rate of the early field-sequential tests. The marginal performance in respect to flicker, evident in those tests, required a change from 120 to 144 fields per second.

The eye rebels also against excessive discontinuity in the apparent motion of the image. This requirement is ordinarily satisfied when flicker is brought under control. But the tolerance to this effect is noticeably reduced if the discontinuity in position is accompanied by a change in color. Color fringing accompanying rapid motion in the image, and color break-up accompanying casual motion of the eye are apparent in field-sequential images. There is evidence that the sensitivity to these latter effects decreases in many individuals with exposure to them over a long period, so it is perhaps proper to subordinate this limitation to that caused by the high rate of field scanning.

Since the latter consideration is basic, it is worthy of more detailed examination. Three conditions should be distinguished with respect to flicker in the field-sequential system. The first occurs when a large part of the image area is occupied with a green color, like that of the green filter used in the camera. So far as this part of the image is concerned, only one out of three successive fields (that producing green light at the receiver) is active; the blue and red fields then contribute but little light. The effective rate of image repetition is then one third of 144 per second, or 48 per second, and flicker is especially noticeable. A similar condition occurs when only red light or only blue light is present in a substantial portion of the image, but since red and blue light are ordinarily less bright than green, the flicker is not so evident in the latter cases.

In the second case, white light occupies a substantial portion of the image area. In this case all three primary fields are active, but the brightnesses of the fields are in the approximate proportion red:blue:green = 33:14:69 (for the standard FCC field-sequential primaries). Since the green primary then exceeds the blue in brightness by about 5 times, and exceeds the red primary by about 2 times, the same general effect is present as in the first case, but since the disparity between fields is less, the effective flicker threshold occurs at higher brightness. Accordingly the second case is less critical as to flicker than the first.

In the third case the successive fields all have the same brightness (in a linear receiver this means that the signal voltages actuating the primaries are in the approximate ratio red:blue:green = 6:14:3). The color then is predominantly blue. In this case, there being no change in brightness from field to field, the flicker rate is 144 per second. This is an excessively high value for freedom from flicker. In fact for such equiluminous fields, the flicker rate is $144-48=96$ per second higher than for the first case (the saturated green).

This represents an enormous difference in flicker performance; by the Ferry-Porter law it is equivalent to a change in flicker-threshold brightness of $10^{96/12.6}=3\times10^7$ times.[13] Actually the Ferry-Porter law does not hold over such extreme ranges. But the fact is that the predominantly blue hue of case 3 may be thousands of times brighter than the saturated green of case 1, for equal freedom from flicker when the field rate is 144 per second.

It thus appears that when the field rate is chosen to be "pleasing" with respect to flicker for white light, it is "less than pleasing" for saturated greens of the same brightness, and greatly "more than pleasing" for blue reproduced by equiluminous fields of the same brightness. This violation of the "pleasing-but-not-more-than-pleasing" rule is inherent in the field-sequential method of scanning.

The net result is that the satisfactory field-scanning rate for field-sequential color is not less than 144 fields per second, despite the fact that substantially lower values would suffice for many combinations of colors, of which case 3, above, is the most striking example.

The excess of performance, thus made necessary in certain instances with respect to flicker, must be matched by a corresponding deficiency of performance in respect to resolution. Unfortunately the latter deficiency applies in every instance to all fields, whereas the excess of flicker performance applies to only certain color combinations.

The resolution deficiency is readily expressed in terms of the ratio of the field frequencies for field-sequential color and black-and-white, i.e., $144/60=2.4$. For a given video bandwidth, and for equal percentage blanking times, the resolution of the color image is then $1/2.4=41.6$ per cent as great as that of the black-and-white image, measured in the total number of resolvable picture elements per frame. In terms of the specific scanning standards, the vertical resolutions in the two systems are in the ratio of the number of lines per frame $405/525=77.2$ per cent, and the horizontal resolutions are in the ratio $525/405\times1/2.4=54$ per cent (about 325 lines in black-and-white, 175 lines in field-sequential color).

The resolution deficiency is subject to amelioration by the presence of color contrast in the color image, and by such resolution-enhancing techniques as "crispening." These are effective, of course, in all color systems, but are particularly useful when the inherent

[13] A difference of 12.6 cps in flicker frequency represents ten times change in flicker threshold brightness.

resolution of the system is low. In a high-resolution system, the improvement they provide is subjectively less impressive because there is less need for improvement.

The effect of limited resolution on the quality of the color-television service may be described in various ways.[14] Perhaps the most useful comparison, from the standpoint of practical operating procedures, is in terms of the solid angle viewed by the camera. If a given viewing angle suffices to portray a given subject when the resolution of the system is 100 per cent, then a reduction to 41.6 per cent (as between the black-and-white system and the field-sequential system) requires the viewing angle to be reduced in the same proportion for the same degree of satisfaction in viewing the same subject matter. Such reduction of viewing angle is accomplished by viewing the subject more closely, by moving the camera closer or by employing a lens of longer focal length.

In other words, much greater reliance must be placed on close-up shots in a system of limited resolution, and this acts as a restriction on the camera operator, technical director, and producer of the program. In effect it reduces the number of objects and events which may be seen together in the image and forces cameras to be switched to establish the relationships between such objects and events. This restriction is evident in comparing the camera techniques currently employed in the two systems.

Little exception can be taken to the color gamut, tonal gradation, and freedom from disturbances of the field-sequential system. The color gamut is somewhat reduced by the use of the so-called "low-flicker" primaries but this is not a serious limitation. The judgments expressed by laymen and technicians alike on the color rendition of the system are almost universally favorable.

An important advantage of the field-sequential system is that it employs only one carrier. In a system employing two carriers (the color-subcarrier system) greater opportunity exists for interference to cause visible (i.e., low-frequency) beat patterns. Moreover, in a two-carrier system, the selective effects of wave interference in the presence of multipath transmission may prove troublesome. Finally, transient disturbances affect all parts (successive fields) of the field-sequential image in the same way (although transients are more visible, due to the higher line-scanning velocity, than in the black-and-white system). In a simultaneous presentation like that of the color-subcarrier system, the possibility exists that such transients may affect one part of the image (its brightness component, defined below) differently from the other parts (hue and saturation components).

In summary, the field-sequential system offers the advantages of simple terminal apparatus (with limited picture size), while not restricting the designer to simple equipment. It has excellent performance with respect to tonal gradation and color gamut. It resists the effects of noise, multipath transmission, interfering carriers, and transmission transients to about the same extent as does the black-and-white system. Counter to these strong points, it finds difficulty in co-operating with the eye in the matter of flicker. Consequently a high field rate must be adopted to avoid flicker in certain circumstances; this high rate is not required in other circumstances and thus represents an excess of performance. The price paid for this excess is a reduction in geometric resolution to about 42 per cent of the black-and-white system.

Development of the Color-Subcarrier System

The alternative color-television system, the color-subcarrier system,[15] represents the culmination of an effort extending over five years or more to find a satisfactory compatible system. Its roots go back to the 50-line color system demonstrated by the Bell Telephone Laboratories in 1929, referred to above. In this early system, three video signals, each identical in principle to the others, were transmitted to carry the information present in the respective primary-color images. The bandwidth consumed was identically three times that required for the equivalent black-and-white image.

The distinguishing characteristic of the terminal apparatus, which links it to all subsequent systems of the same type, is the use of three separate photosensitive devices and three separate image-reproducing devices, all operating simultaneously. In this sense, the 1929 system served as the crude prototype of the "simultaneous color system."

The second demonstration of a simultaneous color system was that shown to the FCC by RCA in the 1946–1947 color hearing, as briefly described in a previous paragraph. This differed from the 1929 system in degree but not in basic principle. Modern scanning standards (525 lines, 60 fields per second) were used, and the signals were transmitted in the form of modulated radio-frequency carriers, rather than as video signals on wires. But three photosensitive devices (e.g., three multiplier phototubes in a tricolor flying spot scanner) and three picture tubes were employed, all operating simultaneously.

This system was intended to be compatible in scan-

[14] A full discussion is given in the Condon Committee Report, "The present status of color television," by the Advisory Committee of Color Television, reprinted in Proc. I.R.E., vol. 38, p. 980; September, 1950. See Chapter 2, Part VII, pp. 982–983.

[15] The form of the color-subcarrier system described here is that recommended in April, 1951 by the Ad Hoc Committee of the National Television System Committee. For an account of this group and its work, see "Plans for compatible color television," *Electronics*, vol. 24, p. 90; August, 1951.

ning with the black-and-white system. As noted above, the carrier signal corresponding to the green primary image was to serve two purposes: to operate black-and-white sets (equipped with frequency converters to accept uhf signals), and to serve as one component of color reception. It was proposed, therefore, that the green carrier might serve as the primary carrier of the transmission, and that the red and blue signals might be sent as subcarriers, imposed on the primary carrier by submodulators and appropriate wave filters.

Many objections to this simultaneous system were raised. The problem of register among the three separate color images at transmitter and receiver, the loss of spectrum space in guard bands between the three sets of sidebands, the possibility of selective attenuation and phase displacements among the carriers and their sidebands, were urged as serious shortcomings. Its advantages were also recognized. Since the three primary images worked in unison, the flicker problem was no more in evidence than in the black-and-white system (which had by then proved itself abundantly satisfactory in this respect). Some measure of compatibility had been achieved. But the system had not been field tested prior to the FCC demonstration, and no accurate measure of its strength and weakness was available.

In perspective, it appears that this second ("1946") simultaneous system took one important step forward, but failed to take another important step. The advance was the proposal of mixed-highs transmission, which recognized that the resolution required in the three primary images was not the same. Tests were conducted to show that, in a color image composed of red, blue and green primaries, the highest resolution was required in the green image, somewhat less resolution in the red image, and substantially less in the blue image.[16]

This fact, which had been recognized by physical oculists for years, and had been reported by a lighting engineer in 1911, revealed to television specialists that a color system which utilizes bandwidth to provide equal resolution in the three primary images is wasteful of spectrum space. The 1946 simultaneous system, wasteful in this respect in requiring guard bands, was partially redeemed by the proposal to limit the resolution of the blue image to about one third that of the green and red images, with proportionate saving in the spectrum occupied by the blue-image sidebands.

The conspicuous failure of the system was that *two* subcarriers and their sidebands occupied regions of the spectrum *separate* from that of the primary carrier. It is now recognized that only one subcarrier is necessary, (since the subcarrier, when synchronously modulated and demodulated, can carry quadrature or three-phase information on two or three color quantities). Further, it is realized that the primary carrier and the subcarrier can occupy the *same* region of the spectrum, if the carrier frequencies are so related that their sidebands are interleaved. The latter relation is satisfied when the subcarrier frequency is an odd multiple of half the line-scanning frequency.

These concepts, particularly the latter, are considered by many to be relatively new to television engineering. In point of fact, neither idea is new and both were available when the 1946 simultaneous system was designed. The writer well remembers the surprise and chagrin with which an early patent, which had expired in 1947, was resurrected in 1950. This patent, covering an invention[17] by Frank Gray, one of television's great unsung pioneers, showed not only that the frequency interleaving of sideband components was feasible, but actually envisaged its application to a color-television system! Such is the lack of communication between successive generations of engineers that apparently no one remembered the patent.

The third appearance of the simultaneous color system came during the 1949–1950 FCC color television hearing, when RCA demonstrated the dot-sequential system. This system used a single subcarrier, modulated by three color quantities in three-phase form and synchronously demodulated to recover the quantities with a minimum of interaction between them. The color-subcarrier sidebands occupied the same portion of the spectrum as the primary carrier sidebands, but the technique of frequency interleaving was imperfectly developed (as judged from the present perspective) and the interference between carrier and subcarrier was unduly prominent.

The interference appeared in the image as a dot structure, and it could be considered that the primary images were made up of collections of such dots, interlaced along each line of the image. It was natural to think of these dots as being laid down in sequence, so by analogy to the field-sequential and line-sequential systems then in evidence before the Commission, the system took the name "dot-sequential color system."

For months there was great confusion as to the proper terminology for this system. From the standpoint of terminal apparatus it was clearly a simultaneous system, since three cameras and three picture tubes were used, each devoted to one of the primary colors, and each operated simultaneously with the others. But from the standpoint of the transmission method, it appeared to be a sequential system, since the camera output signals were sampled in sequence, and the picture tubes were activated in like sequence, the sequence occurring at the rate of three samples for each cycle of the color subcarrier (3×3.58 mc $=10.74$ million samples per second). It now appears that the

[16] Quantitative evidence of this fact is given in the paper by M. W. Baldwin, "Subjective sharpness of additive color pictures," PROC. I.R.E., pp. 1173–1176; this issue.

[17] U.S. Patent 1,769,920, F. Gray. Applied for April 30, 1929, issued July 8, 1930.

sampling technique was incidental to the basic principle of the system. By a modification of the receiver (filtering the color signals before application to the picture tubes) it could be shown that the three picture tubes could in fact operate in simultaneous fashion.

It remained for the full development of a new technique, shunting a monochrome (brightness) signal around the color-subcarrier apparatus, to reveal that the dot-sequential color-subcarrier system was really a simultaneous color-subcarrier system.

When the first demonstration of the dot-sequential system was given in 1949, in its initial "sampled" form, the dot structure in the images impressed most observers as a major drawback and the susceptibility of the color subcarrier to interference was a matter of concern. But basically the system was attractive: it was compatible; it was free from flicker difficulties; it had high resolution capability; and it was highly efficient in the use of the radio spectrum. Consequently many able workers were inspired to carry on after the system was rejected in the FCC decision of October, 1950. While it is too early to assign credit by name without fear of injustice to those unnamed, the names of Loughlin and Bailey of the Hazeltine Corporation, Bradley and Bingley of the Philco Corporation, and Dome and Samulon of the General Electric Company will undoubtedly be added to those of Kell, Brown and their coworkers in RCA, when the history of this phase of television development is finally written down.

Following the FCC decision, three noteworthy demonstrations of different approaches to the color-subcarrier system were held: On December 5, 1950, RCA demonstrated a revised form of its system to the press and acknowledged the contributions of the Hazeltine Corporation. In this demonstration, the shunted monochrome technique (see below) was used, and a notable reduction in the dot structure of the images, in color and black-and-white, was evident. In February, 1951, the Philco Corporation demonstrated to the NTSC Ad Hoc Committee a color-subcarrier system employing a wide-band brightness signal and two color-difference signals modulating the subcarrier in quadrature. Finally in the week of August 6, 1951, demonstrations of color-subcarrier systems were held by General Electric, Hazeltine, RCA and Philco which illustrated the effect of the value of the color-subcarrier frequency, the constant-luminance system (first demonstrated by Hazeltine in April 1950), and the most recent improvement, "oscillating color sequence."

The last stage in the development of the color-subcarrier system, covering the period 1950–1951, has resulted in a substantial refinement in terms of colorimetric concepts. Prior to this stage, the colorimetry of color television was simple, involving the choice of three receiver primaries and three corresponding camera taking characteristics.

A more subtle approach had been prevented by preoccupation with conservation of spectrum space. When spectrum economy was well in hand, the next step was a concerted effort to achieve a high degree of co-operation between the color-subcarrier system and the human eye, by application of the principles of colorimetry.

The three basic color quantities are *brightness*, *hue* (redness, blueness, etc.), and *saturation* (lack of dilution of the hue by white light). A black-and-white television system deals solely with the first quantity, brightness. A compatible color-television signal, intended to be of optimum value to a black-and-white receiver, must provide brightness information without undue disturbance from the hue and saturation components of the color image.

Thus there were two forces, one scientific (the effort to base the color system on the properties of the eye) and one economic (the effort to achieve a system of high compatibility) which conspired to demand a colorimetric revaluation of the system.

From this study came three major advances in the color-subcarrier system. The first was the realization that the color-television signal should be cast into two components, a primary carrier and sidebands for brightness transmission, and a subcarrier and sidebands for hue-plus-saturation ("color-minus-brightness") transmission.

The second step, realized simultaneously with the first, was to proportion the modulation vectors of the subcarrier so that interference from external sources to the subcarrier would create a minimum of brightness disturbance in the image. The latter aim was met by constraining the color subcarrier to approach zero for colors near white.

The third step was the realization that certain simple taking characteristics of the camera, and the signals arising therefrom, could be transformed in electronic computers, known as matrix units, to obtain signals corresponding to brightness on the one hand and to color-minus-brightness on the other.

When the two signals, brightness and color-minus-brightness, are added together they produce color. When the brightness signal alone is present (as during the scanning of white or gray objects), the color subcarrier is inactive and can cause no dot structure or other deleterious cross-effects with the primary carrier. As a result, the isolation of brightness transmission and hue-saturation transmission not only improved the quality of color rendition but greatly improved the structure of the image, both in color and in black-and-white.

To these improved color analysis and synthesis methods, were added refined methods of superimposing the carrier and subcarrier in the same region of the spectrum. Among these refinements were: vestigial sideband modulation of the subcarrier, improved filtering, the use of a balanced modulator as a substitute for critical filtering operations in the transmitter, and alternation of the sequence of the color-modulation vectors on successive fields to minimize the effects of phase distortion and of transients generated in vestigial sideband transmission.

The net result of these measures is that a brightness signal having identically the bandwidth of the black-and-white system (4 mc) and thus having equal resolution, is combined in the same spectrum with a color-minus-brightness (hue-plus-saturation) signal occupying a bandwidth of about 2 mc. The latter signal produces essentially no brightness contrast and, since lack of resolution is less perceptible without such contrast, the resolution of the image is carried substantially by the brightness component. The over-all result closely approaches that produced by a simultaneous system employing a separate 4-mc band for each primary, or 12 mc in all. The fact that an image can now be transmitted on a 4-mc band which, five years ago, would have required 12 mc is, in the writer's opinion, the most striking accomplishment in spectrum conservation in the history of electrical communication.

Since November, 1950, work on the color-subcarrier system has been co-ordinated by the National Television System Committee. As this is written, agreement is being reached within the NTSC panels concerning detailed technical specifications with which to conduct field tests during the latter months of 1951.

No account of the development of the color-subcarrier system is complete without mention of the tricolor picture tube ("color kinescope," see papers on this subject in this issue of the PROCEEDINGS).[18] This type of color tube can be used in both the color-subcarrier and field-sequential systems of color television, and hence is not a major distinguishing feature between the two systems. But it is only fair to say that, without the development of such a picture tube, the color-subcarrier system would be under a most severe handicap, since the dichroic-mirror receivers used in the early demonstrations of the system are conceded to be impractical for home use.

The only form of tricolor tube to be demonstrated publicly to date is the mask-and-dot form invented by Alfred N. Goldsmith and developed in the RCA Laboratories. This tube takes second place only to the image-orthicon camera tube as a *tour de force* in electron optics. Its design and construction combine in a remarkable manner the talents of the electron optician, the phosphor chemist, the photographic technician, the photoengraver, the printer, and the mechanical engineer, not to mention the production man concerned with its assembly and processing.

Since this tube is thoroughly described in the following pages, a brief description suffices here. The viewing screen consists of a glass plate on which are printed some 600,000 separate phosphor dots, like the halftone dots in color printing, 200,000 fluorescing in each of the three primary colors. The phosphor dots are arranged in groups of three, the group constituting a picture element. Three electron guns are used (a single-gun tube has been developed but at the moment does not show the promise of the three-gun type). Each gun is so arranged that it can excite phosphor dots of one color only. By exciting the three guns simultaneously, three primary-color images are created, interspersed dotwise on the viewing screen. The dot structure is so fine that it cannot be discerned at normal viewing distances, and the three images fuse, recreating the image in full color.

The three electron beams are constrained to fall only on the phosphor dots of the associated color by passing them through holes in a metal mask, mounted parallel to, and about one-half inch from, the viewing screen. One such hole is aligned with each group of three phosphor dots. That fact that the metal mask must be pierced by 200,000 holes, each accurately aligned with 200,000 groups of phosphor dots, poses a considerable problem in the manufacture of the tube, so much so that the writer once swore under oath before the FCC (before seeing the tube demonstrated) that he did not believe it could be done. In this he, also, erred on the side of excessive conservatism. By using the techniques of photoengraving and color printing the alignment is arranged en masse. While great care must be used in this alignment process, it poses no more of a problem fundamentally than that met by color printing presses which produce millions of copies of colored pictures each week, each consisting of many millions of aligned color dots.

It appears therefore that the tricolor tube will succumb to the techniques of mass production without too much struggle and will be used, in one form or another, in all the systems of color television, including that one which eventually commands the ultimate support of the viewing audience.

Capabilities and Limitations of the Color-Subcarrier System

Pending the outcome of field tests, no assessment of the NTSC color system can be considered final. But a preliminary outline of its strength and weakness may be stated.

The strong points relate to compatibility and quality of service. The system is fully compatible; the dot structure in the black-and-white rendition of the color signal has been reduced to a residue of such low visibility as to have no practical importance, when constant-luminance modulation and oscillating color sequence are used.

The quality of the color image is high. The resolution and flicker performance are identical to that of the black-and-white system. The color gamut, color bal-

[18] A series of papers on direct-view color kinescopes begins on page 1177 of this issue.

ance and gradation, in the latest demonstrations, are fully equal to the high standards set in similar test demonstrations of the field-sequential system. The system displays high resistance to the effects of random noise and interfering carriers. With respect to the primary carrier, including synchronization of scanning and color phase, the NTSC color system requires no more protection than the black-and-white system. With respect to the subcarrier, the effect of interfering carriers near the subcarrier frequency has been markedly reduced by the constant-luminance modulation method. Whether any special protection against the remaining subcarrier interference effects is necessary must be established in the field test. It is confidently expected that the field test will prove that quality of service can be maintained under the same conditions of interference as now affect the black-and-white service.

The principal reservation concerning field performance has to do with severe conditions of multipath transmission. Since the color subcarrier is, in part, phase modulated, reflected signals may cause partial cancellation or reinforcement of the subcarrier, with consequent disturbance to the color values in the image. If such effects appear prominently in the field test, it will be necessary to assess them relatively to those introduced by similar multipath conditions in the black-and-white and field-sequential color systems.

The remaining doubts concerning the color-subcarrier system lie almost wholly on the cost side of the quality-cost equation. The terminal equipment of the system, involving three superimposed images at transmitter and receiver, can be expected to be more costly, at least for the immediate future, than the simple rotating-disk camera and reproducer. But if the limitations of picture size force more elaborate (i.e., rotating-drum or tricolor-tube) designs on the field-sequential receiver designer, the disparity in terminal equipment cost will largely disappear.

The circuit arrangements of the color-subcarrier receivers are at present more involved than those of field-sequential receivers. A field-sequential receiver, equipped for the two sets of scanning standards, with a crispening circuit and automatic control of color phase can be expected to employ about ten more tubes and crystal diodes than an equivalent black-and-white set. Current models of color-subcarrier receivers employ 54 tubes, about 32 more tubes than a typical black-and-white set. Designers promise that more than half of these 32 tubes will be removed without adverse effect, as more experience with the circuits is gained. If this promise is kept, the color-subcarrier receiver would have about five more tubes than the field-sequential receiver, but this differential would be overcome by the expense, in the latter set, of such items as the filter-disk motor and the saturable reactor required for color phase control. It is, of course, too early to draw any realistic comparison of receiver costs, since a proper correlation can be drawn only between receivers produced competitively for the same market.

Whatever the future trends in cost, at present the color-subcarrier system is demonstrably more complicated than the field-sequential system. In return for this additional complication, higher quality of transmission is achieved. To this long-term advantage must be added the overwhelming short-term advantage of compatibility.

The eventual decision between the color systems, if made on rational grounds, will depend on the relative importance attached to the quality and cost factors. In a few months, sufficient data should be at hand to permit rational conclusions to be reached by engineers, by FCC, and by the master of both, the public.

Color Television and Colorimetry*

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Summary—The high lights of the history of color measurement and of color photography are reviewed. Following this introduction, the principles of modern 3-color colorimetry are developed from a hypothetical experiment in color matching. The conventional theory of "perfect color reproduction" by color television is built up from colorimetric background. Some of the difficulties to be expected in applying colorimetry to color television are brought out.

Finally, there is some discussion which tends to show that colorimetry may not be a sufficiently powerful tool to provide answers to all of the questions which will arise in the reproduction of scenes in color by television. The advantage of colorimetry as a background is indicated, however.

THE RADIO engineer has been faced with new problems with every advance of radio communication, from wireless telegraphy to color television. From one point of view the steps between telegraphy, telephony, and black-and-white television have not been very great. Admittedly, each new communication method has required new techniques. But, in each method of communication the transmitted signal bears a proportional relation to some readily identifiable measure of the material to be transmitted. It is sound pressure (or particle velocity) which is measured and transmitted in a radio-telephone system. Similarly, it is brightness (or more accurately luminance) which is measured and transmitted in a black-and-white television system.

By a logical extension of this line of thought, the quantity measured and transmitted in a color-television system is *color*. At this point, the radio engineer finds he is faced with a new problem. How does one measure color? It is reasonable to expect to find the answer to this question in the science of colorimetry, which may be defined as the measurement and specification of color in numerical terms.

Before we can tackle the application of colorimetry to color television, we must understand some of the fundamental things about color. For that reason the author intends to answer a few questions before discussing the general matter of colorimetry. These questions are:

1. What is color?
2. Why 3-color?
3. How does color in television differ from Kodachrome?
4. Why do we depend on colorimetry in color television?

The discussion under these headings is historical in part, and the general conclusions are repeated in the discussion of 3-color colorimetry. If the reader has a firm grasp of the fundamentals of color, he may wish to skip over these introductory sections.

What Is Color?

Color, as one aspect of our surroundings, has aroused the curiosity of natural philosophers and scientists for at least as long as there is any record of scientific investigation.[1] Much of the groundwork for what we consider today to be technically sound treatment of light and color was laid by Sir Isaac Newton. Most of his work in this field is reported in his "Opticks,"[2] although a few additional experiments are described in his "Lectiones Opticae." Much of this material covers the laws of reflection, refraction, chromatic aberration, and the like, which we would classify as physical optics. However, a large portion of Part II of the First Book of Opticks is devoted to color and its perception.

Newton pointed out[3] that the sensation of color did not arise because light rays were themselves colored but because rays of different wavelengths had "a certain Power and Disposition to stir up a Sensation of this or that Colour." As we shall see later, this idea is contained in our modern definitions of light and of color. After demonstrating that the color sensation was not altered by any further reflection or refraction of a narrow band of wavelengths, Newton concluded that the apparent color of objects was due to selective reflection or transmission of the incident radiation. He pointed out that if the radiation from the sun did not contain more than one wavelength "there would be but one Colour in the whole World."

Newton showed that the appearance of the components disappeared in a mixture of spectrum colors; and also that colors could look alike and have different spectral composition. In particular, he mentioned that the mixture of spectrum red and spectrum yellow appeared like spectrum orange, although differing from spectrum orange in composition. He went on to show that mixtures of neighboring spectrum colors looked like the intermediate spectrum colors, but that mixtures of red and violet produced purples which did not appear in the spectrum.

In further experiments, Newton showed that white could be produced by mixtures of spectrum colors. The resulting white was the same whether the spectrum colors were added together at one time (simultaneously) or whether they were added sequentially at a sufficiently high frequency. The reader will recognize that both these methods of adding colors have been used in experimental color-television systems.

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[1] See bibl. ref. 1.
[2] See bibl. ref. 2.
[3] See "Definition" on p. 124, bibl. ref. 2.

Finally, Newton concluded that all colors "in the Universe" were either spectrum colors or were the result of the mixture of spectrum colors, taken in different proportions. To complete the story, he showed how the color of mixtures of spectrum colors might be calculated, giving this analysis under the title "In a mixture of Primary Colours, the Quantity and Quality of each being given, to know the Colour of the Compound." Since he could see seven distinct colors in his prismatic spectrum (red, orange, yellow, green, blue, indigo, and violet), he assumed seven primaries for this calculation. His process is fundamentally the same as the one we shall discuss later for the mixture of primary lights.

The important facts about color which we have garnered from Newton are:

1. Any given composition of radiation with wavelength arouses a sensation which an observer associates with a particular color.
2. The sensation of this same color can be aroused by a variety of compositions of radiation.
3. The color of objects is affected both by the composition of the radiation from the illuminant and by selective reflection or transmission by the object.

Why 3-Color?

Even before Newton made his demonstrations of the effects of mixing colored lights, some experimenters knew that nearly all colors could be obtained by mixing only three pigments.[4] The difference between the mixture of pigments and the mixture of lights (which is the difference between color printing and color television) was not clearly stated by Newton. This difference was, indeed, a continuing source of confusion until the middle of the nineteenth century when Helmholtz[5] presented a clear exposition of the subject. As an example of this confusion, LeBlon,[6] before 1722, thought he was following Newton when he tried to make color pictures using seven pigments. The failure of the 7-color (pigment) process drove LeBlon to the use of only three colors, and finally to the use of a 3-color (pigment) plus black process. This latter process is the forerunner of modern color printing.

In 1792, Wünsch[7] reported a series of experiments using colored lights obtained from the prismatic spectrum. He found that four of Newton's seven primary colors could be produced by suitable mixtures of the remaining three. As a consequence, Wünsch went on to show that only three colored lights were required in mixtures that would look like any of the known colors.

Thomas Young presented a paper "On the Theory of Light and Colours"[8] before the Royal Society of London, on November 12, 1801. This paper was a logical demonstration, based on the literature from the time of Newton, that light must be wave motion rather than be composed of physical particles. To explain color vision, Young suggested that the retina was made up of resonators which responded differentially to radiation of different wavelengths. In order that the number of different kinds of resonators be kept within reason, Young said " . . . , it becomes necessary to suppose the number limited for instance to the three principal colours, red, yellow, and blue, ..." As the reader will see shortly, these colors happen to be the subtractive (or pigment) primaries.

By the time Young published his lectures[9] in 1807, he had reached the opinion that the three fundamental visual sensations should correspond to the additive (or light) primaries: red, green, and violet. Apparently he reached this conclusion by painting sectors in different colors on a disk and additively combining the reflected lights by spinning the disk.[10] From further experiments with this device, Young concluded, just as Wünsch had concluded from his experiments with spectrum lights, that the impression of all colors could be produced by the additive combination of red, green, and violet lights.

It appears that the choice of red, green, and violet disturbed Kelland who edited Young's lectures for republication in 1845.[11] Kelland added a footnote reference, in which he pointed out that Wünsch[12] had suggested this same set of primary colors, but that Mayer[13] had chosen red, yellow, and blue and that "this is the more common hypothesis."

Wünsch's report of his experiments seems to have been forgotten completely. It is likely that Young's confirmation would have been lost similarly, except that he speculated that color vision might be explained by three sensation mechanisms corresponding to these three primary colored lights. Parenthetically, it should be pointed out that we need not be concerned about this or any other theory of color vision in studying color television. The observed facts, rather than any theory, form the basis on which our study is founded.

In fact, following Young, most experimental effort was still directed toward the study of pigment mixture.[14] Actually, as late as 1849 Maxwell's mentor, Forbes,[15] proposed the systematic classification of all colors on the basis of mixtures of three reference pigments. As was still common, Forbes did not distinguish between the

[4] See bibl. ref. 66.
[5] See bibl. ref. 6.
[6] See bibl. ref. 63.
[7] See bibl. ref. 64.
[8] See bibl. ref. 3(a).

[9] See bibl. ref. 3(b).
[10] Apparently this device for the addition of colored lights has been discovered and forgotten many times. It is credited to the astronomer Ptolemy in the second century by the Encyclopedia Americana. In 1888, Abney and Festing (see bibl. ref. 4(b)) wrote: "Again, in experimenting with Gorham's discs, such as Maxwell employed. . . ." Maxwell saw this device in Forbes' laboratories while he was still in high school (see the introduction to bibl. ref. 7). Today we call this device the "Maxwell disk," largely because of the fundamental nature of the experiments he carried out with it.
[11] See bibl. ref. 3(c).
[12] See bibl. ref. 64.
[13] See bibl. ref. 35.
[14] The author has only found one exception to this generality, that is, the work done by Ludicke (see bibl. ref. 65) and reported in 1810. This latter work seems to have been completely forgotten.
[15] See bibl. ref. 5.

mixture of pigments and lights, and in consequence he stated that Young's choice of red, green, and violet as primary colors was obviously wrong.

The Young three-sensation theory of color vision was "revived by Helmholtz who endeavored to find for it a physiological basis,"[16] in the early 1850's. In his first paper on the subject[17] Helmholtz reported that most colors could be imitated by a mixture of red, green, and violet lights, taken in suitable proportions. He stated also that he could imitate white light by a mixture of only one specific pair of spectrum lights. This obvious contradiction of the philosophy set down by Newton[18] aroused the interest of Grassmann to the point that he made an extended theoretical study of the mixture of colored lights.[19] After proving by pure logic several assumptions which have become basic precepts of colorimetry, Grassmann proved that there must be an infinite number of complementary spectrum colors. Later, Helmholtz improved his experimental procedure and confirmed Grassmann's conclusion.[20]

Meanwhile, immediately upon the receipt of his degree from Cambridge in 1854, Maxwell plunged into a series of experiments with the purpose of testing the Young 3-color theory by measurement.[21] Since Maxwell's interest was directed toward measurement as contrasted with Helmholtz's search for a physiological basis for Young's 3-color theory, we find that Maxwell laid the foundation for the modern numerical 3-color theory.

Maxwell studied color mixtures by using both the spinning disk[22] and a so-called "color box" which was arranged to combine spectrum colors.[23] From these experiments, he concluded that mixtures of three suitably chosen colors taken in different proportions would cover a wide gamut of color. However, even using spectrum colors for primaries, he found it impossible to produce mixtures which looked like all of the other spectrum colors.[24]

We can sum up the results of Wünsch, Young, and Maxwell, as they apply to color television, somewhat like this: Mixtures appearing like nearly all possible colors can be produced using only *three* colored lights in combination. We shall see later that the impossibility of producing every color by mixing three colored lights is not a very important limitation on a color-television system.

How Does Color in Television Differ from Kodachrome?

The use of a mixture of only three colored lights, instead of the whole spectrum, in the reproduction of a scene in color is credited to Maxwell.[25] There is no indication, however, that this was his original intention. The fact is that in a paper published in 1857,[26] Maxwell described Young's three-sensation theory of color vision. In order to clarify the idea, he suggested an analogy with a "supposed case taken from the art of photography." To represent the red sensation in the visual process, he proposed the projection by red light of a lantern slide, the negative for which was made through a red glass. Similarly, the green and violet sensations were to be represented by lantern slides made and projected through green and violet glasses, respectively. To extend the analogy to cover the color response produced in the brain by the three independent color sensations, Maxwell suggested superimposing the three projected images on the screen. It was obviously his thought that the combined image on the screen was a good parallel to the combined effect of the sensations in the brain. He stated also that the colors in the combined screen image would not look right because in viewing the screen the process would be repeated. That is, in making the analogy the visual steps would have occurred once and in viewing the combined image, the process would be duplicated.

Maxwell demonstrated this analogy in another lecture in 1861. The lantern slides for this demonstration were made by Thomas Sutton, the editor of *Photographic Notes*. The process so interested Sutton that he published not only his description of it but also Maxwell's own account of his lecture.[27] It is interesting that, in the 4 years between these two lectures, Maxwell had overcome his doubts that color photographs could be made in this way. He said of a picture of a colored ribbon that, except for the deficiencies of the available photographic materials, the result "would have been a truly coloured image of the riband." Actually, Maxwell's doubts were valid. Almost 30 years were to pass, however, before the rational basis for making 3-color additive photographs was to be demonstrated by F. E. Ives.[28]

The reader who has any knowledge of color printing will ask at this point: why the insistence on work done in the middle of the nineteenth century; what of LeBlon's 3-color prints made in 1722?[29] The answer is that the methods are different; that one is an example of the process we use in color television, and that the other is an example of the color process used in Kodachrome.

The process described by Maxwell involved the combination of colored lights, and his is the first known description of the process. This method of producing a color reproduction is known as the *additive* method. Today we know of no other practical method of producing a color-television picture. In the television case, the colored lights are produced by colored phosphors on

16 See bibl. ref. 6, 7.
17 See bibl. ref. 8.
18 See bibl. ref. 2.
19 See bibl. ref. 9.
20 See bibl. ref 6.
21 See bibl. ref. 10.
22 See bibl. ref. 7(a)–(7d).
23 See bibl. ref. 7(e).
24 See bibl. ref. 7(e), 7(h).
25 See bibl. ref. 11.
26 See bibl. ref. 7(b).
27 See bibl. ref. 67.
28 See bibl. ref. 12.
29 See bibl. ref. 11, 63.

kinescope screens, or by color filters in front of the phosphors. These colored lights may be combined either by half silvered or by dichroic mirrors in a simultaneous system. Alternatively, the three colored lights may be placed so close together that the observer sees them as one. In a sequential system, the combination is made by presenting the three colors in sequence so rapidly that they add together in the observer's visual system.

The process used by LeBlon, and by his successors to the present day, depends on a different principle. In most practical cases, it is impossible to show this difference clearly. However, in Kodachrome the essentially different element of LeBlon's process is present in a pure form.

In viewing a Kodachrome picture, we start, not with colored light, but with white light. The Kodachrome image is made up of three separate layers, the images in these layers corresponding to the amounts of red, green, and blue in the original subject. The image in the layer corresponding to red light in the subject is a positive photograph of this red. It is therefore dense where there was no red light in the subject and thin where the subject contained large amounts of red. It is obvious that this layer should only affect red light incident on it and that the green and blue components of white light falling on it should be transmitted freely. The color of the transmitted light is the mixture of green and blue, commonly called "minus-red" or "cyan." Similarly, the image in the layer corresponding to green in the subject modulates only the green rays from white light falling on it, and transmits both red and blue rays. The color of this layer is, therefore, blue-red, and this color is known as "minus-green" or "magenta." The third layer modulates only the blue rays, and transmits both red and green. Its color is minus-blue or yellow. Since each layer takes away, or absorbs, a part of the incident light, this is known as the *subtractive* method of color reproduction.

Obviously, color pictures can be made on a white paper base, using the same principle as the Kodachrome process for transparencies. In this case, light must pass through the modulating layers to the white base and be reflected through the layers again before reaching an observer's eye. Provided these images are made up of homogeneous dyes which transmit and absorb in different spectral regions as described above, such prints on paper are truly subtractive. However, if we use pigments to form the images, an additional complication arises. When light falls upon a mixture of particles of pigments, some of it is reflected singly from individual particles, and some of it is reflected many times between particles before reaching an observer's eye. Consequently, ordinary color printing has some of the characteristics of both the additive and the subtractive processes. For this reason, the production of a pleasing print has been largely empirical in the past.

Fundamentally, however, there are these two color processes. The first in our interest in television is the additive, in which colors are produced by the additive combination of colored lights. The other, which is much more common in our experience, is the subtractive process, in which white light is successively modified by three layers of what might be considered band-elimination materials. The usual primaries for additive color processes are red, green, and blue. As mentioned above, the bands of radiation transmitted by the ideal subtractive color materials correspond to cyan (blue-green), magenta, and yellow. Many materials used for the subtractive process may depart so far from the ideal that they appear to be blue, red, and yellow; and in consequence, these 3-color names are frequently used to designate the primaries for printing or painting.

Why Do We Depend on Colorimetry in Color Television?

In an earlier paragraph, the close parallel between Maxwell's demonstration of color photography and color television was pointed out. Why, then, can we not find the answer to our color problems in television in the art of additive color photography? The answer is that no such art ever developed.

Actually, F. E. Ives, using photographic emulsions which were sensitive over the entire visible spectrum,[30] repeated Maxwell's demonstration in 1888. Later in the same year, he realized that spectral sensitivity characteristics in the camera channels should be related to certain characteristics of color mixture that Maxwell had measured, and he corrected his technique accordingly.[31] Later he arranged to market 3-color cameras, projectors, viewers, and steroviewers for additive color photography. However, the apparatus was complicated, the care required in the photographic steps was great, and each set of positives had to be registered to view the resulting color pictures.[32] Consequently, this process never became a success commercially. Later some screen-plate color photographic processes were developed which were additive in principle.[33] However, the color techniques used were empirical.

The fundamental relations, stated by F. E. Ives, between certain characteristics of vision and the sensitivity of the taking channels were used by his son Herbert E. Ives in the design of a color-television system in 1929.[34] However, these principles did not begin to receive any great consideration until, in 1937, Hardy and Wurzburg wrote a paper showing that the theoretical basis for additive color reproduction lay in the science of colorimetry.[35]

And why should this delay have occurred, or why should not color-reproduction theory have developed, particularly, since color printing had gained wider and wider circulation over this same period? In an earlier paragraph it was pointed out that color printing was

[30] See bibl. ref. 12(a).
[31] See bibl. ref. 12(b).
[32] Through the kindness of Herbert E. Ives, the author has had the privilege of examining some of these pictures. If and when color television produces equally pleasing results, other present-day color processes will do well to look to their laurels.
[33] See bibl. ref. 11, 13.
[34] See bibl. ref. 14.
[35] See bibl. ref. 15.

fundamentally a subtractive process, diluted with some characteristics of the additive process. In consequence, much of its development has been along empirical lines; and its stalwarts have been impatient of theory.[36] Such impatience arose because it was far too complicated to modify the theory of additive color mixture to fit the hybrid color process involved; and there seemed to be no hope of gaining commercially useful results from a theory of the necessary complexity. It is only recently, through the application of scanning methods to the making of color plates, that the advantages of any color theory could be realized practically in subtractive color printing.[37]

All of these technical developments in color reproduction since 1937 have been based on knowledge gained in the field of colorimetry. But how does it happen that color theory has advanced in colorimetry, while remaining almost static in the field of color reproduction?

The first suggestions of color measurement in the modern sense were made almost simultaneously with the first suggestions for additive color reproduction. Both Maxwell and Grassmann suggested that any color could be specified in terms of a mixture of colors which appeared like it. In two papers by Maxwell,[38] we find the suggestion that any color be specified in terms of the mixture of three "standard" colors which matches it. Grassmann recommended specifying a color in terms of the mixture of white and saturated colored light which matches it.[39] This saturated light is identified by its wavelength in the spectrum. We find both these methods for the specification of a color in use today.[40]

It is likely, however, that the specification of color in numerical terms would have gone the way of additive color reproduction if Abney,[41] and a little later F. E. Ives,[42] had not resurrected it at a time when such specification began to be of commercial importance. Be that as it may, colorimetry has developed as a science almost continuously since about the beginning of this century.

To sum up, additive color reproduction and colorimetry have a common beginning in the work of Maxwell. Prior to our interest in color television, no additive color process has appeared that has been sufficiently important commercially to call for the development of a separate theoretical background. Colorimetry, in contrast, with a strong commercial interest in the specification of color, has fostered a continuous growth of theory and of measuring techniques. Fortunately, it is possible to apply much of the theory of colorimetry to the problem of additive color reproduction.

Fundamentals of Color

To help in understanding what it is we mean when we say that a color-television system reproduces *color*, there is quoted below a definition of that word by the Committee on Colorimetry of the Optical Society of America:[43]

> "Color consists of the characteristics of light other than spatial or temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye."

From the point of view expressed in this definition, light and color are neither radiant energy, nor are they sensation. Rather, *light* "is the *aspect* of radiant energy of which human observers are aware through the *visual sensations* . . . ." *Color* is one characteristic or dimension of light; and in addition to color, light may have characteristics which convey impressions of form and of fluctuation or of motion.

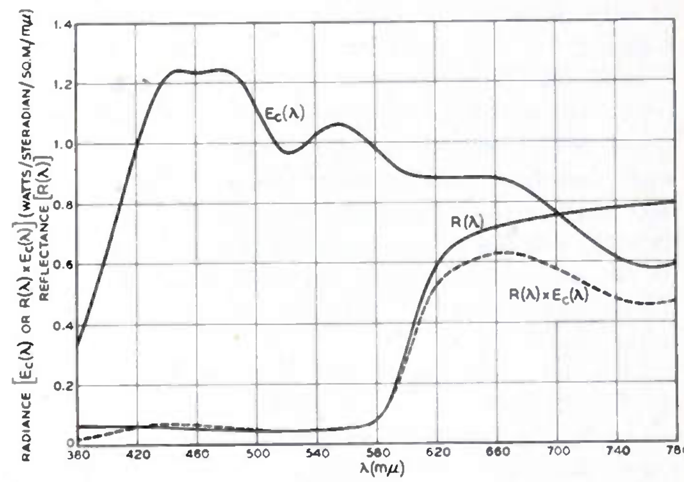

Fig. 1—Compositions of radiance for sample colors.
$E_C(\lambda)$ = Radiance of reference surface, irradiated by Illuminant *C*.
$R(\lambda)$ = Directional reflectance of Munsell Chip 5R4/14.

As a further aid in understanding the meaning of *color*, let us consider the radiance[44] compositions shown in Fig. 1. The curve labeled $E_c(\lambda)$ represents the radiance of an "ideal" surface[45] irradiated by a source of artificial daylight. (This particular radiance composition corresponds to "Illuminant *C*,"[46] which was standardized by the International Commission on Illumination (ICI) in 1931.)[47] If we were to look at this ideal surface so irradiated, we would call it "white" (or possibly "bluish-white") and say it was very bright.[48] These words describe the color sensation evoked by this radiant energy.

[36] See bibl. ref. 11.
[37] See bibl. ref. 16.
[38] See bibl. ref. 7(c), 7(e).
[39] See bibl. ref. 9.
[40] See bibl. ref. 17, 19(d).
[41] See bibl. ref. 20.
[42] See bibl. ref. 21.

[43] See bibl. ref. 19(c).
[44] Radiance, which is power per unit solid angle radiated per unit of projected area, is used throughout this discussion to avoid complications which depend solely on the geometry of the problems.
[45] An "ideal" surface is one which absorbs no radiation and which diffuses perfectly all radiation falling on it.
[46] In a private communication, Dr. Deane B. Judd advises the author of a trend toward the replacement of the term "Illuminant A" (or B, or C) by the term "Standard Source A" (or, B, or C). Examples of the use of this newer terminology are found in bibl. ref. 31 and 40.
[47] See bibl. ref. 22–24.
[48] The numerical values of radiance in Fig. 1 are somewhat greater than you would find outdoors on a clear day.

Suppose we replace the ideal surface by a piece of paper, the directional reflectance of which varies as is shown by the curve $R(\lambda)$ in Fig. 1. The radiance from this surface will be distributed as is shown by the curve $[R(\lambda) \times E_c(\lambda)]$. If we were to look at the piece of paper, we would say it was *red*, and probably that it was not as bright as the ideal surface had been. This is a case of a different color sensation evoked by a different composition of radiance.

Identical color sensations to those evoked in these two examples could be aroused by an infinite variety of radiance compositions. In particular, Newton[49] showed, and it was confirmed by Helmholtz,[50] that the sensation of white could be produced by the additive combination of pairs of suitably related spectrum colors. Similarly, Wünsch,[51] Young,[52] and Maxwell[53] showed that both the white and the red, as well as almost all other color sensations, could be produced by the additive combination of only three suitably chosen colored lights or primary colors.

It is that latter fact that forms the basis for color television. We can produce three colored lights by means of colored phosphors in picture tubes, or we can start with phosphors, which radiate energy over the greater part of the visible spectrum, and use color filters to produce the colored lights. Variation of the signals applied to the picture tubes will vary the strength of these colored lights, and their mixture will produce almost all color sensations.

We must know how to vary the strength of these receiver primaries to produce the same color sensation as any given composition of radiance would produce at the television camera. This question is the one that colorimetry can answer.

3-Color Colorimetry

The whole philosophy of 3-color colorimetry can be set down in a few statements. The statements are formal expressions of the results of experiments; and they are strictly true only under the limited conditions of color measurement.

Rules of Colorimetry

These rules (axioms) are:

1. Any color can be matched by a mixture of no more than three colored lights.

   This fundamental principle was stated by Wünsch in 1792.[54] As Maxwell pointed out,[55] it requires interpretation in some cases. This matter will be discussed later.

2. A color match made at one radiance level holds over a wide range of radiance levels.

   This rule can be derived by repeated application of rules 5 or 6 below. It has been shown to fail for very high[56] or very low[57] levels of illumination.

3. The components of a mixture of colored lights cannot be resolved by the eye.

   This fact has been known for a long time. It was stated in almost these words by Newton.[58]

4. The luminance[59] of a mixture is equal to the sum of the luminances of its components.

   This is one of the assumptions made and proved by Grassmann, with certain reservations on the validity of his proof however.[60] It was tested thoroughly by Abney and Festing.[61] It has been considered axiomatic for a long time (for example, see H. E. Ives,[62] and the report of the Committee on Colorimetry of the Optical Society of America).[63]

5. Color matches obey the law of addition; that is, if color (M) matches color (N) and if color (P) matches color (Q), then the additive mixture of colors (M) and (P) matches the additive mixture of colors (N) and (Q).

   This rule is known as Grassmann's law. It is one of the assumptions made and proved by Grassmann.[60]

6. Color matches obey the law of subtraction; that is, if the additive mixture of colors (M) and (P) matches the additive mixture of colors (N) and (Q) and if color (P) matches color (Q), then color (M) matches color (N).

   This is an obvious corollary to statement 5.

7. Color matches obey the transitive law; that is, if color (M) matches color (N) and if color (N) matches color (P), then color (M) matches color (P).

   This statement was implied by both Newton[58] and by Maxwell[64] in discussing their experimental results. It was used by Grassmann[60] in his analysis of complementary colors. Helmholtz[65] stated it explicitly.

8. A color match can be stated in the form of a color equation. As an example, the statement that color (C) is matched by the additive mixture of M units of color (M), N units of color (N), and P units of color (P) can be written in the form

$$(C) = M(M) + N(N) + P(P).$$

If we interpret the symbol = as "color matches,"

[49] See bibl. ref. 2.
[50] See bibl. ref. 6.
[51] See bibl. ref. 64.
[52] See bibl. ref. 3.
[53] See bibl. ref. 7.
[54] See bibl. ref. 64.
[55] See bibl. ref. 7(e).

[56] See bibl. ref. 25.
[57] See bibl. ref. 26.
[58] See bibl. ref. 2.
[59] Luminance is the quantity measured in a photometer when the fields are color-matched. It is the technical name for the photometric brightness of a uniform, small field.
[60] See bibl. ref. 9.
[61] See bibl. ref. 4.
[62] See bibl. ref. 27.
[63] See bibl. ref. 19(c).
[64] See bibl. ref. 7.
[65] See bibl. ref. 6.

the symbol + as "additively mixed with," this equation is an obvious abbreviation of the descriptive sentence. However, the color equation has broader implications than this. If we assume the existence of color space, every color is represented by a point in that space. The co-ordinates of the point corresponding to the color (C) are given by the quantities M, N, and P, where the symbols (M), (N) and (P) represent unit vectors along the axes on which these co-ordinates are measured. These quantities (M), (N), and (P) are analogous to vector operators in this interpretation of the color equation. Such equations were used, in the first sense, by Grassmann[60] and, in both these senses, by Maxwell.[66]

It will be recalled that we expected colorimetry to provide an answer to the question: what is the strength of three television receiver primaries which, in an additive mixture, will color match a given composition of radiance at the television camera. The fifth rule, that color matches obey the law of addition, contains part of the answer. We can apply this rule by considering separately all of the possible color matches to spectrum colors, corresponding to the given radiance in narrow bands extending from $\lambda-(\Delta\lambda/2)$ to $\lambda+(\Delta\lambda/2)$. The strength of each primary to match the whole distribution is given by the sum for all wavelengths of all of these incremental components.

Obviously, we can carry out this calculation only if we know the strength of the primaries required to match spectrum colors. Such data, called "Tristimulus Values of Spectral Stimuli of Equal Radiance" (or sometimes "Color-Mixture Data for the Spectrum"), are fundamental in colorimetry. How are they obtained?

The Fundamental Experiments

We cannot calculate or predict the values of color-mixture data for the spectrum. Such data actually define a composition of radiance, corresponding to the mixture of three primary colors, which appears exactly like a spectrum color. As such, these data are one measure of the visual process of people. It is obvious that the data must be collected by observations on people.

The instrument used in these observations is a colorimeter.[67] This instrument has a divided visual field. The color to be matched is presented in one half of the field and the mixture of primaries is presented in the other half. Calibrated attenuators are provided to adjust the strength of each of the primaries. Since color vision varies over the area of the retina,[68] the field of most colorimeters is of the order of 2 or 3 degrees. The division between the two halves of the field is made sharp to permit the adjustment of identity of their appearance with as little difficulty as possible.

The reader can be excused if he thinks the color-mixture data for the spectrum is evaluated by determining the radiances of the colorimeter primaries which color-match known radiances of spectrum colors.[69] The colorimetrist has very good reasons for avoiding such *absolute* measurements.

Let us see how the colorimetrist collects these data, and let us find out what errors he minimizes or avoids by making *relative* measurements. First, he would choose a set of primaries for use in his colorimeter. He can choose colored lights for the primaries which would be obtained by filtering the light from a tungsten lamp, or he can choose spectrum colors which would be obtained through the use of the equivalent of a prism and slits. It is not likely that he would choose the same primaries that we would choose for a color-television receiver. This fact need not worry us, for as we shall see later, when color-mixture data corresponding to one set of primaries are known, it is possible to calculate similar information for any other set of primaries.

Let us assume that our colorimetrist selects spectrum primaries for his measurements; furthermore, let us assume that these primaries correspond to radiance in narrow bands around these wavelengths:[70]

Red	700.0 millimicrons (mμ)
Green	546.1 millimicrons (mμ)
Blue	435.8 millimicrons (mμ).

The first step in the colorimetrist's experiment is not the matching of spectrum colors. Instead, he matches a specified "reference white." As we shall see, the units in which he measures the strength of the primaries in any other mixture are established by this match. Practically, the "reference white" might be the illuminant which the colorimetrist would use to irradiate samples of materials to be measured. For our purpose, however, let us assume that the "reference white" corresponds to constant radiance per millimicron at all wavelengths, the so-called "equal-energy" white.[71] The setting of the three attenuators corresponding to this color match are recorded. Let us call the transmission of the attenuators under this condition S_r, S_g, and S_b, respectively. In careful work, these values correspond to the means of repeated observations, including observations with the unknown and the mixture sides of the colorimeter field interchanged.

The second step in the experiment is to color-match spectrum colors. When the spectrum color corresponds to radiation in narrow bands located between 700.0 and 546.1 millimicrons, we find that the attenuators

[66] See bibl. ref. 7(b), 7(d), 7(e).
[67] See bibl. ref. 19(e).
[68] See bibl. ref. 7(g).

[69] Actually Maxwell, in making the first known measurements of this kind, did do much of this sort of thing (see bibl. ref. 7(e)). He recorded data, taken with his "color box" (colorimeter), in terms of the width of the slits in his spectroscope.

[70] These are known as the National Physical Laboratory (NPL) primaries, and were standardized by the ICI in 1931 (see bibl. ref. 22–24).

[71] Let us not worry how equal-energy white might be produced. The complication of thought which would follow the assumption of a more easily produced "reference white" adds nothing to our understanding of this particular experimental procedure.

in the paths of the primaries can be adjusted until the two halves of the field look alike or match (except that if we are very fussy there will be some difficulty near 575 mμ). However, as we decrease the wavelength of the spectrum color below 540 mμ, we run into trouble. Before we give up, let us try transferring one or more of the primaries to the unknown side of the field. When we provide for such transfer, we can find settings of the colorimeter for which the two halves of the colorimeter field match for any spectrum color. At this point we have learned that the first rule of colorimetry (that any color can be matched by a mixture of no more than three colored lights) is true only if we interpret it correctly.

Actually, when we transfer a primary to the unknown-color side of the colorimeter, the color match is made between the mixture of that primary and the unknown in one half of the colorimeter field, and the mixture of the remaining two primaries in the other half of the field. Expressing this color match in the form of a color equation, we have

$$(C) + M(M) = N(N) + P(P) \tag{1}$$

where (C) = the unknown color, and M, N, and P = the amounts of the primaries (M), (N), and (P). We know that the amount M of primary (M) would be matched by itself in the other half of the colorimeter field. As a color equation

$$M(M) = M(M). \tag{2}$$

The sixth rule of colorimetry tells us that the subtraction of color matches is a valid operation. We can, therefore, subtract the color match expressed by equation (2) from the one expressed by equation (1), with the result

$$(C) = -M(M) + N(N) + P(P). \tag{3}$$

In this form of the expression for the color match, the primaries all appear on the same side of the equation, but the amount of the transferred primary is negative. Actually, the existence of negative light is impossible, but we can call this light negative as long as we keep in mind the physical significance of the expression.

Call the transmission of the attenuators in the paths of the primaries corresponding to a match to a spectral color I_r, I_g, and I_b. As pointed out above, these transmissions are recorded as positive or negative quantities, depending on which side of the colorimeter field the primary occupied in the mixture. Now form the ratios

$$\begin{aligned} R &= I_r/S_r \\ G &= I_g/S_g \\ B &= I_b/S_b. \end{aligned} \tag{4}$$

A color match to a particular spectrum color is defined by stating that a mixture of R units of the red primary, G units of the green primary, and B units of the blue primary matches the spectrum color. It is obvious that the absolute size of the units is determined by the color match to the "reference white." This size is such that a mixture of one unit of each of the three primaries matches "reference white." It is obvious also that the numbers of these units depend on the radiance of each of the spectrum colors, and in this experiment these radiances are not necessarily the same for all wavelengths.

The introduction of units based on the "reference-white" match has the result that all observers are forced to report the same number of units, i.e., one for each of the primaries in their mixture which matches the white. Observers will still disagree about colors which are different from the "reference white," and their disagreement will increase the less like the white the color in question is. However, since a large fraction of the important colors are not too far from white, the practical colorimetrist decreases the dispersion of the results to a considerable degree by this procedure.

There are other reasons why, in colorimetry, the amounts of primaries in mixtures are measured in terms of the match to reference white. If the primaries were measured in units of radiance or of luminance, the numbers expressing a color match to white might differ for the three primaries by an order of magnitude or so. The use of the same number of significant figures for the measures of the primaries would require different numbers of decimal places which is awkward. Such numbers also would give no indication of the importance of each primary in a mixture. However, when the units are based on a white match, the resulting numbers satisfy an instinctive feeling that all three primaries are of equal importance in making a mixture that appears white or gray.

We find another reason for the use of units based on the white match. Beginning with Newton,[72] colors have been represented by points on a plane diagram. Such diagrams are bounded by polygons, the vertices of which correspond to primaries. On these figures, it is customary to place the point corresponding to white at the center of the polygon of primaries. Newton stated that the point corresponding to a mixture of primaries could be located by finding the center of gravity of weights equivalent to the strength of the primaries, the weights being located at the points corresponding to the primaries. Using only three primaries, and making the resulting triangle equilateral, it is obvious that the white point will fall at the center of the triangle if the weights are equal. As Lambert showed,[73] the weights can be made equal by measuring the strengths of the primaries in terms of the strengths that mix to match white. Lambert also anticipated our next step, of normalizing the weights of the primaries. He did this not to reduce observer differences, as we do in colorimetry, but for the sole reason of obtaining numbers to plot in the color triangle.

[72] See bibl. ref. 2.
[73] See bibl. ref. 28, 35(b).

In colorimetry, the second step in reducing observer differences is normalizing the data. New quantities are calculated from R, G, and B by using these relations

$$
\begin{aligned}
r &= R/(R+G+B) \\
g &= G/(R+G+B) \qquad (5)\\
b &= B/(R+G+R).
\end{aligned}
$$

The reference white in terms of these "chromaticity co-ordinates" must have the values (1/3, 1/3, 1/3). Also, each of the primaries must be represented by the chromaticity co-ordinates (1, 0, 0), (0, 1, 0) or (0, 0, 1). These two steps in treating the data have the effect of eliminating observer differences for four colors, the reference white and the three primaries. The result is decreased dispersion of all color data.[74]

To clarify the concept of these "chromaticity co-ordinates," let us consider a color space in which a color is represented by the co-ordinates R, G, and B measured along three axes represented by (R), (G) and (B). If we change the intensity of this color, each of the co-ordinates R, G, and B will be changed proportionately. The locus of points corresponding to changes of intensity is a straight line passing through the origin and the point (R, G, B). The direction of this locus obviously is a measure of the color when its intensity component is suppressed. These "chromaticity co-ordinates," as defined by (5), are a convenient way of identifying the direction of this locus of points.

Chromaticity co-ordinates of spectrum colors for the "standard observer" are shown in Fig. 2. These curves apply to the spectrum primaries we have been considering (red, 700.0 mμ; green, 546.1 mμ; and blue, 435.8 mμ). The values were obtained by averaging the results of experiments similar to our hypothetical one, for 17 observers. The numerical values, at intervals of 5.0 mμ, were standardized by the ICI in 1931 as a definition of the chromaticity characteristic of the "standard observer."[75]

It is to be noticed that the sum of the three chromaticity co-ordinates is always unity. Consequently, only two of these co-ordinates are independent quantities. However, a color is completely specified by three independent quantities so that chromaticity co-ordinates are not a complete specification of color. The careful reader will have noticed, too, that no mention has been made of the strength of the reference white nor of any spectrum color which was matched. This omission was intentional. The normalizing process applied to the mixture data in calculating the chromaticity co-ordinates eliminated the radiance or the luminance dimension of the color matches.

There are two reasons for suppressing the strength aspect of the color matches. The measurement of radiance or of luminance in a colorimeter is difficult, and is avoided if it possibly can be. The colorimetrist argues, too,[74] that observers disagree more in measuring luminance than they do in measuring the chromaticity co-ordinates of colors. The dispersion of the color data is improved, at the expense, however, of a loss of part of it. How do we regain this lost information?

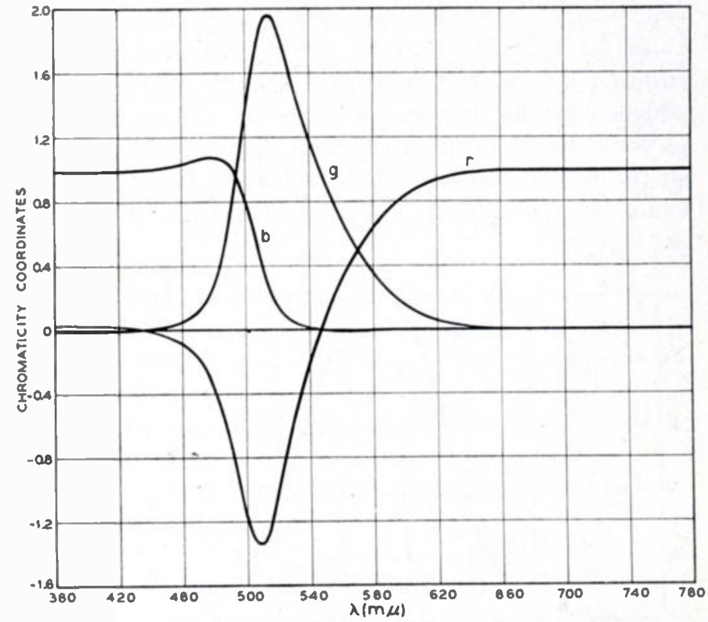

Fig. 2—Chromaticity co-ordinates of spectrum colors for the Standard Observer.
Spectrum primaries: Red = 700.0 mμ; Green = 546.1 mμ; Blue = 435.8 mμ.
Reference white = equal-energy white.
$L_r : L_g : L_b = 1 : 4.5907 : 0.0601$.

In practical colorimetry the third dimension of a color is regained by an independent measurement of luminance with a photometer. The color-mixture data for the spectrum are obtained by combining the chromaticity co-ordinates of the spectrum with photometric data for equal-energy spectrum colors. The particular photometric information used is known as the "luminosity curve."

As implied by the name, the luminosity curve expresses the relation (as a curve) between the luminance and the radiance of spectrum colors. Data for this function are gathered by adjusting the radiances of spectrum colors in the two halves of a photometer field until their luminances appear to be equal. To avoid comparisons of greatly dissimilar fields, these measurements are made either by a step-by-step method or by a flicker method.[76] In the step-by-step method, comparisons are made between a first and second spectrum color, between the second and a third, and so on, the spacing in wavelength always being kept small enough that the comparisons can be made without too much difficulty. In the flicker method, the two radiances are applied alternately in the same field, and advantage is taken of the fact that chromaticity difference disappears at a frequency lower than that required to suppress flicker due

[74] See bibl. ref. 17.
[75] See bibl. ref. 22, 24.
[76] See bibl. ref. 19(c), 29.

to small luminance differences. Under suitable conditions, these two methods give results which are in agreement.

The results of these observations are reduced to show the luminance of spectrum colors of equal radiance, and are then plotted in the form of a curve reaching unity at its peak. Such a curve, representative of normal vision under good lighting conditions, is given in Fig. 3. Data for this curve at 10 millimicron intervals were adopted by the ICI in 1924,[77] and in 1931 it was reaffirmed as the luminosity curve for the standard observer.[78] Based on the new definition of the lumen, and on the new International Temperature Scale, the peak value of the luminosity curve corresponds to 680 lumens per watt.[79]

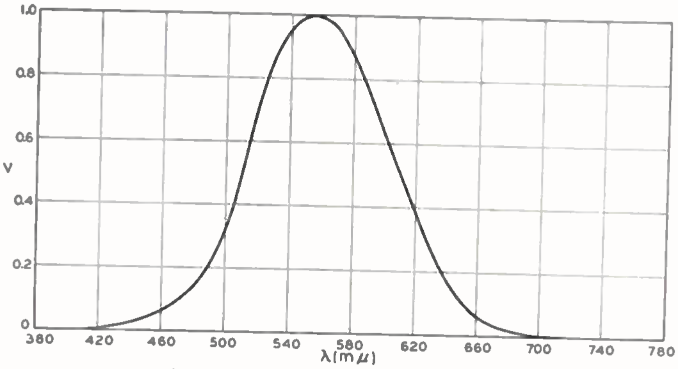

Fig. 3—Luminosity curve for the Standard Observer. At 555 mμ, one watt is equivalent to 680 lumens.

Calculation of Color-Mixture Data for the Spectrum

The "tristimulus values of spectral stimuli of equal radiance" can be calculated from the luminosity curve and the chromaticity co-ordinates of the spectrum. As we have seen, any color is completely specified by three independent numbers. The tristimulus values form one set of such numbers. The chromaticity co-ordinates, taken together with the luminance, form another set of three such numbers. The steps in calculating the tristimulus values of spectral stimuli of equal radiance from the chromaticity co-ordinates of the spectrum in combination with the luminosity curve are given below.

Fundamentally, these calculations depend on two facts: First, when two colors are matched their luminances are equal; and, second, the mixture of one unit of each of the primaries color-matches the reference white (which, in the case we are considering, is equal-energy white). There are two definitions, too, on which these calculations depend: First, the luminosity curve shows the luminance of spectral stimuli of equal radiance; and, second, the chromaticity co-ordinates of the spectrum are the *proportions*, measured in units of primaries, in which the primaries are mixed to match spectrum colors.

As a first step, let us make use of the equality of luminances in the case of color matches. The luminance of a spectrum color, specified by one watt per steradian per square meter of radiance at wavelength λ_1, is equal to 680 $v(\lambda_1)$ lumens per steradian per square meter. In this expression, $v(\lambda_1)$ is the ordinate of the luminosity curve at wavelength λ_1. The luminance of the mixture of primaries which color-matches this spectrum color is equal, by the fourth rule of colorimetry, to the sum of the luminances of each of the primaries. We may express this equality of luminances as

$$680v(\lambda_1) = L_r\bar{r}(\lambda_1) + L_g\bar{g}(\lambda_1) + L_b\bar{b}(\lambda_1) \qquad (6)$$

where

L_r, L_g, L_b = luminosity coefficients (luminance of one unit) of the primaries (R), (G), and (B).

$\bar{r}(\lambda_1)$, $\bar{g}(\lambda_1)$, $\bar{b}(\lambda_1)$ = tristimulus values of the spectrum color, specified by one watt per steradian per square meter of radiance at wavelength λ_1.

A little thought will reveal that we do not know the values of the luminosity coefficients, and that the tristimulus values are exactly the tristimulus values of spectral stimuli of equal radiance that we are trying to calculate.

When we apply the fact that for any one wavelength the tristimulus values are in direct proportion to the chromaticity co-ordinates of the corresponding spectrum color, we reduce the number of unknown quantities in (6) from six to four. This proportionality can be expressed by introducing an unknown multiplier $K(\lambda)$. In terms of this multiplier and the chromaticity co-ordinates of the spectrum, the tristimulus values of spectral stimuli of equal radiance are

$$\begin{aligned}\bar{r}(\lambda_1) &= K(\lambda_1)r(\lambda_1)\\ \bar{g}(\lambda_1) &= K(\lambda_1)g(\lambda_1)\\ \bar{b}(\lambda_1) &= K(\lambda_1)b(\lambda_1).\end{aligned} \qquad (7)$$

It might be possible to devise a further experiment to evaluate the luminosity coefficients of the primaries. However, this experimental step is made unnecessary by applying methods of successive approximation devised independently by Judd[80] and Wright.[81] In these methods, the calculation is begun with rough values for the luminosity coefficients. Such rough values might be gotten by a slight modification of the colorimeter which was used in determining the chromaticity co-ordinates of the spectrum (or they might be intelligent guesses). If we designate these rough values by primes on the luminosity coefficients and if we substitute these values and also (7) into (6) and solve the resulting equation for $K(\lambda_1)$, we have

$$K(\lambda_1) = \frac{680v(\lambda_1)}{L_r'r(\lambda_1) + L_g'g(\lambda_1) + L_b'b(\lambda_1)}. \qquad (8)$$

[77] See bibl. ref. 30.
[78] See bibl. ref. 22–24.
[79] See bibl. ref. 31.
[80] See bibl. ref. 32.
[81] See bibl. ref. 33.

When this calculation is made for several wavelengths and the results used to calculate the tristimulus values of spectral stimuli of equal radiance, these tristimulus values may be plotted as in Fig. 4.

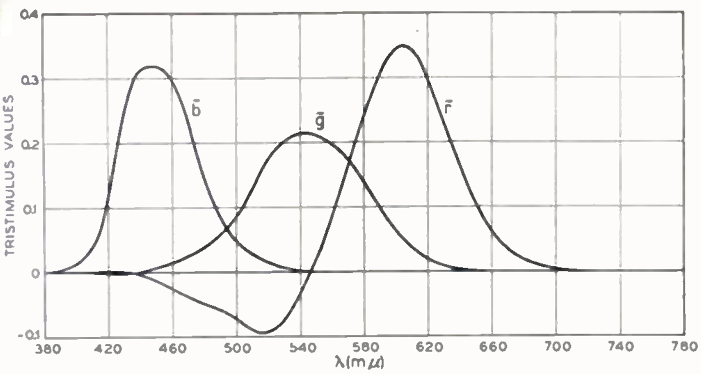

Fig. 4—Tristimulus values of spectral stimuli of equal radiance for the Standard Observer (standard color-mixture data for the spectrum).
Spectrum primaries: Red = 700.0 mμ; Green = 564.1 mμ; Blue = 435.8 mμ.
Reference white = equal-energy white.
$L_r:L_g:L_b = 1:4.5907:0.0601$

The check of our approximation comes when we use these calculated values to evaluate the mixture that matches the reference white (equal-energy white in the case under consideration). By application of the fifth rule of colorimetry, the amount of each primary in a mixture which matches equal-energy white is equal to the sum of all the ordinates of the corresponding curve (or the area under the curve). However, by definition the units in which the primaries are measured are such that a mixture of one unit of each primary matches equal-energy white. The areas under the curves in Fig. 4 must be equal, therefore, and they will be equal only if the assumed values for the luminosity coefficients of the primaries are correct. If the areas are found to be unequal, the calculations must be repeated with revised values for the luminosity coefficients of the primaries, the methods of Judd[80] or of Wright[81] being used to find these new values. In practice, the convergence of this method is rapid.

For the set of spectrum primaries under consideration (red, 700.0 mμ; green, 546.1 mμ; and blue, 435.8 mμ), and when the mixture of one unit of each primary matches equal-energy white, the ratios of the luminosity coefficients are[82]

$$L_r:L_g:L_b = 1:4.5907:0.0601.$$

Curves of the tristimulus values for spectral stimuli of equal radiance, calculated in this way, are plotted in Fig. 4. Values at intervals of 5.0 mμ were standardized by the ICI in 1931.[82]

Let us see what is represented by these curves in Fig. 4. Although they are called "tristimulus values of spectral stimuli of equal radiance," they are not curves of the *absolute* values of amounts of the primaries which, when mixed, would match a particular quantity of radiance of a spectral stimulus. In fact, as long as we specify the units in which the primaries are measured in terms of a match to a reference white of *unspecified* intensity, we cannot have results in absolute units. These curves differ, however, from the chromaticity coordinates plotted in Fig. 2. The chromaticity coordinates are admittedly relative quantities, expressing fractions of a whole mixture. The tristimulus values are consistent between wavelengths—for example, the ratio between $\bar{r}$ at 460 mμ and at 660 mμ is exactly the ratio of the numbers of units of the red primary that would enter mixtures matching the same quantity of spectral radiance at these two wavelengths.

The thoughtful reader may wonder in what way $\bar{r}$, $\bar{g}$, and $\bar{b}$ differ from the quantities R, G, and B defined by (4). Provided the colorimeter were operated by the standard observer, and provided the spectral radiance in the unknown side of the colorimeter field were constant for all wavelengths, there would be no difference. All of the steps following (4) have been introduced only because physical apparatus and real observers are frail.

Use of Data for Spectrum Primaries

The basis for all modern colorimetry is contained in the eight rules recited earlier, the tristimulus values of spectral stimuli of equal radiance, the luminosity coefficients of the three spectrum primaries, and the value 680 lumens per watt corresponding to the peak of the luminosity curve. Let us use these data to calculate what we can about the spectral compositions of radiance which are shown in Fig. 1.

The curve labeled $[R(\lambda)\times E_c(\lambda)]$ in this figure shows the variation of radiance with wavelength (in watts per steradian per square meter per millimicron) from the sample of red paper. At any wavelength λ_0, the radiance in a band of width $\Delta\lambda$, extending from $(\lambda_0-\Delta\lambda/2)$ to $(\lambda_0+\Delta\lambda/2)$ cannot be distinguished in chromaticity from the spectrum colors we have been discussing. The radiance in this band is of course equal to $[R(\lambda_0)\times E_c(\lambda_0)]\Delta\lambda$ (in watts per steradian per square meter).

The tristimulus values of spectral stimuli of equal radiance, plotted in Fig. 4, are proportional to the number of units of each of the spectrum primaries which, when mixed, will match a given quantity of spectral radiance. The numbers of units of each primary required to match the radiance $[R(\lambda_0)\times E_c(\lambda_0)]\Delta\lambda$ are

$$\begin{aligned} \Delta R_o &= K_c\bar{r}(\lambda_0)[R(\lambda_0)\times E_c(\lambda_0)]\Delta\lambda \\ \Delta G_o &= K_c\bar{g}(\lambda_0)[R(\lambda_0)\times E_c(\lambda_0)]\Delta\lambda \text{ (units)} \qquad (9) \\ \Delta B_o &= K_o\ (\lambda_0)[R(\lambda_0)\times E_c(\lambda_0)]\Delta\lambda \end{aligned}$$

where K_c is a constant of proportionality. The values $\bar{r}(\lambda_0)$, $\bar{g}(\lambda_0)$, and $\bar{b}(\lambda_0)$ are read from the curves in Fig. 4 for the wavelength (λ_0), or are found in the tables standardized by the ICI.[82]

[82] See bibl. ref. 22, 24.

To determine how many units of each primary are required in a mixture which will match the color of the whole radiance-wavelength distribution, we apply the law of addition (the fifth rule) to the individual matches calculated for successive narrow wavelength bands. Performing these additions, and allowing the widths of the subbands to become infinitesimal, we find that

$$R_c = K_c \int_0^\infty \bar{r}(\lambda)[R(\lambda) \times E_c(\lambda)]d\lambda$$

$$G_c = K_c \int_0^\infty \bar{g}(\lambda)[R(\lambda) \times E_c(\lambda)]d\lambda \text{ (units)} \quad (10)$$

$$B_c = K_c \int_0^\infty \bar{b}(\lambda)R(\lambda) \times E_c(\lambda)]d\lambda.$$

These expressions give the number of units of each primary which, when mixed together, color-match the radiant flux from the red paper. That is, if the radiant flux from the red paper were applied to the unknown side of a colorimeter field and the strength of the primaries were adjusted for a color match, a "standard observer" would obtain the values shown in (10).

It should be kept in mind that the quantity $[R(\lambda) \times E_c(\lambda)]$ appearing in (10) is the radiance per unit wavelength of any distribution that is to be color-matched by the mixture of R_c, G_c, and B_c units of the three primaries. We may use this equation to calculate matches to equal-energy white, to Illuminant *C*, to the radiant flux from our red paper, or to any other given composition of radiance.

Suppose we do use (10) to calculate the matches (a) to an equal-energy white of one watt per steradian per square meter per millimicron, (b) to Illuminant *C* as plotted in Fig. 1 (the curve labeled $E_c(\lambda)$), and (c) to the radiance from the red paper, shown as $[R(\lambda) \times E_c(\lambda)]$ in Fig. 1. In the case of the equal-energy white, for which the assumed radiance per millimicron is one watt per steradian per square meter, the areas indicated by (10) are the areas included by the curves in Fig. 4. In the case of the radiance of the red paper, the products of the tristimulus values of spectral stimuli of equal radiance by the spectral composition of radiance may be plotted as in Fig. 5. In this case, the areas under these curves are the areas indicated by (10). Similar curves could be drawn to show the corresponding areas for the radiance distribution corresponding to an ideal diffuser irradiated by Illuminant *C*. Evaluating the areas under these curves, we find the number of units of the primaries in these three cases to be

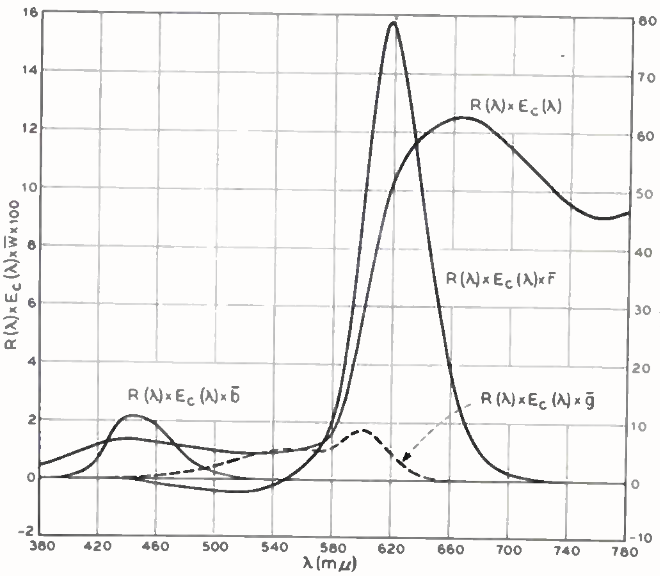

Fig. 5—Composition of radiance with wavelength for Munsell Chip 5R4/14 irradiated by Illuminant *C*, and distribution weighted by the standard color-mixture data for the spectrum, for the spectrum primaries.
Spectrum primaries: Red = 700.0 mμ; Green = 546.1 mμ; Blue = 435.8 mμ.
Reference white = equal-energy white.
$L_r:L_g:L_b = 1:4.5907:0.0601$.

TABLE I

	Equal-Energy White	Ill. *C*	Red Paper and Ill. *C*
Red	$3.782\ K_c$	$3.275\ K_c$	$1.644\ K_c$
Green	$3.782\ K_c$	$3.867\ K_c$	$0.308\ K_c$
Blue	$3.782\ K_c$	$4.461\ K_c$	$0.236\ K_c$

In order that the units in which the primaries are measured fit the convention that the equal-energy white is matched by a mixture of one unit of each primary, the constant K_c must have the value 1/3.782. Under this condition, the three colors in Table I are described by mixtures of the numbers of units of the three primaries shown in Table II.

TABLE II

	Equal-Energy White	Ill. *C*	Red Paper and Ill. *C*
Red	1 unit	0.866 unit	0.435 unit
Green	1 unit	1.022 units	0.082 unit
Blue	1 unit	1.180 units	0.062 unit

The figures in Table II may be interpreted in this way. Under the reference condition, a mixture of one unit of each spectrum primary matches an equal-energy reference white for which the radiance is one watt per steradian per square meter per millimicron. If the strengths of the primaries are readjusted to color-match the radiance distribution $[R(\lambda) \times E_c(\lambda)]$ in Fig. 1, the red primary must be decreased to 0.435 times one unit, the green primary to 0.082 times one unit, and the blue primary to 0.062 times one unit. The figures in the column headed "*Ill. C*" are interpreted in the same way.

We could calculate the luminance of each of these colors by following a similar procedure. However, a somewhat different approach uses the numbers we have already calculated, and is therefore a little easier.

We have found that the luminosity coefficients of the spectrum primaries are in the ratios

$$L_r:L_g:L_b = 1:4.5907:0.0601.$$

The luminosity coefficient of each primary can be written as

$$L_r = K_L$$

$$L_g = 4.5907 K_L \text{ (lumens/steradian/square meter)[83]}$$

$$L_b = 0.0601 K_L.$$

Applying the rule that the luminances of components of a mixture add, we find that the luminance of a mixture of R units of red primary, G units of green primary, and B units of blue primary is given by

$$L_c = K_L(R + 4.5907G + 0.0601B) \text{ (candles/square meter).} \quad (11)$$

When this relation is applied to the three colors we have just considered, we find the luminances given in Column I of Table III.

TABLE III

LUMINANCES OF CERTAIN COLORS

Equal-Energy White	4.6508 K_L	72,660 candles/sq m
Ill. C (Fig. 1)	5.6305 K_L	86,970 "
Red Paper and Ill. C (Fig. 1)	0.8126 K_L	12,700 "

We can find the value of K_L by calculating the luminance of any one of these colors. It is easiest to calculate the luminance of the equal-energy white corresponding to one watt per steradian per square meter per millimicron. This luminance is equal to the product of the area under the luminosity curve (shown in Fig. 3) and the value of 680 lumens per watt, corresponding to the peak of this curve. When we go through this calculation, we find that the luminance of this equal-energy white is 72,660 candles per square meter. The value of K_L must therefore be 72,660/4.6508 or 15,625. The luminances of the other two colors were calculated using this value of K_L, and are shown in Column II of Table III.

Some of the procedures we have followed in preparing Tables II and III would be thought quite odd by a colorimetrist. As we have learned, his whole procedure is aimed at relative answers, and we have gone beyond his usual techniques. Let us backtrack and find out what he would have done with these data.

Consider first the luminance dimension of the colors we have been considering. It is quite unusual to know the absolute values of radiance, such as are shown in Fig. 1. These data usually would be presented to the colorimetrist as distributions of radiance, i.e., as compositions of radiance normalized to unity at some wavelength. Practically, then, he could not calculate their luminance. However, his interest lies largely in assigning numbers which describe a color in terms of some sort of reference. In the case of a transmitting medium (stained glass, for example) he might compare its color, when illuminated, with the color of the illuminant. In the case of a reflecting medium (the red paper referred to here) he might compare its color, when illuminated, with the color of an ideal reflector under the same illumination. In the one case, the reference is a perfectly transparent transmitting medium; in the second the reference is a perfectly diffusing reflector.

In the examples we have been considering, Illuminant C was the color of a perfectly diffusing reflector irradiated by a source of radiance having the spectral distribution of radiance of Illuminant C. The value of luminance shown in Column I of Table III is therefore a reference to which a colorimetrist would refer the luminance of the red paper sample. The colorimetrist would give the ratio of the figures 0.8126 and 5.6305, or 14.43 per cent, and call it the "luminance factor" for the red paper under Illuminant C.

For most applications of color, the luminance factor is an adequate measure of the luminance of a surface. The absolute level of luminance depends on the illumination level.[84] The relative luminance of adjacent surfaces, similarly illuminated, is measured by their luminance factors. However, the aesthetic appeal of a combination of adjacent surfaces depends largely on their relative, not on their absolute, luminances.

Chromaticity Co-ordinates

Just as absolute values of luminance are not too important in a large part of the colorimetrist's work, the numbers of units of primaries matching a color are not too useful. It should be obvious in any case that the tristimulus values for the three colors in Table II depend on the radiance of a particular equal-energy white. These numbers would be different if the reference white were more or were less intense.

TABLE IV

	Equal-Energy White	Ill. C	Red Paper and Ill. C
r	0.3333	0.2822	0.7511
g	0.3333	0.3333	0.1409
b	0.3333	0.3845	0.1080

The chromaticity co-ordinates, which were discussed earlier, are quantities which eliminate the intensity aspect implied in the tristimulus values. Since, in his work, the colorimetrist is not concerned with absolute values, he would express the chromatic aspect of color in its chromaticity co-ordinates. These co-ordinates are given by (5), which is repeated here for convenience.

$$r = R/(R + G + B)$$
$$g = G/(R + G + B) \quad (5)$$
$$b = B/(R + G + B).$$

If we substitute values from either Tables I or II in (5), we find these colors have the chromaticity co-ordinates shown in Table IV.

[83] One lumen per steradian per square meter is equal to one candle per square meter.

[84] The number of lamps that are lighted determines the level of illumination.

Graphic Representation of Colors

The earliest suggestion the author has found that an individual color might be represented by a point in "color space" was made by Lambert in 1772.[85] He proposed representing surface colors in the form of a pyramid, where the projection on a horizontal plane corresponded to a color triangle and the projection on the vertical axis corresponded to the amount of black or white in the mixture. A similar method of representation in three-dimensional space is used today for the colors of surfaces in the Ostwald[86] system of color notation.

Newton suggested the representation of colors in a plane figure.[87] His diagram took the form of a circle, the center of which represented white. The circumference of the circle was divided into seven arcs, corresponding to the seven principal colors he saw in the spectrum, and the lengths of the arcs were made proportional to the seven musical intervals in an octave. At the center of gravity of each arc he placed a small circle, the area of which was proportional to the number of "rays" of the corresponding color in a given mixture. The character of the mixture, colorwise, was indicated by the position of the center of gravity of the seven small circles. The radius, drawn through this point, intercepted the circle at a point which corresponded to the primary the mixture was most like, and the distance from the center of the circle indicated the "Fulness" of the mixture. This method of representing colors is much like the representation of chromaticity co-ordinates on a Maxwell triangle which is used today.

The representation of colors on a triangle seems to have been done first by Tobias Mayer in 1758.[88] In both Mayer's triangle and in Lambert's adaptation of it,[85] the primaries were pigment colors. In his discussion of the three-sensation theory of color vision, Young showed colors on a triangle, with his three primary colored lights at the vertices.[89] This same representation was used by Maxwell.[90]

In addition to using the color triangle, Maxwell represented colors in three-dimensional space.[91] Color representation in three-dmensional space is illustrated in Fig. 6.[92] The three orthogonal axes correspond to the three primaries (R), (G), and (B). Every color is represented by a point in the color space defined by this coordinate system. The co-ordinates of a point representing a color, such as C in Fig. 6, are the tristimulus values of that color (listed in Table II for the colors we have been considering). The reference white is shown as the point (1, 1, 1). The similarity of this representation to that of a point in three-dimensional vector space is obvious.

It will be noted that the effect of change of the intensity component of a color is to move the point at which it is plotted along a line passing through the origin.[93] The direction of this line is therefore a measure of the chromatic aspects of a color. One way of describing the direction of such a line in space is to define the point at which it intersects a reference plane. A particular refernce plane, shown in Fig. 6, is the one passing through the points (1, 0, 0), (0, 1, 0), and (0, 0, 1). The co-ordinate planes define a triangle on this reference plane which is called a "Maxwell triangle."[94] When points in this plane are specified in trilinear coordinates, it is found that the specification is precisely in terms of the "chromaticity co-ordinates" which we have discussed previously. The chromaticity co-ordinates of spectrum colors (from Fig. 2) and of the colors we have been considering (from Table IV) are plotted in a Maxwell triangle in Fig. 7.

However, only two of the chromaticity co-ordinates of a color are independent quantities. There is no advantage in plotting and showing three numbers as is

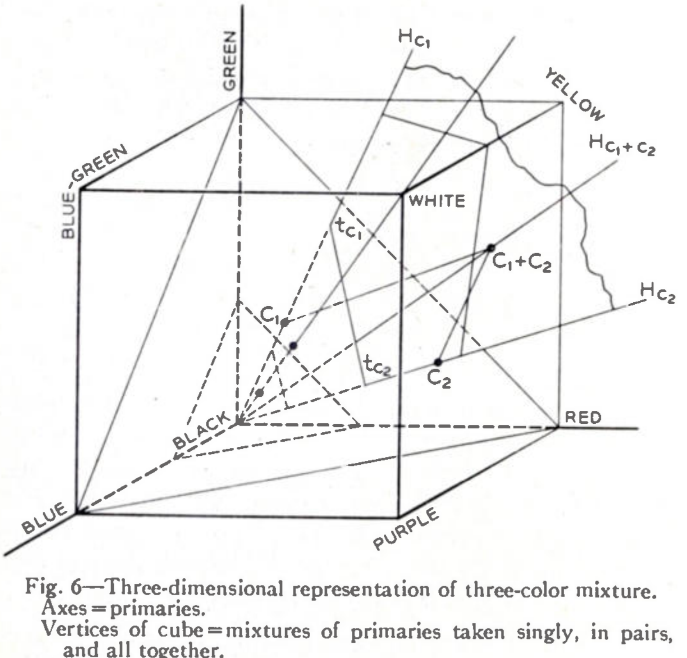

Fig. 6—Three-dimensional representation of three-color mixture.
Axes = primaries.
Vertices of cube = mixtures of primaries taken singly, in pairs, and all together.
C_1 and C_2 = particular colors.
C_1+C_2 = additive mixture of C_1 and C_2.
H_{c1}, H_{c2}, H_{c1+c2} = hue lines of C_1, C_2, and of C_1+C_2.
t_{c1} and t_{c2} = projections of colors C_1 and C_2 in the Maxwell triangle.
$t_{c1}-t_{c2}$ = trace of plane containing colors C_1 and C_2 in the Maxwell triangle.

[85] See bibl. ref. 28, 35(b).
[86] See bibl. ref. 34.
[87] See bibl. ref. 2.
[88] See bibl. ref. 35.
[89] See bibl. ref. 3.
[90] See bibl. ref. 7(a), 7(b), 7(e).
[91] See bibl. ref. 7(e).
[92] This is a copy of Fig. 1 in a paper published in the *Journal of the Franklin Institute* in 1915 by H. E. Ives (see bibl. ref. 36(a)).
[93] Since the luminance of a mixture is equal to the *scalar* sum of the luminances of the primaries, the relation between the length of vector in this color space and the luminance of a color changes with every change of direction of the vector. This is a severe limitation on the general usefulness of the three-dimensional representation.
[94] It is not clear from Maxwell's papers whether he referred to this triangle, corresponding to a set of physical primaries, or whether a Maxwell triangle is more properly one which circumscribes the spectrum locus, i.e., one corresponding to a set of nonphysical primaries.

done in the Maxwell triangle. Not only for this reason, but also because it is easier, is it customary to plot two of the chromaticity co-ordinates of colors in rectangular co-ordinates. Such color triangles, or more properly, chromaticity diagrams, are projections of the Maxwell triangle on one of the co-ordinate planes in

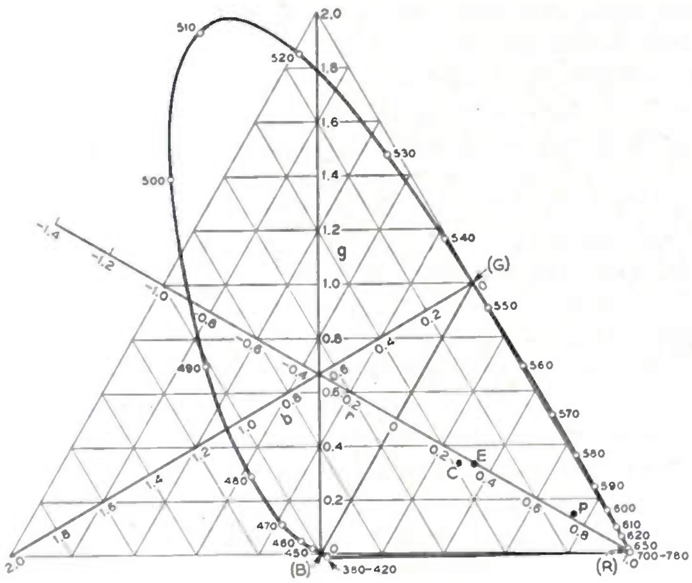

Fig. 7—Maxwell triangle for spectrum primaries for the Standard Observer.
Spectrum primaries: Red $(R) = 700.0$ mμ Green $(G) = 546.1$ mμ; Blue $(B) = 435.8$ mμ.
Reference white = equal-energy white
$L_r : L_g : L_b = 1 : 4.5907 : 0.0601$.
E = equal-energy white.
C = Illuminant C.
P = Munsell Chip 5R4/14 irradiated by Illuminant C.

Fig. 6. Obviously, we can use any one of the three possible projections, i.e., we can plot red-green, red-blue, or blue-green chromaticity diagrams. The red-green chromaticity co-ordinates of spectrum colors and of the several colors we have considered are plotted on a chromaticity diagram in Fig. 8.

Additive Mixture of Colors

The properties and limitations of additive mixtures can be learned by studying just how such mixtures appear in the graphical representations we have just considered.

Of the rules of colorimetry quoted earlier, the fifth was a statement that color matches obey the rule of addition. Let us see what this leads to. Consider two colors, each of which is matched by a mixture of three primaries. We can write these matches as color equations thus:

$$(C_1) = R_1(R) + G_1(G) + B_1(B) \tag{12}$$

and

$$(C_2) = R_2(R) + G_2(G) + B_2(B) \tag{13}$$

where R_1, G_1, B_1, R_2, G_2, and B_2 are tristimulus values. When we apply the fifth rule, we find that

$$(C_1) + (C_2) = (R_1 + R_2)(R) + (G_1 + G_2)(G) + (B_1 + B_2)(B). \tag{14}$$

Now what does this mean in the various graphical representations of colors?

Consider first the three-dimensional representation shown in Fig. 6. The two colors (C_1) and (C_2) are represented by two vectors, extending from the origin to points the co-ordinates of which are the tristimulus values. The co-ordinates of the extremity of the vector corresponding to the mixture of these two colors are equal to the coefficients of the unit vectors (R), (G), and (B) in (14). The addition of color vectors in color space in this way was first discussed by Maxwell.[95] If we consider the plane which includes the two color vectors, the vector corresponding to their additive mixture will be seen to lie in it. Additionally, the magnitude and direction of this vector are given by the diagonal of the parallelogram of which the two component color vectors are two sides. Grassmann pointed out that this construction was like that used in determining the magnitude and direction of the resultant of two forces.[96]

Because the Maxwell triangle is of little practical utility, additive mixture on this diagram shall not be discussed.

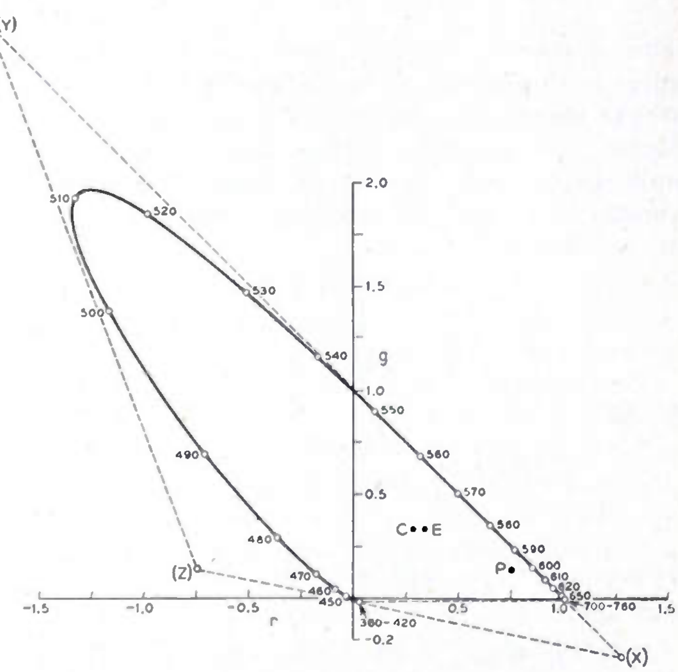

Fig. 8—Red-green chromaticity diagram for spectrum primaries for the Standard Observer.
Spectrum primaries: Red $(R) = 700.0$ mμ; Green $(G) = 546.1$ mμ; Blue $(B) = 435.8$ mμ.
Reference white = equal-energy white.
$L_r : L_g : L_b = 1 : 4.5907 : 0.0601$.
E = equal-energy white.
C = Illuminant C.
P = Munsell Chip 5R4/14 irradiated by Illuminant C.
(X), (Y), and (Z) = Standard ICI nonphysical primaries.

When colors are specified by their luminances and by their positions on a chromaticity chart, we know L and the chromaticity co-ordinates, say r and g, for each of the colors. How do we find their additive mixture?

[95] See bibl. ref. 7(e).
[96] See bibl. ref. 9.

It will be recalled that

$$b = 1 - (r + g) \tag{15}$$

$$r = R/(R+G+B)$$
$$g = G/(R+G+B) \tag{5}$$
$$b = B/(R+G+B)$$

$$L = RL_r + GL_g + BL_b. \tag{16}$$

When (5) and (16) are solved for R, G, and B in terms of r, g, and L, we find:

$$R = rL/(rL_r + gL_g + bL_b)$$
$$G = gL/(rL_r + gL_g + bL_b) \tag{17}$$
$$B = bL/(rL_r + gL_g + bL_b)$$

where b is given by (15). These values of R, G, and B can be substituted in (14) for the mixture of two colors. The results are the tristimulus values for the mixture. By substituting these values in (5) and (16), we arrive at the chromaticity co-ordinates and luminance of the mixed color. Proceeding with the algebra, we find that

$$L_{1+2} = L_1 + L_2. \tag{18}$$

This statement, that the luminance of a mixture is equal to the sum of the luminances of its components, checks our algebra since it is a confirmation of the fourth rule set down earlier. The chromaticity co-ordinates of the mixture of two colors whose individual chromaticity co-ordinates are (r_1, g_1, b_1) and (r_2, g_2, b_2) are found to be

$$r_{1+2} = K_1 r_1 + K_2 r_2$$
$$g_{1+2} = K_1 g_1 + K_2 g_2 \tag{19}$$
$$b_{1+2} = K_1 b_1 + K_2 b_2$$

where

$$K_1 = \frac{L_1/D_1}{(L_1/D_1) + (L_2/D_2)}$$

$$K_2 = \frac{L_2/D_2}{L_1/D_1 + L_2/D_2} = 1 - K_1$$

and

$$D_1 = r_1 L_r + g_1 L_g + b_1 L_b; \quad D_2 = r_2 L_r + g_2 L_g + b_2 L_b.$$

Let us consider the significance of this result. The point in a chromaticity diagram corresponding to a mixture is seen to lie on a line connecting the points corresponding to the two components of the mixture. The position of the mixture point on this line corresponds to the position of the center of gravity of two weights proportional, respectively, to L_1/D_1 and L_2/D_2 located at the positions of the components of the mixture. It will be recalled that Newton suggested this analogy in his discussion of color mixture.[97]

This analysis can be extended readily to the treatment of a mixture of three colors. However, with the analogy to the center of gravity of a system of more than two weights in mind, it is seen that the mixed color can fall anywhere *within* the triangle formed by the lines connecting the chromaticity co-ordinates of the component colors. The position of the mixture point within this triangle depends on the relative luminances of the components. Negative values of one or more of the component luminances would be required to produce a mixture outside this triangle—a physical impossibility. As predicted by the fourth rule of colorimetry, the luminance of the mixture is equal to the sum of the luminances of its components.

In this discussion there has been no limitation placed on the colors to be mixed additively. The only requirement given was that their chromaticity co-ordinates and their relative luminances be known. Obviously, they might be a different set of primaries for colorimetry or a set of primaries for use in a color-television system. However, we have demonstrated that we can study the problems of mixture for one set of primaries on the chromaticity chart prepared for another set.

This is a most important conclusion. The experiments that have been described thus far, and the procedures for calculation that have been developed, are all that we need to know to apply colorimetry to color television. From this point on, we will be concerned only with mathematical treatment of these fundamental facts for the sole purpose of putting them into forms that will be easier to use.

The ICI Nonphysical Primaries

Since we need only one chromaticity chart to study all color-mixture problems, the set of primaries on which that chart is based should be chosen with care. That is, the reference system should be the simplest possible one to use. Let us see what conditions it will be desirable to meet with a set of primaries (X), (Y), and (Z), which we might use in place of the spectrum primaries (R), (G), and (B).[98] Some of the desirable conditions, and means for obtaining them are the following:

1. It will be recalled that evaluation of the amounts of the primaries in a mixture involves integration of radiance-wavelength distribution, using the tristimulus values of spectral stimuli of equal radiance as weighting functions (see (10)). In general, neither of these factors is in the form of an analytic function, so that numeric integration is necessary. To simplify the numeric integration and to minimize the possibility of error, the tristimulus values of spectral stimuli of equal radiance should not change sign over the range of wavelengths within the visible region. This result is obtained if the triangle corresponding to the three reference primaries wholly includes the locus of the chroma-

[97] See bibl. ref. 2.

[98] The philosophy set down here is essentially that followed by the ICI in 1931 in establishing the system of primaries (X), (Y), and (Z) (bibl. ref. 22, 24). This philosophy was foreshadowed by proposals by Deane B. Judd in 1930 (bibl. ref. 37).

ticity co-ordinates of the spectrum (the spectrum locus).

2. To lessen the labor of calculation, the tristimulus values of spectral stimuli of equal radiance should be zero over as large a part of the range of visible wavelengths as is possible. Examination of the chromaticity diagram in Fig. 8 shows that the spectrum locus approximates a straight line over the greatest range of wavelength from 780 mμ toward shorter wavelengths. If one side of the new color triangle is tangent to the spectrum locus at 780 mμ, these colors can be matched by mixtures of the two primaries (X) and (Y), and the value of (Z) will be zero. One side of the new triangle is defined, therefore, by the line $X-Y$ in Fig. 8.
3. Calculation of the luminance of a color would be easier if the luminosity coefficients of two of the primaries were equal to zero. The luminance of the color then would be equal to the luminance of the number of units of the third primary required to match the color. This result $(L_X=L_Z=0)$ is obtained by placing the primaries (X) and (Z) on the line defined by

$$rL_r + gL_g + bL_b = 0 \tag{20}$$

where $b=1-(r+g)$.

This line is shown in Fig. 8. It is obvious that the new primary (X) must be located at the intersection of this line and the tangent line $(X-Y)$ be located in the preceding paragraph. The chromaticity co-ordinates of primary (X) in terms of the spectral primaries are

$$r = 1.2750$$
$$g = -0.2778$$
$$b = 0.0028.$$

4. There is no arbitrary requirement which can be set to fix the position of the third side of the new triangle. However, if the amounts of the two primaries (Y) and (Z) are to be sensitive to changes of chromaticity of physical colors (those within the spectrum locus), these primaries should be located as near the spectrum locus as possible. That is, in order that the range of magnitudes of the primaries be large, as colors matched by the mixture vary over the possible range, the primary color triangle should be no larger than is required to include these colors within it. The necessary compromise was included in the recommendation of the ICI.[99] The chromaticity co-ordinates of the new primary (Y), in terms of the spectral primaries, are

$$r = -1.7394$$
$$g = +2.7674$$
$$b = -0.0280.$$

[99] See bibl. ref. 22.

The chromaticity co-ordinates of the new primary (Z) are

$$r = -0.7429$$
$$g = +0.1409$$
$$b = +1.6020.$$

5. The new system of primaries becomes fully specified when the scales in which they are measured are set. For convenience, the ICI recommended that a mixture of one unit of each primary should match "equal-energy" white.[100]

At this point we have gone as far with the ICI primaries as we had with the spectrum primaries when we chose their wavelengths and also the reference white. We must have tristimulus values of spectral stimuli of equal radiance in terms of the new primaries if we are to make use of them. Since the new primaries are nonphysical, we cannot duplicate the experimental procedure we described for the spectrum primaries.

This is, of course, a problem of general interest, for we will want to know how to specify colors in terms of mixtures of specific primaries that are convenient to the problem in hand. We are justified, therefore, in considering the problem in detail.

Most fundamentally, the problem is one in color matching. We want to know the amounts of each of a second set of primaries which, when mixed, will match a color that we know is matched by a mixture of three reference primaries. This problem can be solved in two steps. The first step is to find the amounts of each of the first set of primaries which, when mixed, will match a unit of each one of the second set of primaries. These relations are found by applying the transitive law (Rule 7) to the mixture of the first set of primaries and the mixture of the second set of primaries which match the second reference white. The second step is to find the amounts of each of the second set of primaries which, when mixed, will match a unit of each one of the first set of primaries. These relations are found by applying the transitive law to the mixture of the first set of primaries and the mixture of the second set of primaries which match any color. It will be noted that the size of units of the second set of primaries is fixed by the first step and that the result of the second step is our desired answer.

This problem has been treated by the methods of vector algebra (color equations) by Ives[101] and by Guild.[102] Their analyses assumed the same reference white for both the first and the second sets of primaries. For that reason, the analysis in the Appendix has been prepared for the case of different reference whites.

A further insight into this problem may be gained by considering the three-dimensional representation of color illustrated in Fig. 6. You will recall that the co-

[100] It will be recalled that "equal-energy" white is characterized by a radiance distribution that is independent of wavelength.
[101] See bibl. ref. 36.
[102] See bibl. ref. 38.

ordinates of any point in this color space are the tristimulus values of a color in terms of the primaries for which the co-ordinate axes were drawn. The chromaticity co-ordinates of any color fix the direction of a vector from the origin by establishing the point in the plane (1, 0, 0), (0, 1, 0), and (0, 0, 1) through which the vector passes.

Lines corresponding in directions to the second set of primaries can be drawn by plotting their chromaticity co-ordinates in the Maxwell triangle plane and connecting these points with the origin. This construction is shown in Fig. 9.[103]

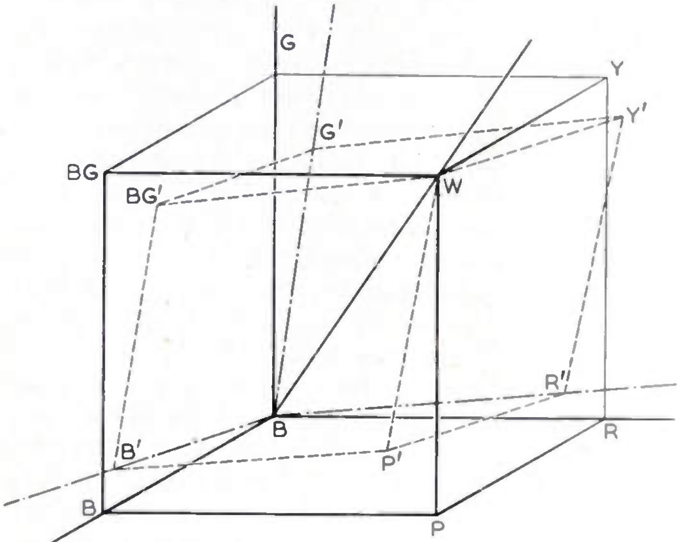

Fig. 9—Transformation from one set of primaries to another.
R, G, B = primaries of the first set.
R', G', B' = primaries of the second set, plotted in the co-ordinate system of the first set.
Vertices of cube = mixtures of primaries of the first set, taken singly, in pairs, and all together.
Vertices of parallelopiped = mixtures of primaries of the second set, taken singly, in pairs, and all together.

The scales on which amounts of the second set of primaries are measured are found by projecting the point corresponding to the second reference white onto each of the lines corresponding to the second set of primaries. The length of each of these projections (designated by BR', BG', and BB' in Fig. 9) is equal to a unit of the corresponding primary of the second set. (In the case of Fig. 9, the same reference white W is used for both systems of primaries.) Projections of other points, fixed in this color space by their tristimulus values in terms of the first set of primaries, onto the lines corresponding to the second set of primaries, when measured in terms of these unit amounts, are the required tristimulus values in terms of the second set of primaries.

When we apply the results of the Appendix to the case of the transformation from the spectrum primaries (R), (G), and (B) to the ICI primaries (X), (Y), and (Z), we find that

$$X = 2.7690R + 1.7518G + 1.1300B$$
$$Y = 1.0000R + 4.5907G + 0.0601B \qquad (21)$$
$$Z = 0.0000R + 0.0565G + 5.5943B$$

and

$$L_X = 0$$
$$L_Y = 1 \qquad (22)$$
$$L_Z = 0$$

where X, Y, and Z are the tristimulus values of a color in terms of the new primaries, and R, G, and B the tristimulus values in terms of the spectral primaries. In making this transformation the chromaticity co-ordinates of the new primaries were given the values determined in the preceding paragraphs. The reference white for both the system of spectral primaries and the new system of ICI primaries (X), (Y), and (Z) is equal-energy white. If we assume that the luminance of the reference white for the new system is unity when the luminances of units of the spectral primaries (R), (G), and (B) are 1, 4.5907, and 0.0601, respectively, the tristimulus values of the new white are given by (47(a)) and are

$$R_w = G_w = B_w = 1/(1 + 4.5907 + 0.0601). \qquad (23)$$

The tristimulus values R, G, and B in (21) can be those of any color. In particular, they may be the tristimulus values of a spectral stimulus of equal radiance. When such values from Fig. 4 (or from the standard tables)[104] are substituted into this equation, the resulting tristimulus values X, Y, and Z are the tristimulus values for a spectral stimulus of equal radiance ($\bar{x}$, $\bar{y}$, and $\bar{z}$) in terms of the new primaries. The results of such calculation are plotted in Fig. 10.

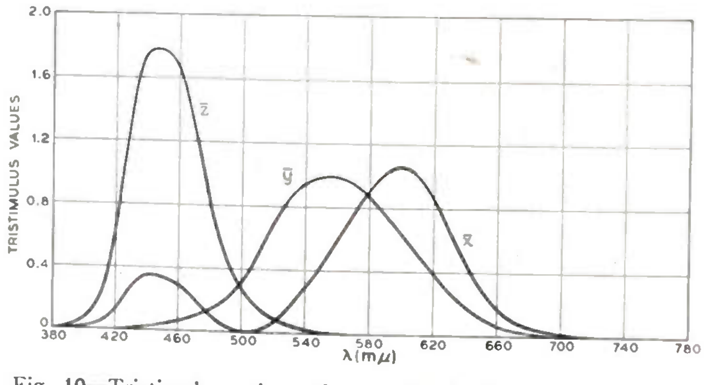

Fig. 10—Tristimulus values of spectral stimuli of equal radiance for the Standard Observer (standard color-mixture data for the spectrum).
ICI nonphysical primaries (X), (Y), (Z).
Reference white = equal-energy white.
$L_x : L_y : L_z = 0 : 1.0 : 0$.

The color-mixture data ($\bar{x}$, $\bar{y}$, and $\bar{z}$) and the chromaticity co-ordinates (x, y, z) for the spectrum were standardized for the standard observer by the ICI in 1931.[105]

[103] Fig. 9 is a copy of Fig. 2 of Ives' 1915 paper (bibl. ref. 36(a)). It is a general representation of a new set of primaries in the co-ordinate system of the old set.

[104] See bibl. ref. 22. 24.

[105] See bibl. ref. 22–24.

Hardy has interpolated between the standardized values, and has tabulated these quantities at intervals of one millimicron.[106]

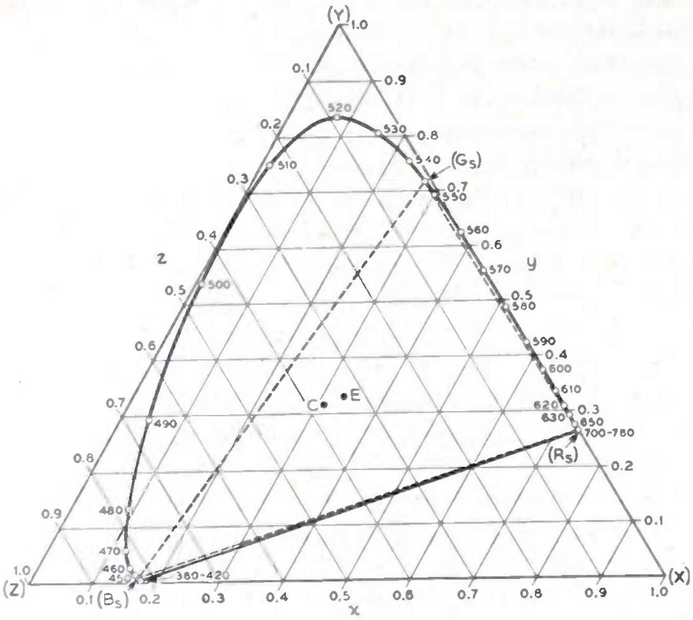

Fig. 11—Maxwell triangle for the ICI primaries (X), (Y), (Z) for the Standard Observer
Reference white = equal-energy white.
E = equal-energy white.
C = Illuminant C.

One condition placed on this new system of primaries was that the luminance of a color be proportional to its tristimulus value Y. The color-mixture curve for the spectrum corresponding to the (Y) primary (the $\bar{y}$ curve) should therefore be the same as the luminosity curve. Comparison of the curves in Figs. 3 and 10 shows this to be the case.

We can represent colors graphically in terms of these new primaries in the same way as we represented them in terms of the spectrum primaries. A Maxwell triangle in the (X), (Y), (Z) co-ordinates is shown in Fig. 11, and the $x-y$ chromaticity diagram is shown in Fig. 12. In each of these figures, the chromaticity co-ordinates of the spectrum have been plotted to show the spectrum locus, and, in addition, points representing some of the other colors we have been considering are shown. On these figures, the co-ordinates of equal-energy white are (1/3, 1/3, 1/3) because we chose the size of units of the primaries to make this so. The co-ordinates of Illuminant C are (0.3101, 0.3163, 0.3736). The chromaticity co-ordinates of the spectrum primaries we considered first are shown in Table V.[107]

TABLE V

	x	y	z
R_S (700.0 mμ)	0.7347	0.2653	0.0000
G_S (546.1 mμ)	0.2738	0.7174	0.0088
B_S (435.8 mμ)	0.1666	0.0089	0.8245

[106] See bibl. ref. 39.
[107] These chromaticity co-ordinates were standardized by the ICI in 1931 (bibl. ref. 22, 24).

Use of the ICI Nonphysical Primaries

The ICI system of specific nonphysical primaries was recommended for use with two purposes in mind. First, it represents a common frame of reference in which all laboratories, procurement agencies, and the like, can specify colors with very little possibility of misunderstanding. Second, the primaries were so selected that the possibility of making arithmetical errors in calculating the tristimulus values of colors (i.e., in indirect colorimetry)[108] is minimized. How is this system used?

Earlier, the use of the color-mixture data for the spectrum in terms of the spectrum primaries, and the way to calculate color matches from these data, was discussed. The procedure for using the ICI nonphysical primaries is similar.

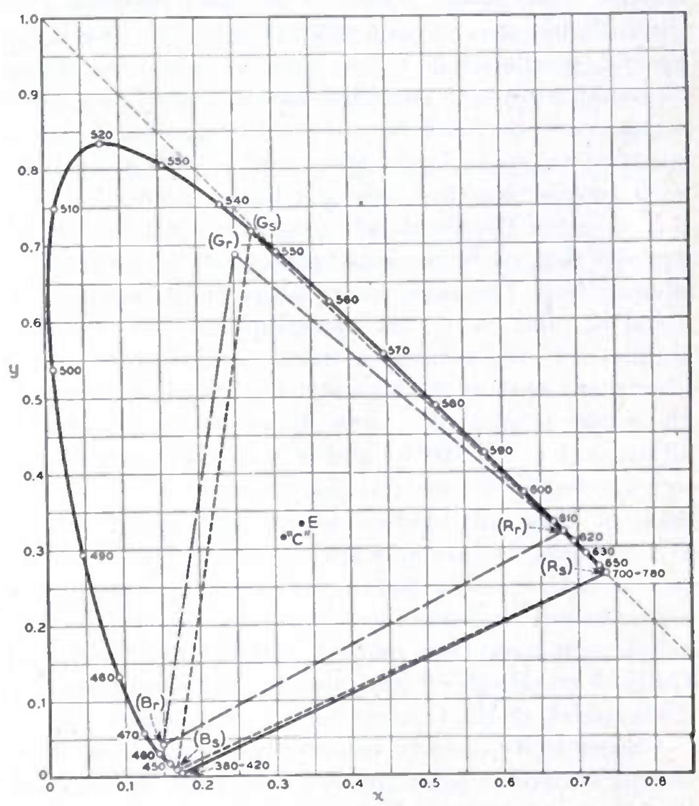

Fig. 12—x-y chromaticity diagram for the ICI primaries (X), (Y), (Z) for the Standard Observer
Reference white = equal-energy white.
E = equal-energy white.
C = Illuminant C.
(R_s), (G_s), (B_s) = spectrum primaries.
(R_r), (G_r), (B_r) = receiver primaries.

The composition of radiance corresponding to the color of a material sample is given by the product of the composition of radiance of the illuminant and the relative reflectance of the sample. The tristimulus values of this color are given by the expressions

$$X_c = \int_0^\infty \bar{x}(\lambda)[E(\lambda) \times R(\lambda)]d\lambda$$

[108] Direct colorimetry is the process of making color matches in a colorimeter. Indirect colorimetry is the process of calculating color matches from spectrophotometric data for the sample and standardized color-mixture data for the spectrum.

$$Y_c = \int_0^\infty \bar{y}(\lambda)[E(\lambda) \times R(\lambda)]d\lambda \qquad (24)$$

$$Z_c = \int_0^\infty \bar{z}(\lambda)[E(\lambda) \times R(\lambda)]d\lambda.$$

These tristimulus values are the amounts of the three primaries (X), (Y), and (Z) which, when mixed, would match the sample color for the standard observer. The units in which these primaries are measured are such that a mixture of one unit of each matches equal-energy white.

At the same time that the ICI adopted this system of nonphysical primaries, they adopted recommendations about methods of illuminating and measuring the relative reflectance $(R(\lambda))$. They also recommended three illuminants, any one of which might be used in the general specification of the color of materials. These illuminants are (a) a gas-filled lamp operated at a color-temperature of 2,854°K,[109] (b) this same lamp with a specified two-part liquid filter, and (c) the same lamp with another specified two-part liquid filter.[110]

The use of Illuminant A[111] obviously is indicated for samples that are to be viewed principally under artificial illumination. The color-temperature of Illuminant B is 4,800°K, and it is an approximation to noonday sunlight. It represented a minor modification of the illuminant used at the National Physical Laboratory in their color work at that time. The color-temperature of Illuminant C is 6,500°K, and it is an approximation to average daylight. Spectral distributions of radiance of each of these illuminants were standardized by the ICI.[110] Since the products $\bar{x}(\lambda) \times E(\lambda)$, and the like, appear in (24), it is a matter of convenience in colorimetric computation to have these products tabulated. Such tabulations have been made by Judd,[112] by Smith and Guild,[113] by Hardy,[114] and also by the Committee on Colorimetry of the Optical Society of America.[115]

Chromaticity co-ordinates of a color sample in terms of this system of primaries are calculated in the same way that we calculated such co-ordinates for the spectral primaries, that is,

$$\begin{aligned} x_c &= X_c/(X_c + Y_c + Z_c) \\ y_c &= Y_c/(X_c + Y_c + Z_c) \\ z_c &= Z_c/(X_c + Y_c + Z_c). \end{aligned} \qquad (25)$$

[109] The recommendation of the ICI was a color-temperature of 2,848°K. The adoption of the new International Temperature Scale made the change to 2,854°K necessary to preserve the radiance distribution of Illuminant A (bibl. ref. 40).

[110] See bibl. ref. 22–24.

[111] In a private communication, Dr. Deane B. Judd advises the author of a trend toward the replacement of the term "Illuminant A" (or B, or C) by the term "Standard Source A" (or B, or C). Examples of the use of this newer terminology are found in bibl. refs. 31 and 40.

[112] See bibl. ref. 23.

[113] See bibl. ref. 24.

[114] See bibl. ref. 39.

[115] See bibl. ref. 19(d).

The colorimetrist specifies a color by a pair of its chromaticity co-ordinates (say, x_c and y_c) and by its luminance or, more usually, by its luminance factor. You will recall that this system of primaries was set up in such a way that the luminance of a color is proportional to the tristimulus value Y_c. Provided the radiance distribution $[E(\lambda) \times R(\lambda)]$ is known in units of power per steradian per square meter per unit of wavelength, the luminance can be calculated from the value of Y_c, and the fact that one watt at the peak of the curve $\bar{y}$ is equivalent to 680 lumens.[116] It is customary, however, to give the luminance factors of a colored surface or medium. This factor is given by

$$\beta = Y_c/Y_r \qquad (26)$$

where Y_r is the Y-tristimulus value of an ideal diffusing surface illuminated in the same way as the colored sample. The value of Y_r is found by substituting $R(\lambda) = 1$ in (24).

We have seen how to evaluate the color of the additive mixture of two colors when each is specified by its luminance and its chromaticity co-ordinates in terms of the spectrum primaries. The procedure is the same, but the arithmetic is a little easier in this system of (X), (Y), (Z) primaries since the luminosity coefficients of two of these primaries are zero. By analogy to (19), we find the chromaticity co-ordinates of an additive mixture of two colors, specified by x_1, y_1, L_1 and x_2, y_2, L_2, are given by the relations

$$\begin{aligned} x_{1+2} &= K_1x_1 + K_2x_2 \\ y_{1+2} &= K_1y_1 + K_2y_2 \\ z_{1+2} &= K_1z_1 + K_2z_2 \end{aligned} \qquad (27)$$

where,

$$K_1 = \frac{L_1/y_1}{(L_1/y_1) + (L_2/y_2)}$$

$$K_2 = \frac{L_2/y_2}{(L_1/y_1) + (L_2/y_2)} = 1 - K_1.$$

Other Methods of Specifying Color

Specification of a color by its tristimulus values in terms of the ICI primaries (X), (Y), and (Z) is only one of many ways of specifying a color. As has been pointed out, the chromaticity co-ordinates and luminance or luminance factor form a preferred alternative in most colorimetry.

The chromaticity co-ordinates are only one way of defining the chromaticity aspect of color. Dominant wavelength and purity, referred to the same illuminant that was used in finding the chromaticity co-ordinates, are alternate quantities in which chromaticity may be

[116] When the tristimulus values of self-luminous sources are given in the American Standard Method for Specification of Color (bibl. ref. 31), the units in which primaries (X), (Y), and (Z) are measured are adjusted so that the tristimulus value Y is equal to the luminous flux in lumens.

expressed. Conversion from one method of expression to the other is treated by Hardy,[117] Judd,[118] and by the Committee on Colorimetry of the Optical Society of America.[119]

There are a variety of other methods of color specification which have advantages in specific cases. These systems are described fully in two papers by Judd.[120] The reader who is interested in this aspect of color specification is advised to consult these papers, to each of which an extensive bibliography is appended.

Color Television

The preceding pages contain a general history of the development of the theory and a discussion of the fundamental principles of colorimetry. The way in which these principles may be applied in the design of a color-television system form the subject of the remainder of this paper.

Basically, colorimetry is the specification of a color by giving the strength of three lights which, in an additive mixture, match that color. In the first few decades of development of colorimetry, an observer would actually make such color matches in a colorimeter. It was recognized, even by Maxwell, that the differences between the visual processes of typical observers were so great that direct colorimetry was none too precise a method for color specification. To avoid the effects of observer differences, indirect colorimetry was developed. Indirect colorimetry is based on spectrophotometric measurements of radiance and on standardized observer responses. In 1931, the ICI recommended the use of color-mixture data for the spectrum which was based on the best measurements of the color characteristics of observers that were available.[121]

The tristimulus values of a color, for which the spectral composition of radiance is given, are found by evaluating these integrals[122]

$$R = \int_0^\infty \bar{r}(\lambda)[R(\lambda) \times E(\lambda)]d\lambda$$
$$G = \int_0^\infty \bar{g}(\lambda)[R(\lambda) \times E(\lambda)]d\lambda \qquad (28)$$
$$B = \int_0^\infty \bar{b}(\lambda)[R(\lambda) \times E(\lambda)]d\lambda$$

where,

R, G, B = tristimulus values of the color corresponding to the radiance composition $[R(\lambda) \times E(\lambda)]$

$\bar{r}, \bar{g}, \bar{b}$ = tristimulus values of spectral stimuli of equal radiance for the set of primaries (R), (G), and (B) under consideration.

The color-mixture data for the spectrum $\bar{r}$, $\bar{g}$, and $\bar{b}$, and the corresponding tristimulus values of the color are those for the "standard observer" when these data are based on those standardized by the ICI in 1931.

The primaries (R), (G), and (B) for which the tristimulus values are given by (28) may be any set of primary colors, physical or nonphysical.[123] The problem of converting color-mixture data corresponding to one set of primaries to another is treated in the Appendix. It is shown that that

$$R_2 = \begin{vmatrix} R_1 & r_g & r_b \\ G_1 & g_g & g_b \\ B_1 & b_g & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} R_w & r_g & r_b \\ G_w & g_g & g_b \\ B_w & b_g & b_b \end{vmatrix}$$

$$G_2 = \begin{vmatrix} r_r & R_1 & r_b \\ g_r & G_1 & g_b \\ b_r & B_1 & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & R_w & r_b \\ g_r & G_w & g_b \\ b_r & B_w & b_b \end{vmatrix} \qquad (54)$$

$$B_2 = \begin{vmatrix} r_r & r_g & R_1 \\ g_r & g_g & G_1 \\ b_r & b_g & B_1 \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & R_w \\ g_r & g_g & G_w \\ b_r & b_g & B_w \end{vmatrix}$$

$$L_{r2} = (r_r L_{r1} + g_r L_{g1} + b_r L_{b1}) \begin{vmatrix} R_w & r_g & r_b \\ G_w & g_g & g_b \\ B_w & b_g & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix}$$

$$L_{g2} = (r_g L_{r1} + g_g L_{g1} + b_g L_{b1}) \begin{vmatrix} r_r & R_w & r_b \\ g_r & G_w & g_b \\ b_r & B_w & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix} \qquad (57)$$

$$L_{b2} = (r_b L_{r1} + g_b L_{g1} + b_b L_{b1}) \begin{vmatrix} r_r & r_g & R_w \\ g_r & g_g & G_w \\ b_r & b_g & B_w \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix}$$

[117] See bibl. ref. 39.
[118] See bibl. ref. 41.
[119] See bibl. ref. 19(d).
[120] See bibl. ref. 41, 42.
[121] See bibl. ref. 22–24.
[122] Since the visible spectrum is limited to the range 380–380 mμ, these integrals need be evaluated only over this range.

[123] Nonphysical primaries are primaries the chromaticities of which lie outside the spectrum locus, and consequently are primaries which cannot be produced by physical lights. The ICI primaries (X), (Y), and (Z) are nonphysical in this sense. The engineer will commit no error if he considers such primaries as no more than a convenient reference co-ordinate system.

where,

$$R_w = r_wL_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1})$$
$$G_w = g_wL_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1}) \qquad (47(a))$$
$$B_w = b_wL_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1}).$$

In these expressions,

R_1, G_1, B_1 = tristimulus values of a color in terms of the first set of primaries,

R_2, G_2, B_2 = tristimulus values of the same color in terms of the second set of primaries,

r_r, g_r, b_r; r_g, g_g, b_g; r_b, g_b, b_b = chromaticity co-ordinates of the second set of primaries in terms of the first set,

r_w, g_w, b_w = chromaticity co-ordinates of the reference white for the second set of primaries in terms of the first set,

R_w, G_w, B_w = tristimulus values of the reference white for the second set of primaries in terms of the first set,

L_{r1}, L_{g1}, L_{b1} = luminosity coefficients of the primaries of the first set,

L_{r2}, L_{g2}, L_{b2} = luminosity coefficients of the primaries of the second set,

L_w = luminance of the reference white for the second set of primaries.

Equations (28), (54), and (57), taken together with the color-mixture data for the spectrum standardized by the ICI,[124] contain all of the information we require to apply the principles of indirect colorimetry to color television.

But what about color television? If we consider each element of a scene separately, a composition of radiance $[R(\lambda) \times E(\lambda)]$ is presented to the camera for that element. At the receiver that same element of the scene is represented by the mixture of three colored lights. These lights might be produced by colored phosphors on picture tubes and the addition performed by viewing them through dichroic or through half-silvered mirrors. Alternatively, these lights might be produced by viewing a white phosphor through color filters in rapid succession. These three colored lights should be thought of as a set of primaries—receiver primaries—the mixture of which should match the color of successive elements of the scene before the camera.

These color matches will be obtained for the standard observer if the strengths of the three lights are equal to the tristimulus values of the successive scene elements for the receiver primaries. Neglecting, for the moment, transformation of color co-ordinates in the television system, and assuming linearity in all parts of the system, the currents from the camera should be proportional to these tristimulus values. Examination of (28) will show that this result is obtained provided the spectral sensitivity of each channel of the camera is proportional to the corresponding color-mixture curve for the spectrum. This conclusion seems to have been reached first by F. E. Ives for color photography in 1888.[125] It was applied to color television in 1929 by H. E. Ives and A. L. Johnsrud.[126]

Primaries for a Television Receiver

Today we do not have much freedom of choice of the sources of primaries to be used in a television receiver. Such sources must be capable of modulation at the frequencies resulting from scanning. The most practical sources at this time are fluorescent screens in cathode-ray tubes (picture tubes).

From the point of view of color reproduction, it is of little moment whether the primaries are formed through the use of separate phosphors or through the combination of color filters and mixed phosphors. In either case, the receiver primaries will correspond to radiance distributions of considerable width measured in millimicrons. The chromaticity co-ordinates of such primaries will be inside the spectrum locus, and the color triangle corresponding to these primaries will be smaller than a triangle for spectrum primaries.

As we have seen, the chromaticities of colors that can be produced by a set of primaries lie within the color triangle corresponding to the primaries. The larger the triangle, the greater the gamut of colors that can be produced. From this point of view, it is desirable to use primaries of large purity, i.e., which are nearly spectrum colors. The purity of a primary can be increased, however, only by decreasing the width of the radiance distribution in wavelength. If we require purer primary colors than we can obtain directly from phosphors, filters must be used with the phosphors, resulting in a decrease of useful radiance. For efficient use of phosphors, i.e., to produce primaries of high luminance, it is desirable, therefore, to use the colors that can be obtained directly from phosphors, even if this results in desaturated primaries.

There is another reason why it may be desirable to use desaturated primaries in a television receiver. It has been found in direct colorimetry that observer differences can be minimized by making the color triangle of the primaries no larger than is necessary to include the variation of chromaticities to be measured.[127]

There is every indication that it is undesirable to use receiver primaries of greater purity than is necessary. The choice, obviously, must be a compromise. For discussion purposes, let us assume the use of a set of primaries which were recommended by an RMA committee a few years ago.[128] These primaries were specified as having the same chromaticities as these combinations:

Red —Illuminant *C* and Wratten No. 25 Filter
Green—Illuminant *C* and Wratten No. 58 Filter
Blue —Illuminant *C* and Wratten No. 47 Filter.

[124] See bibl. ref. 22–24.

[125] See bibl. ref. 12.
[126] See bibl. ref. 14.
[127] See bibl. ref. 43, 44.
[128] See bibl. ref. 45. Other sets of primaries have been discussed by CBS, NTSC, RCA, and by this same RMA committee. This is not the place to consider the differences between these several choices of primaries.

It was recommended also that the white corresponding to equal signals on the three picture-tube grids—the equal picture-tube-signal white—should be Illuminant C.

The combinations of filters and an illuminant set down above are a convenient way of specifying the chromaticities of receiver primaries. To use these data, we must evaluate the chromaticities of these primaries and their color-mixture data for the spectrum. As a first step, we must find the distributions of radiance corresponding to each combination. The radiance-wavelength distribution of Illuminant C was standardized by the ICI, and is tabulated in a number of references.[129] Typical transmission of Wratten filters has been tabulated by their supplier, the Eastman Kodak Company.[130] The radiance distribution for each filter-illuminant combination is given by the product of these data, and is plotted in Fig. 13 for the three combinations under consideration.

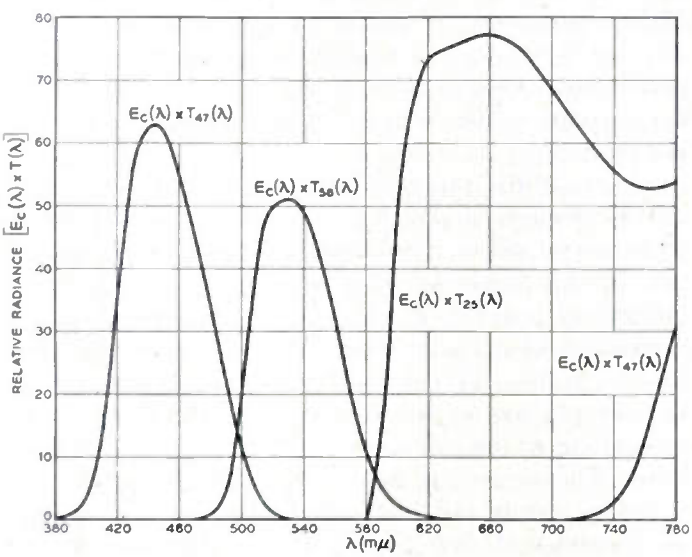

Fig. 13—Distribution of radiance for Wratten filters and Illuminant C.
$T_{25}(\lambda)$ = transmittance of Wratten No. 25 filter.
$T_{47}(\lambda)$ = transmittance of Wratten No. 47 filter.
$T_{58}(\lambda)$ = transmittance of Wratten No. 58 filter.

The tristimulus values for each of the colors corresponding to the distributions of radiance in Fig. 13 are found by substituting these values into (28). It is most convenient to use the standard values $\bar{x}$, $\bar{y}$, and $\bar{z}$ of the color-mixture data for the spectrum corresponding to ICI primaries (X), (Y), and (Z) in making these calculations.[131] Using the tristimulus values calculated in this way, we can calculate the chromaticity co-ordinates of each of the receiver primaries. These chromaticity co-ordinates of these RMA primaries are given in Table VI.[132] The chromaticity co-ordinates of these primaries, and the corresponding color triangle are shown on the $x-y$ chromaticity diagram, Fig. 12. As we have seen already, the chromaticity co-ordinates of

TABLE VI

Receiver Primary	x	y	z
Red	0.6805	0.3193	0.0002
Green	0.2500	0.6885	0.0615
Blue	0.1477	0.0412	0.8111

Illuminant C in terms of the ICI nonphysical primaries (X), (Y), and (Z) are (0.3101, 0.3163, 0.3736).

When we substitute these figures into (54) and (57), we find that the relations between the tristimulus values of a color in terms of the two systems of primaries are

$$\begin{aligned} R_r &= 2.2842X - 0.7959Y - 0.3755Z \\ G_r &= -0.8078X + 1.7215Y + 0.0596Z \\ B_r &= 0.0447X - 0.0958Y + 0.8906Z \end{aligned} \tag{29}$$

and also that

$$\begin{aligned} L_{r_r} &= 0.2456 \\ L_{g_r} &= 0.6976 \\ L_{b_r} &= 0.0568. \end{aligned} \tag{30}$$

We can interpret (30) as meaning that the luminances of the three receiver primaries, when they are mixed to match Illuminant C, are in the ratios

$$L_r : L_g : L_b = 1 : 2.8406 : 0.2314. \tag{31}$$

If we examine (54) and (57), it will become apparent that the tristimulus values of the reference white for the receiver primaries serves only to set the scale of R_r, G_r, and B_r, and the relative luminance of units of the receiver primaries L_{r_r}, L_{g_r}, and L_{b_r}. In the case of two receivers having primaries of identical chromaticities but for which the equal-signal whites are different, identical color reproduction can be obtained from the same three signals provided the proper gain changes are introduced in one or the other receiver. That is, the equal-signal white can be thought of as a specification of the relative gains in the three color-signal channels.

Camera Spectral Sensitivities

A straightforward and logical approach to the problem of spectral sensitivities of the television camera to be used with this receiver is to assume that these sensitivity characteristics are identical to the color-mixture curves for the spectrum for the receiver primaries. Let us calculate these curves for the standard observer and find out where this approach leads us.

When the tristimulus values for spectral stimuli of equal radiance for the ICI nonphysical primaries ($\bar{x}$, $\bar{y}$, and $\bar{z}$) are substituted for X, Y, and Z in (29), the tristimulus values R_r, G_r, and B_r are the corresponding color-mixture data for the spectrum $\bar{r}_r$, $\bar{g}_r$, and $\bar{b}_r$ for

[129] See bibl. ref. 19(d), 22, 23, 24, 39.
[130] See bibl. ref. 46.
[131] Some saving in calculation results from the use of the tabulated functions $\bar{x}E_c(\lambda)$, $\bar{y}E_c(\lambda)$, and $\bar{z}E_c(\lambda)$ (bibl. ref. 19(d), 23, 24, 31, 39, 41).
[132] Similar calculations have been made for the combination of each of three illuminants and every one of the Wratten filters by David L. MacAdam (bibl. ref. 47).

the receiver primaries. These calculations have been made, and the results are shown in Fig.14.

Under the conditions we set down in the specification of this particular set of receiver primaries, if a camera having the spectral sensitivities shown in Fig. 14 were irradiated by Illuminant C, or by any other composition of radiance which color matched Illuminant C, the currents in its three output circuits would be equal. These equal signal currents would produce a color match (for the standard observer) to Illuminant C on the receiver.

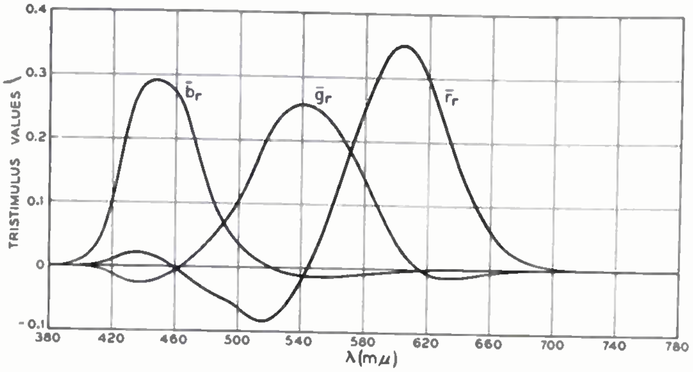

Fig. 14—Tristimulus values of spectral stimuli of equal radiance for the Standard Observer (standard color-mixture data for the spectrum).
Receiver primaries = (R_r), (G_r), (B_r)
Reference white = Illuminant C.
$L_r : L_g : L_b = 1 : 2.8407 : 0.2314$.

Each of these characteristics in Fig. 14 is positive for part of the range of visible wavelengths and is negative for the remainder of the range. Obviously, we must use photocathodes in the camera to convert from radiance to electric currents. The combination of the spectral sensitivity characteristic of a cathode and the transmission characteristic of an optical filter are the variables we can use to approximate each of these characteristics. But, we do not know how to produce the reversals of current with change of wavelength required by these curves. We know of no simple way of approximating these sensitivity characteristics which are required if the color-television system is to color-match any radiance-wavelength distribution, even though the corresponding color is reproducible by a mixture of the receiver primaries.

We can, of course, conceive of a very complicated camera in which each loop of the sensitivity curve between crossings of the zero axis is treated by a separate filter and photocathode. If we follow this approach, we find that we would require three filters and photocathodes, with their outputs combined with the proper signs, to produce each of the spectral sensitivity characteristics shown in Fig. 14.

This sort of complication is quite unnecessary. If we examine (54) for the relations between the tristimulus values of colors in terms of two different sets of primaries, we find the relations are of the form

$$
\begin{aligned}
R_2 &= K_1R_1 + K_2G_1 + K_3B_1 \\
G_2 &= K_4R_1 + K_5G_1 + K_6B_1 \\
B_2 &= K_7R_1 + K_8G_1 + K_9B_1.
\end{aligned}
\qquad (32)
$$

The quantities $K_1 \cdots K_9$ depend only on the chromaticities of the second set of primaries and the tristimulus values of the second reference white, all in terms of the first set of primaries. The important fact is that these quantities are constant, that they depend only on the constants of the two sets of primaries, and that they are independent of the tristimulus values of colors expressed in terms of either set of primaries.

If we have a camera, the spectral sensitivities of which correspond to a set of primaries (R_1), (G_1), and (B_1), the currents from this camera will be proportional to the tristimulus values R_1, G_1, and B_1 of a color in front of the camera. If our receiver primaries are (R_2), (G_2), and (B_2), we need only provide electrical circuits to perform the operations indicated by (32) to derive the currents necessary to control the receiver primaries. These operations are simple to carry out electrically. All that is required is the addition (or subtraction, depending on the signs of the K's) of fractions of the camera currents to derive the currents required to control the receiver.[133]

We can utilize this possibility to eliminate the necessity for regions of positive and negative sensitivity in the spectral sensitivity characteristics of the camera. One of the properties of a color triangle is that the mixture of positive amounts of the corresponding primaries can be made to match only those chromaticities that lay within it. If color-mixture data for the spectrum is to be positive for all wave-lengths, the triangle corresponding to the primaries must include the spectrum locus. The desired camera sensitivity characteristics, therefore, can be obtained only if the camera primaries are nonphysical. Instead of trying to establish chromaticities for a set or sets of camera primaries which require suitable spectral sensitivity characteristics, this problem is better attacked from the other end.

If we replace R_1, G_1, and B_1 by $\bar{x}$, $\bar{y}$, and $\bar{z}$, respectively in (32), the quantities R_2, G_2, and B_2 become the color-mixture data for the spectrum for a set of unspecified primaries. Judd has shown that only one restriction need be placed on this process.[134] That is:

$$
\begin{vmatrix} K_1 & K_2 & K_3 \\ K_4 & K_5 & K_6 \\ K_7 & K_8 & K_9 \end{vmatrix} \neq 0. \qquad (33)
$$

We can select values of $K_1 \cdots K_9$, subject to this restriction, which give us spectral sensitivity character-

[133] This operation has been called "matrixing" in some discussions. The analogy to the matrix operation, which is used in vector algebra to change from one system of co-ordinates to a second, is obvious.
[134] See bibl. ref. 37.

istics for the camera which are practical. Of course, we must include an electrical co-ordinate transformation between the camera and the receiving picture tubes so that the voltages applied to them are proportional to the tristimulus values of colors in terms of the receiver primaries.

This method of combining the color-mixture data for the spectrum $\bar{x}$, $\bar{y}$, and $\bar{z}$ to obtain new curves of special shapes has been done for a variety of purposes. Judd has made this kind of transformation to obtain spectral sensitivity curves which might be used to explain some kinds of color blindness.[135] Szekeres has made a similar transformation in an effort to find the "physiological primaries" of vision.[136] Marriage performed the same operations to find "the narrowest possible linear combination of the C.I.E. curves not involving negative values," in connection with a study of color photography.[137] The values of the constants $K_1 \cdots K_9$ used in these respective studies are given in Table VII.

It is likely that no one of these transformations yields the best characteristics for a color-television camera. In addition to the requirement that each color-mixture curve can be duplicated by the spectral sensitivity characteristics of a combination of a filter and a photocathode, we must consider noise. In a co-ordinate transformation, it is clear that the signals from separate camera tubes will be added or subtracted to obtain the signals to control each picture tube. However, since the camera tubes are independent noise sources, the noises will add even if the signals are subtracted. For illustration, let us assume that one of the picture tubes should be controlled by a current proportional to the ICI tristimulus value X. If the camera has the spectral sensitivities suggested by Judd's figures, 46 per cent of X is present in the output of the camera green channel. However, to isolate this quantity from the total output of the camera green channel, we must subtract 10.1 per cent of the output of the camera blue channel and 135.9 per cent of the output of the camera red channel from the output of the camera green channel. In obtaining 46 per cent of X, we have gotten, also, all of the noise from the camera green channel, increased by 10.1 per cent of the noise from the camera blue channel, and by 135.9 per cent of the noise from the output of the camera red channel. Obviously, we have a method here to which much thought must be given before the best compromise is found.

[135] See bibl. ref. 48.
[136] See bibl. ref. 49.
[137] See bibl. ref. 50.

The application of electrical methods of transformation of color co-ordinates in color-television systems is not restricted to the camera. It is possible that advantages might be gained by using different color co-ordinates in the part of the system between the camera and the picture tubes than is used at these two ends of the system. This is another section of the field of color television that has not been explored and the best compromises found yet.

Shortcoming of this Color System

It is well to recall at this point the fundamental principles of color mixture. When three physical colors are added together, the chromaticity of their mixture lies within the triangle formed by connecting their chromaticities on a chromaticity diagram. The gamut of chromaticities which can be produced by the receiver primaries (R_r), (G_r), and (B_r) lies within the corresponding triangle shown in Fig. 12.

Provided we expend sufficient effort in a television system, we have seen that it is possible to obtain currents which are proportional to the tristimulus values of any color in terms of these receiver primaries. It is possible, therefore, to color match (for the standard observer) any color the chromaticity of which lies within the triangle formed by the receiver primaries. This statement assumes linearity in all parts of the system, or at least that all nonlinearities have been corrected by suitable means.

The area covered by this triangle seems quite small in proportion to the area covered by the spectrum locus. Let us see how to judge the relative importance of the colors that can be reproduced and those which cannot.

The UCS Color Triangle

The ICI color triangle for the primaries (X), (Y), and (Z) is decidedly nonuniform in perceptual terms. That is, the linear distance between the chromaticities of two colors which are just perceptibly different varies over a wide range over the triangle. In particular, in the area near the spectrum locus at 520 mμ, the linear distance corresponding to just perceptible steps of chromaticity is many times greater than elsewhere in the figure. In the $x-y$ chromaticity chart, which is the best of the three projections of the Maxwell triangle from this point of view, the length of a just perceptible step near 400 mμ is only about 1/20 as great as it is near 520 mμ.

TABLE VII

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9
Judd	0	1	0	−0.460	1.359	0.101	0	0	1
Szekeres	1.8517	0.6642	0	−1.0630	0.3321	0.0020	0.2113	0.0037	0.9980
Marriage	0.4684	0.6323	−0.1007	−0.5050	1.3964	0.1086	0	0	1

A number of linear transformations of the ICI triangle have been proposed to produce a triangle in which this effect is lessened. (As we have seen, such linear transformations correspond to plotting the color triangle in terms of new sets of primaries.) The first of these transformations[138] is the Judd Uniform Chromaticity Scale (UCS) triangle,[139] shown in Fig. 15. This triangle corresponds to a set of nonphysical primaries since the points (0, 0), (1, 0), and (0, 1) lie outside the spectrum locus.

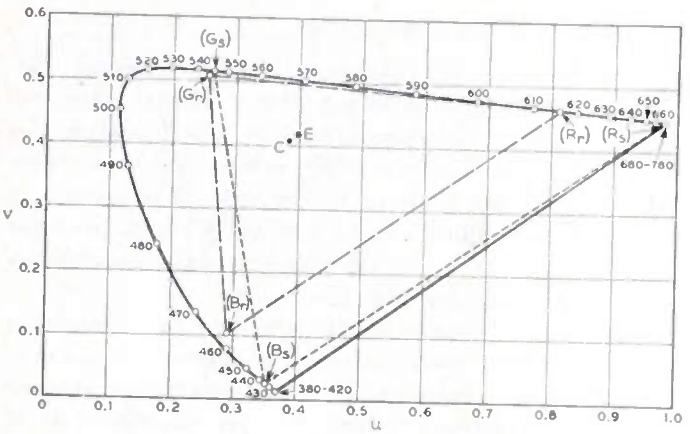

Fig. 15—Judd's Uniform Chromaticity Scale color triangle (UCS).
E = equal-energy white.
C = Illuminant C.
(R_s), (G_s), (B_s) = spectrum primaries.
(R_r), (G_r), (B_r) = receiver primaries.

In devising the Uniform Chromaticity Scale triangle, Judd made use of all the available data on perceptible differences of chromaticity. He tested this representation by checking linear distances between points representing the chromaticity of pairs of colors against the known perceptibility or sensibility of difference between these colors. In particular, he subjected the UCS triangle to these tests.

A. Sensibility to change of dominant wavelength at constant purity.
   1. Sensibility at unit purity (spectral colors).
   2. By ratios of sensibility at purity p to that at unit purity.
B. Sensibility to change of purity at constant dominant wavelength.
   1. Sensibility as a function of purity.
   2. Sensibility for purity nearly zero (off-whites).
   3. The number of perceptible steps between zero and unit purity as a function of dominant wavelength.
C. Other test.
   1. Sensibility to change of color temperature.[140]
   2. Sensibility to change of Lovibond number.[140]

Judd concluded from all these tests that about 90 per cent of the available data were represented properly by the UCS triangle within the uncertainty of the experimental observations on which these data were based.

Suppose we plot the triangle corresponding to the RMA receiver primaries on the UCS triangle in Fig. 15. We see that the areas which cannot be reproduced by these primaries ((R_r), (G_r), and (B_r)) appear differently than they do on the ICI $x-y$ chromaticity diagram (Fig. 12). The large area in the blue-green region has been shrunk, and the purple-magenta area appears larger on the UCS triangle. However, this representation shows more accurately the relative importance of the areas that cannot be reproduced by mixtures of these receiver primaries.

In this connection, it is interesting to note that there have been proposals to reduce certain flicker problems in television receivers by choosing a blue primary having a dominant wavelength near 480 mμ. The serious degradation of color reproduction that would result from such a move can be estimated by examining Fig. 15.

Colors to be Reproduced

We may interpret the preceding discussion as showing that no more than one-half of all distinguishable chromaticities can be reproduced (color-matched) by mixtures of the primaries suggested for use in a television receiver. Before we reach the conclusion that color television is impractical, let us look into the practical importance of the areas that cannot be reproduced. Obviously, the spectrum locus lies outside the triangle formed by the receiver primaries, but it would lie outside the triangle formed by any set of physical primaries. That is, spectrum colors cannot be reproduced by any 3-color additive system. This, however, is not a serious limitation on color television.

Another family of colors, some members of which fall outside this triangle, are filtered lights. It is possible that some colors used in stained glass windows fall into this class. We shall see later that the luminances of colors outside this triangle are apt to be low, and it is not too obvious that they would be used. The colors of some phosphors and of some fluorescent materials also may lie outside this triangle. At the moment, all we can say is that colors can be produced that cannot be reproduced by this set of television-receiver primaries. Whether it is important that such colors be reproduced accurately is another matter.

In any case, the colors discussed above probably will be present only in a small number of television scenes. Let us examine the more usual colors. The entire gamut of fast or permanent surface colors is represented in the color chips of the Munsell[141] and of the Ostwald[142] systems of color notation. The gamut of reasonably fast

[138] Judd discusses several of these transformations in "Colorimetry" (bibl. ref. 41).
[139] See bibl. ref. 19(d), 51.
[140] See "Colorimetry" (bibl. ref. 41) for a description of these methods of color designation.

[141] See bibl. ref. 52.
[142] See bibl. ref. 34.

colors is covered by the cards of the Textile Color Card Association.[143] A color-television system capable of reproducing all of these colors would be expected to reproduce practically all of the colors of costumes, sets, and the like, that might be used in television productions, as well as all of the more drab colors found in spot news or other scenes from outside the studios. Another gamut of colors which forms a guide to what might be considered useful is the one produced by printing inks.[144] The irregularly shaped outline in the $x-y$ chromaticity diagram in Fig. 16 represents the locus of maximum purities of all these colors, i.e., of the Munsell and the Ostwald samples, the TCCA colors, and the gamut covered by printing inks.

The triangle corresponding to the suggested television-receiver primaries is shown in this same figure. It is seen that all of the colors of paper and of cloth, except for a limited range of the blue-greens, can be color-matched by mixtures of these primaries. There seems to be no indication that any colors found in nature lie outside the locus shown in Fig. 16.

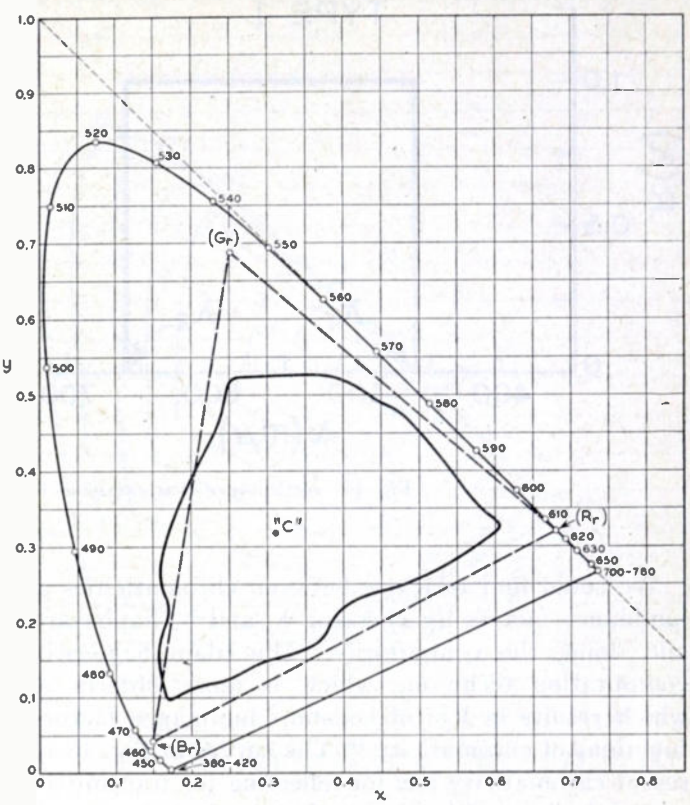

Fig. 16—Locus of extreme purities of pigments, dyes, and inks for Illuminant C.
C = Illuminant C.
(R_r), (G_r), (B_r) = receiver primaries.

Maximum Luminance Factors

The gamut of surface colors indicated by the locus shown in Fig. 16 seems to be quite restricted. Is there any good reason for this to be so? Actually there is, and we find the answer in the maximum luminance factors of surface colors.

As MacAdam has pointed out, Ostwald reached the empirical conclusion that the attainment of maximum purity with pigments requires that the spectral reflectance characteristic have only the values unity and zero. He drew the further conclusion that the characteristic should display only one continuous reflectance band or only one continuous absorption band in the range of visible wavelengths.[145] That is, in the Ostwald system of color specification, "full colors" are colors of the maximum attainable purity.[142]

MacAdam pointed out, too, that Schrödinger had established a confirmation of Ostwald's conclusion by studying the shape of the color-mixture data for the spectrum in conjunction with possible spectrophotometric characteristics of surface colors.

Through an ingenious application of the parallel between color-mixture and center-of-gravity problems, MacAdam proved the theorem: "The maximum attainable purity (closest approach to the corresponding spectrum color) for a material having a specified dominant wavelength and visual efficiency will be attained if the material has a spectrophotometric curve which is everywhere either zero or unity, and which has, at most, two transitions between these values within the region of visible radiation."[145] (Visual efficiency is an older term for the quantity we call luminance factor.) It is seen that Ostwald's and Schrödinger's conclusions are either supported by or are corollary to this theorem.

The conditions set forth in this theorem are satisfied by reflectance (or transmittance) wavelength characteristics of one of the two shapes shown in Fig. 17. The first, designated as Type I, requires perfect reflection between the limiting wavelengths λ_1 and λ_2 and perfect absorption elsewhere. The second, designated as Type II, requires perfect absorption between the limiting wavelengths λ_1, and λ_2 and perfect reflection elsewhere.

You will recall that the luminance factor of any surface (β) is equal to the ratio Y_c/Y_{ref}, where

$$Y_c = \int_0^\infty \bar{y}(\lambda)\left[E(\lambda) \times R(\lambda)\right]d\lambda \tag{34}$$

and

$$Y_{ref} = \int_0^\infty \bar{y}(\lambda)E(\lambda)d\lambda. \tag{35}$$

Using these relations, we find that the luminance factors of the two types of surface shown in Fig. 17 are

$$\beta_{I}(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} \bar{y}(\lambda)E(\lambda)d\lambda \Big/ \int_0^\infty \bar{y}(\lambda)E(\lambda)d(\lambda) \tag{36}$$

$$\beta_{II}(\lambda_1, \lambda_2) = 1 - \beta_{I}(\lambda_1, \lambda_2). \tag{37}$$

[143] See bibl. ref. 53.
[144] See bibl. ref. 54.
[145] See bibl. ref. 55.

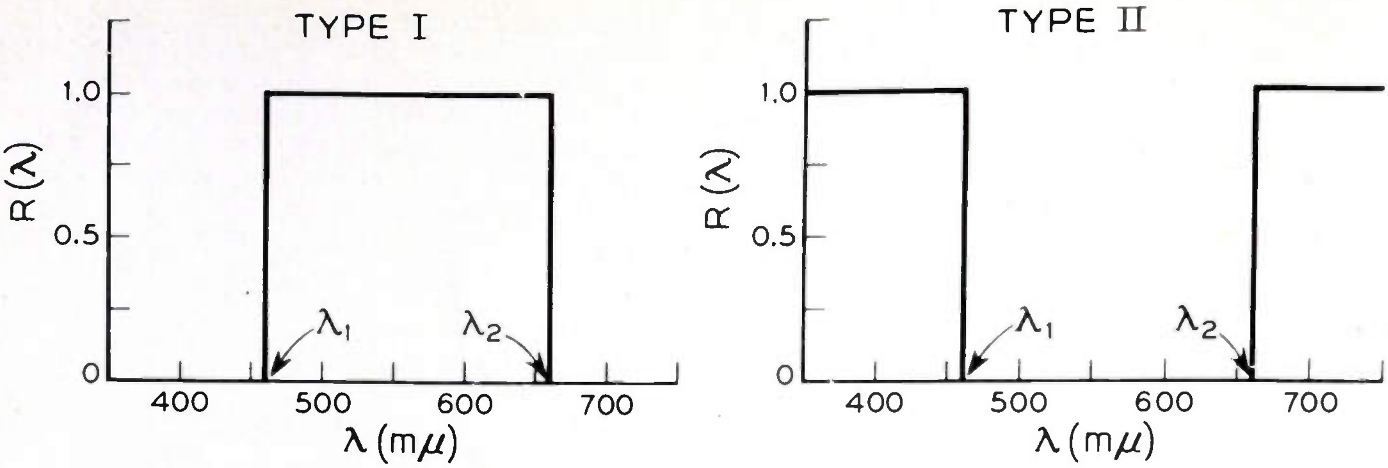

Fig. 17—Reflectance characteristics for surfaces having maximum luminance factors.

We could find relations between chromaticities and luminance factors by choosing λ_1 and λ_2 haphazardly and doing the computation. MacAdam has used a computation technique which is more orderly and which results in loci of constant luminance factor as functions of chromaticity.[146] The curves in Fig. 18 represent chromaticity loci for reflecting (or transmitting) materials of equal luminance factor when the source is Illuminant *C*.[147] Similar curves are shown in Fig. 19 for the case where the source is Illuminant *A*. These show the maximum luminance factor that can be obtained for any given chromaticity co-ordinates. In order to reach these maximum values, the reflectance-wavelength characteristics must be of the types shown in Fig. 17.

The reflectance-wavelength characteristics produced by known pigments or dyes differ from these ideal shapes. Such departures may appear in a number of ways, but it is characteristic that the transitions between absorption and reflection are never so abrupt as to amount to a discontinuity. Some dyes do produce a fairly steep transition between nearly complete reflection of long waves and nearly complete absorption of short waves. Such surfaces, producing red and yellow colors, may depart only by small amounts from the ideal.

Pigments or dyes intended to produce band-pass characteristics do not behave nearly as well. The transitions are seldom very sharp and the reflectance usually misses zero and unity by substantial amounts. Consequently, the luminance factor of blue and of green materials usually falls far short of the theoretical maxima.

Pigments or dyes intended to produce band-elimination (or single-absorption-band) characteristics fail at least as badly as the materials producing band-pass characteristics. High luminance factors, in consequence, are rare in the case of purple and magenta colored materials.

We see, as a consequence of the shortcomings of physical pigments and dyes, that only for red, orange, and yellow materials are high purity and high luminance factors found together. Green, blue, and magenta materials of high purity will have low luminance factors, much lower than we would expect from MacAdam's theory.

Now let us see what practical significance there is in this conclusion. The colors in any scene can be specified by the variations of two quantities, luminance and chromaticity, i.e., chromaticity taken alone is not a complete specification of color. Judd has pointed out that differences in chromaticity are less apparent for dark colors than for light colors.[148] That is, the just perceptible difference in chromaticity increases in size as the luminance factor of a material decreases. We may draw the important conclusion from this fact that perfection of color reproduction of a scene is less important in the areas of smaller luminance. Unless the scene is of low key, i.e., having the greater part of its area of low luminance, those portions least likely to be reproduced accurately by a color-television system need not be reproduced accurately.[149] This is one of the phenomena taking place in viewing scenes and pictures which makes color reproduction at all practical. It is an effect, however, that could not be predicted solely from colorimetric considerations.

Effect of Imperfect Camera Sensitivity Characteristics

As we have seen, it is possible in theory so to shape the spectral sensitivity characteristics of a color-tele-

[146] See bibl. ref. 56.

[147] Figures 18 and 19 were plotted from the numbers that MacAdam tabulated in his paper (bibl. ref. 56).

[148] See bibl. ref. 41.

[149] As pointed out earlier, it is possible that, under some circumstances, spectra, stained glass windows, fluorescent-dyed materials, and the like, may form part of a television presentation. In such cases, the general conclusions drawn here obviously are invalid.

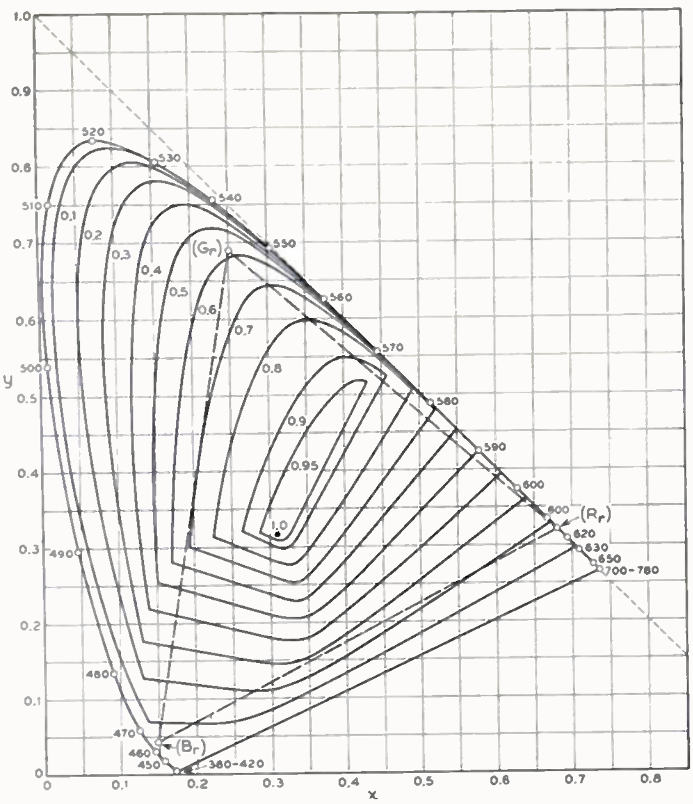

Fig. 18—Loci of maximum luminance factors for Illuminant *C*. (R_r), (G_r), (B_r) = receiver primaries.

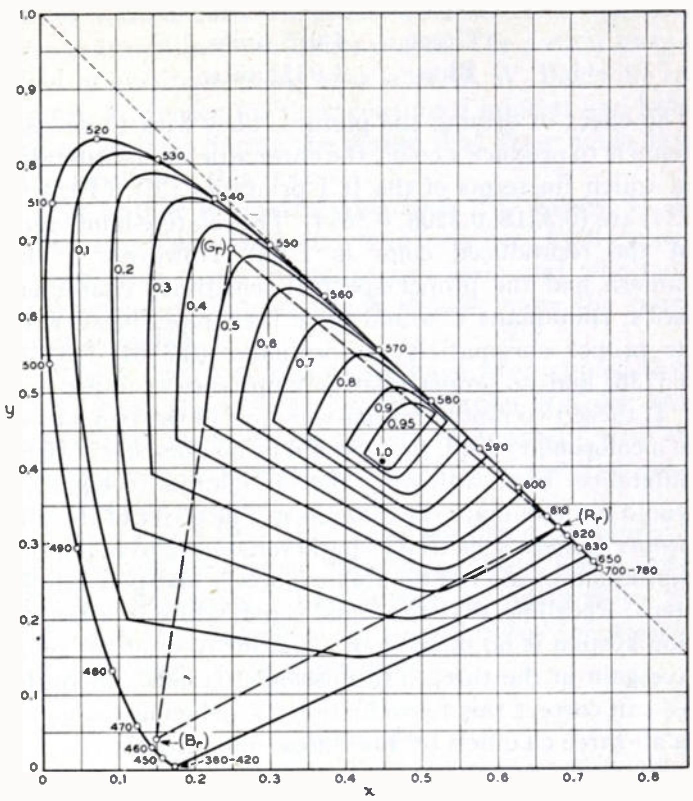

Fig. 19—Loci of maximum luminance factors for Illuminant *A*. (R_r), (G_r), (B_r) = receiver primaries.

vision camera that all colors within the triangle formed by the receiver primaries ((R_r), (G_r), and (B_r)) will be color-matched perfectly (for the Standard Observer). If the color to be transmitted lies outside this triangle, the voltage at the grids of one or two of the picture tubes will become negative. However, the corresponding receiver primary or primaries can go no further negative than zero. Negative light is an unknown quantity. As a result, colors outside the receiver triangle will be reproduced along the periphery of that triangle. The color produced by the receiver corresponds to the mixture of those primary amplitudes which are positive.

Practically, the spectral sensitivity characteristics of a color-television camera will deviate from the ideal characteristics. The ideal characteristics, it will be recalled, are proportional to the color-mixture data for the spectrum corresponding to the camera primaries. In the simplest case, the deviations from the ideal will arise from small errors in matching the ideal characteristics. However, in some color-television systems it may be desirable (or even necessary) to do no electrical transformation of color co-ordinates. Under this condition, the camera primaries must be the same as the receiver primaries. As we have seen (Fig. 14, for example) the camera spectral sensitivity characteristics, under this condition, must have both positive and negative lobes in the important range of wavelengths. In this situation, there is a strong tendency to forget about any other than the major positive lobe in designing the television camera. What effect do such departures from the ideal curves have on color reproduction?

There is no simple answer to this question. The error in the colors reproduced by a system having incorrect camera characteristics is different for every error and for every composition of radiance producing a color to be reproduced. The effect can be determined only by calculating the strength of the receiver primaries for a variety of compositions of radiance and comparing the results with ideal values. The calculations for the actual system are similar to those we have made several times in evaluating tristimulus values corresponding to given radiance-wavelength distributions. In performing the integrations, however, the color-mixture data for the spectrum are replaced by the actual spectral sensitivity characteristics.

As an example of the results one might expect, let us calculate the effect of neglecting all but one principal positive lobe in the characteristics shown in Fig. 14. Since the reference white (or equal picture-tube-signal white) corresponding to these characteristics was chosen to be Illuminant *C*, the first step in the calculation is the determination of the signals corresponding to this color. The camera currents are found to be

Red	1.185 units
Green	1.075 units
Blue	1.035 units.

The effect of driving the picture tubes with these currents is to produce a color, the chromaticity co-ordinates of which (in terms of the ICI primaries (*X*), (*Y*), and (*Z*)) are (0.3218, 0.3208, 0.3674). The relative luminance of the reproduced color is 1.100. However, if the camera had the proper spectral sensitivity characteristics, Illuminant *C* would have been reproduced with its proper chromaticity co-ordinates (0.3101, 0.3162, 0.3736) and its proper relative luminance of unity.

If these two reproductions were put in the two halves of a colorimeter field, there would be no question of their difference. Even adjusting the luminances to equality would not eliminate the difference. The effect of the improper camera sensitivity characteristics is to make the reproduction too red by about a dozen just-perceptible steps. Recalling that the equal-signal white in a television system is no more than a specification of the relative gain in the three transmission channels, obviously we can correct this reproduction by reducing the gains in all three channels by the ratios indicated above.

When the television system is adjusted to reproduce the equal-signal white correctly, we can predict its performance with other colors by further calculation. Such calculations have been made for twelve compositions of radiance corresponding to twelve colors spaced fairly evenly in hue around the hue circuit. In every case, the reproduced color was found to be different in dominant wavelength and of lesser purity than the original. The shifts can be visualized most readily by converting the color specifications into revised Munsell notation.[160] In Munsell terms, the worst hue shift was 3 units. This hue shift may be compared with the hue steps of 2.5 units in the 40 hue edition of the Munsell Book of Color.[161] The greatest change in value was 0.3 unit, while the steps in the Munsell Book of Color are 1.0 unit. Chroma changes as great as 3.5 units were calculated, while the chroma steps in the Munsell Book of Color are 2.0 units.

Every one of these distortions in color reproduction would be quite evident in a colorimeter. It is possible that the difference between the original and the reproduced colors in a television scene could be detected upon direct comparison. In practical color-television broadcasting, the typical observer at a receiver has no access to the original. Under this condition, it is likely that these distortions of color are not important.

Discussion

To this point the author has followed the conventional treatment of the application of the principles of colorimetry to the problems of color reproduction.

[160] See bibl. ref. 57.
[161] See bibl. ref. 58.

Prior to the active development of color television, there has been no easy way in which this conventional colorimetric approach could be tested under the conditions of picture viewing. Some aspects of this practical problem will be discussed here.

All of the data on which indirect colorimetry is based applies strictly for the Standard Observer only. When we use such data for the design of a color-television system, we must realize we are establishing a system which will produce color matches for the Standard Observer. The unit amplitudes of the three receiver primaries are those required by the Standard Observer in a mixture which color matches the specified equal picture-tube-signal white. Similarly, the camera spectral sensitivity characteristics are proportional to the color-mixture data for the spectrum for the Standard Observer. It is not known how seriously color reproduction is affected by the fact that no observer sees mixtures in the same way as the Standard Observer.

In passing, it should be pointed out that this comment in no way deprecates the value of standardized data for use in indirect colorimetry for color specification purposes. However, the purpose of color television is so different from that of indirect colorimetry that it is well to keep these observations in mind.

In direct colorimetry, the effect of observer differences was minimized by letting each observer adjust the size of the units in which the primaries were measured. An individual, watching a reproduction by color television, could make a similar adjustment by varying the relative gains in the three color channels. Such adjustments are impractical, however, when a television viewer is a member of a group. The effect on color reproduction of the compromise which is necessary here will be learned only when there has been more experience with color television.

In this same direction, there is a possibility that a set of color-mixture data for the spectrum can be found that will suit the typical television viewer better than the data recommended by the ICI. As another possibility, it may be that less saturated receiver primaries than were suggested above would produce satisfactory results for a larger fraction of the color-television audience. These and similar questions of compromises should be studied in laboratories equipped for psychological research before any general conclusions can be drawn about color television.

There is one important consideration that tends to offset this pessimism. That is the fact that a member of the television audience is not likely to be able to compare the reproduction with the original. Parenthetically, it may be pointed out that where such comparison might be possible (as in the case of a standard package for a commercial product) it is likely that the original used before the camera will be modified to make the reproduction satisfactory. If the picture on the receiver is pleasing and coincides with the viewer's mental image of the original, he is apt to be well satisfied.[152] Experience in other fields of color reproduction bears out this point of view. Some very bad reproductions in the colorimetric sense prove to be quite satisfactory to the viewers.

We, of course, do not know how much a guide experience in other fields of color reproduction may be. In color television we have, for the first time, the possibility of perfect color matching in the colorimetric sense. And, at least for one observer at a time, it is possible theoretically to establish perfect individual colorimetric color matches. This possibility has not existed before in any practical sense. Systems of color photography, printing, and the like, have all suffered from serious distortions of color, and only in painting has anything close to perfect reproduction been possible. In each of these arts, the reproduction has been on paper (or canvas) where the possible range of luminances is restricted. In these arts, it is known that controlled distortion is preferred to exact reproduction of color.

The explanations offered for the preference for distorted reproduction in the prior arts depend in part on the limited available luminance range of the reproduction, and in part on the color distortions inherent in these processes. Over and above these factors, however, there are many physical and psychological factors which cannot be neglected.

The reproduced scene is bounded by borders which do not exist in the original. Beyond these borders the surroundings of the reproduction bear no relation to the original scene. There is evidence that this fact alone contributes appreciably to the effect of the reproduction. Of equal importance is the fact that the colors of a reproduction satisfy an observer only if they match his conception or recollection of what they should be. Both of these phenomena are complicated by the effect of the color of the local ambient illumination, color of the surroundings of the observer, and the like.[153]

There would be little point in entering a discussion of these differences between color reproduction in the colorimetric sense and in the pictorial sense at our present state of knowledge of such things. However, we do know enough to realize that formal colorimetry as a basis for analysis of color-television systems can be no more than a point of departure. It may be found that the psychological phenomena control the system to such an extent that errors of reproduction considered enormous in the colorimetric sense are of little practical importance.

Acknowledgments

This paper essentially is a review of the classic theory of colorimetry and of the formal application of colorimetry to color reproduction. In its original form, it was a set of notes around which discussion of color television was centered in these Laboratories. The author owes a debt of gratitude to his associates M. W. Baldwin, Jr., and A. G. Jensen for their continued interest and helpful suggestions during the period that these notes have developed into this text.

The author is grateful also to R. M. Evans, D. B. Judd, and Knox McIlwain, who have been kind enough to read this paper in manuscript form and who have recommended changes which should make the paper more valuable.

Figs. 6 and 9 of this paper have been copied from H. E. Ives' paper, "The Transformation of Color Mixture Equations from One System to Another," with the kindly given permission of the Editor of the *Journal of the Franklin Institute.*

Figs. 18 and 19 of this paper are based on figures in D. L. MacAdam's paper, "Maximum Visual Efficiency of Colored Materials." The author is indebted to the Editor of the *Journal of the Optical Society of America* for permission to use these data.

Appendix

Transformation of the Co-ordinates of a Color from One System of Primaries to Another

Calculation of the tristimulus values of a color in terms of a second set of primaries when these values are known in terms of a first set of primaries is a general problem. When direct colorimetry was common practice, such co-ordinate transformation was necessary to express the results of measurement with a laboratory colorimeter in terms of sets of primaries used in other laboratories. In color television we have the possibility of using a camera having spectral sensitivity characteristic corresponding to one set of primaries and of using a different set of receiver primaries.

The problem of transformation of the color co-ordinates of a color has been studied by Ives[154] and by Guild.[155] The same "reference white" was assumed for both sets of primaries in each of these published analyses. In the interest of generality, the problem is treated here without this restriction.

Statement of the Problem

We are given the tristimulus values R_1, G_1, and B_1 of some specific color in terms of one set of primaries. We want to know the tristimulus values R_2, G_2, and B_2 of this same color in terms of another set of primaries. The second set of primaries are specified by their chromaticity co-ordinates in terms of the first set of primaries, and the reference white for the second set of primaries is specified by its chromaticity co-ordinates in terms of the first set of primaries, and by its luminance.

[152] See bibl. ref. 59.
[153] See bibl. ref. 59–61.
[154] See bibl. ref. 36.
[155] See bibl. ref. 38.

The data we have for the new primaries may be expressed by the following unit color equations:

$$\begin{aligned}(R_2)' &= r_r(R_1) + g_r(G_1) + b_r(B_1)\\ (G_2)' &= r_g(R_1) + g_g(G_1) + b_g(B_1)\\ (B_2)' &= r_b(R_1) + g_b(G_1) + b_b(B_1)\end{aligned} \quad (38)$$

$$(W_2)' = r_w(R_1) + g_w(G_1) + b_w(B_1). \quad (39)$$

In these expressions (R_1), (G_1), and (B_1) represent unit quantities of the first set of red, green, and blue primaries, respectively. The lower case letters r, g, and b are chromaticity co-ordinates.

The successive steps in solving the problem outlined here are given below. There are two major portions of the solution. First, the size of units of the second set of primaries are found by color matches to the new reference white. Second, color matches to the specified color are studied to find the new tristimulus values.

Evaluation of Units of the Second Set of Primaries

1. Write the tristimulus values of the new reference white for both sets of primaries.

As a part of the study of the rules governing color mixture on a chromaticity diagram, we have learned how to determine the tristimulus values of a color from its luminance and its chromaticity co-ordinates. Therefore, we may substitute the data for the new reference white in terms of the first set of primaries into (17). The color equation for the new reference white is found to be

$$1.0(W) = \frac{L_w[r_w(R_1) + g_w(G_1) + b_w(B_1)]}{r_wL_{r1} + g_wL_{g1} + b_wL_{b1}} \quad (40)$$

where L_{r1}, L_{g1}, and L_{b1} are the luminosity coefficients of the first set of primaries.

By definition, the reference white for the second set of primaries is matched by a mixture of one unit of each of the second set of primaries. The color equation expressing this color match is

$$1.0(W) = 1.0(R_2) + 1.0(G_2) + 1.0(B_2). \quad (41)$$

2. Write the tristimulus values of units of the second set of primaries in terms of the first set of primaries.

Since the chromaticity co-ordinates of any color are equal to the ratios of the individual tristimulus values of the color to the sum of its tristimulus values, the tristimulus values of any color are equal to its chromaticity co-ordinates increased by a multiplier. We can write

$$\begin{aligned}1.0(R_2) &= \rho(R_2)'\\ 1.0(G_2) &= \theta(G_2)'\\ 1.0(B_2) &= \beta(B_2)'\end{aligned} \quad (42)$$

where ρ, θ, and β are unknown multipliers.

Substituting the values of $(R_2)'$, $(G_2)'$, and $(B_2)'$ from (38) into (42), we have the color equation

$$\begin{aligned}1.0(R_2) &= \rho[r_r(R_1) + g_r(G_1) + b_r(B_1)]\\ 1.0(G_2) &= \theta[r_g(R_1) + g_g(G_1) + b_g(B_1)]\\ 1.0(B_2) &= \beta[r_b(R_1) + g_b(G_1) + b_b(B_1)].\end{aligned} \quad (43)$$

3. Apply the transitive law to the two mixtures which match the new reference white.

The transitive law of colorimetry (Rule 7 in the text) tells us that colors which match a common color match one another. When this rule is applied to the color matches expressed by color equations (40) and (41), we find that

$$1.0(R_2) + 1.0(G_2) + 1.0(B_2) = \frac{L_w[r_w(R_1) + g_w(G_1) + b_w(B_1)]}{r_wL_{r1} + g_wL_{g1} + b_wL_{b1}}. \quad (44)$$

4. Replace the units of the second set of primaries by their tristimulus values in terms of the first set and solve for ρ, θ, and β.

The tristimulus values of units of the second set of primaries are given by (43). When these values are substituted in (44), we have

$$\begin{aligned}&\rho[r_r(R_1) + g_r(G_1) + b_r(B_1)]\\ &\quad + \theta[r_g(R_1) + g_g(G_1) + b_g(B_1)]\\ &\quad + \beta[r_b(R_1) + g_b(G_1) + b_b(B_1)]\\ &= \frac{L_w[r_w(R_1) + g_w(G_1) + b_w(B_1)]}{r_wL_{r1} + g_wL_{g1} + b_wL_{b1}}.\end{aligned} \quad (45)$$

In a color equation, such as (45), the coefficients of each of the unit primaries (R_1), (G_1), and (B_1) must form identities. That is

$$\begin{aligned}\rho r_r + \theta r_g + \beta r_b &= L_wr_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1})\\ \rho g_r + \theta g_g + \beta g_b &= L_wg_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1})\\ \rho b_r + \theta b_g + \beta b_b &= L_wb_w/(r_wL_{r1} + g_wL_{g1} + b_wL_{b1}).\end{aligned} \quad (46)$$

The solutions of this set of three simultaneous equations are

$$\rho = \begin{vmatrix} R_w & r_g & r_b \\ G_w & g_g & g_b \\ B_w & b_g & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix}$$

$$\theta = \begin{vmatrix} r_r & R_w & r_b \\ g_r & G_w & g_b \\ b_r & B_w & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix} \quad (47)$$

$$\beta = \begin{vmatrix} r_r & r_g & R_w \\ g_r & g_g & G_w \\ b_r & b_g & B_w \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix},$$

where

$$R_w = L_w r_w/(r_w L_{r1} + g_w L_{g1} + b_w L_{b1})$$
$$G_w = L_w g_w/(r_w L_{r1} + g_w L_{g1} + b_w L_{b1}) \qquad (47a)$$
$$B_w = L_w b_w/(r_w L_{r1} + g_w L_{g1} + b_w L_{b1}),$$

i.e., R_w, G_w, and B_w are the tristimulus values of the new reference white in terms of the old primaries.

The tristimulus values of units of the second set of primaries in terms of the first set are found by substituting the values for ρ, θ, and β from (47) into (43).

Evaluation of the Tristimulus Values of a Color in Terms of the Second Set of Primaries

5. Write the tristimulus values of a specified color for both sets of primaries.

The color equations, expressing the mixture of the first set of primaries which matches a specified color is

$$(C) = R_1(R_1) + G_1(G_1) + B_1(B_1). \qquad (48)$$

The color equation, expressing the mixture of the second set of primaries which matches the same specified color is

$$(C) = R_2(R_2) + G_2(G_2) + B_2(B_2). \qquad (49)$$

6. Apply the transitive law to the two mixtures which match a specified color.

Exactly as in step three above, we can write

$$R_2(R_2) + G_2(G_2) + B_2(B_2) = R_1(R_1) + G_1(G_1) + B_1(B_1). \qquad (50)$$

7. Replace the units of the second set of primaries by their tristimulus values in terms of the first set and solve for R_2, G_2, and B_2.

The tristimulus values of units of the second set of primaries in terms of the first set were evaluated in the first section of this Appendix. When these values are substituted in the color equation (50), we have

$$\begin{aligned} R_2\rho[r_r(R_1) + g_r(G_1) + b_r(B_1)] &\\ + G_2\theta[r_g(R_1) + g_g(G_1) + b_g(B_1)] &\\ + B_2\beta[r_b(R_1) + g_b(G_1) + b_b(B_1)] &\\ = R_1(R_1) + G_1(G_1) + B_1(B_1). & \qquad (51)\end{aligned}$$

Treating this color equation in the same way that we treated (45), we write separate identities for the coefficients of each primary

$$\begin{aligned} R_2\rho r_r + G_2\theta r_g + B_2\beta r_b &= R_1 \\ R_2\rho g_r + G_2\theta g_g + B_2\beta g_b &= G_1 \qquad (52) \\ R_2\rho b_r + G_2\theta b_g + B_2\beta b_b &= B_1. \end{aligned}$$

The solutions of this set of three simultaneous equations are

$$R_2 = \begin{vmatrix} R_1 & r_g & r_b \\ G_1 & g_g & g_b \\ B_1 & b_g & b_b \end{vmatrix} \Bigg/ \rho \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix}$$

$$G_2 = \begin{vmatrix} r_r & R_1 & r_b \\ g_r & G_1 & g_b \\ b_r & B_1 & b_b \end{vmatrix} \Bigg/ \theta \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix} \qquad (53)$$

$$B_2 = \begin{vmatrix} r_r & r_g & R_1 \\ g_r & g_g & G_1 \\ b_r & b_g & B_1 \end{vmatrix} \Bigg/ \beta \begin{vmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{vmatrix}.$$

The analytical treatment of the transformation of color co-ordinates is completed when the values for ρ, θ, and β from (47) are substituted into (53). The result is

$$R_2 = \begin{vmatrix} R_1 & r_g & r_b \\ G_1 & g_b & g_b \\ B_1 & b_g & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} R_w & r_g & r_b \\ G_w & g_g & g_b \\ B_w & b_g & b_b \end{vmatrix}$$

$$G_2 = \begin{vmatrix} r_r & R_1 & r_b \\ g_r & G_1 & g_b \\ b_r & B_1 & b_b \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & R_w & r_b \\ g_r & G_w & g_b \\ b_r & B_w & b_b \end{vmatrix} \qquad (54)$$

$$B_2 = \begin{vmatrix} r_r & r_g & R_1 \\ g_r & g_g & G_1 \\ b_r & b_g & B_1 \end{vmatrix} \Bigg/ \begin{vmatrix} r_r & r_g & R_w \\ g_r & g_g & G_w \\ b_r & b_g & B_w \end{vmatrix}.$$

Luminosity Coefficients of the Second Set of Primaries

The luminance of a mixture of the second set of primaries is equal to the sum of the luminance contributions of each of the primaries. That is, the luminance of a color, the tristimulus values of which in terms of the new primaries are R_2, G_2, and B_2, is given by

$$L_C = R_2 L_{r2} + G_2 L_{g2} + B_2 L_{b2} \qquad (55)$$

where L_{r2}, L_{g2}, and L_{b2} are the luminosity coefficients of the second set of primaries.

The luminosity coefficients of the second set of primaries can be determined from their tristimulus values in terms of the first set of primaries, and the luminosity coefficients of the first set of primaries. That is

$$\begin{aligned} L_{r2} &= R_r L_{r1} + G_r L_{g1} + B_r L_{b1} \\ L_{g2} &= R_g L_{r1} + G_g L_{g1} + B_g L_{b1} \qquad (56) \\ L_{b2} &= R_b L_{r1} + G_b L_{g1} + B_b L_{b1}. \end{aligned}$$

These tristimulus values were determined in the first part of this Appendix. We can substitute these values into (56), and one form of the result is

$$\begin{aligned} L_{r2} &= \rho[r_r L_{r1} + g_r L_{g1} + b_r L_{b1}] \\ L_{g2} &= \theta[r_g L_{r1} + g_g L_{g1} + b_g L_{b1}] \qquad (57) \\ L_{b2} &= \beta[r_b L_{r1} + g_b L_{g1} + b_b L_{b1}]. \end{aligned}$$

Values of ρ, θ, and β are given by (47).

List of Symbols

(C) = a color corresponding to a specified composition of radiance with wavelength.

CIE = Commission Internationale de L'Eclairage. Usually termed International Commission on Illumination (ICI) in American references.

E = radiance of a source.

$E(\lambda)$ = radiance of a source, described by the relation between radiance in narrow wavelength bands and wavelength.

$E_A(\lambda)$, $E_B(\lambda)$, $E_C(\lambda)$ = radiance of ICI Illuminants A, B, and C,[156] respectively, specified by distributions of radiance with wavelength.

I_r, I_g, I_b = transmittances of the red, green, and blue attenuators, respectively, in a colorimeter when a match is obtained with a color.

ICI = international Commission on Illumination.

K_c = a constant, introduced in the text, to permit expression of a color match in absolute terms.

K_L = a constant, introduced in the text, to facilitate evaluation of the luminance of a mixture of three primary colors.

L = luminance.

L_r, L_g, L_b = luminosity coefficients of primaries (R), (G), and (B), respectively.

$R(\lambda)$ = directional reflectance of a surface at wavelength λ.

(R), (G), (B) = unit quantities of primary colors red, green, and blue.

(R_s), (G_s), (B_s) = unit quantities of spectrum primaries.

(R_r), (G_r), (B_r) = unit quantities of television-receiver primaries.

$\bar{r}$, $\bar{g}$, $\bar{b}$ = tristimulus values of spectral stimuli of equal radiance (color-mixture data for the spectrum) in terms of primaries (R), (G), and (B).

R, G, B = tristimulus values of a color in terms of primaries (R), (G), and (B).

r, g, b = chromaticity co-ordinates of a color in terms of primaries (R), (G), and (B).
$r = R/(R+G+B)$, and so on.

S_r, S_g, S_b = transmittances of the red, green, and blue attenuators, respectively, in a colorimeter when a match is obtained with the reference white.

$T(\lambda)$ = relative transmittance of a medium at wavelength λ.

UCS = Judd's Uniform Chromaticity Scale.

$v(\lambda)$ = ordinate of the luminosity curve.

(X), (Y), (Z) = unit quantities of the nonphysical primary colors recommended for use in 1931 by the ICI.

$\bar{x}$, $\bar{y}$, $\bar{z}$ = tristimulus values of spectral stimuli of equal radiance (color-mixture data for the spectrum) in terms of primaries (X), (Y), and (Z).

X, Y, Z = tristimulus values of a color in terms of primaries (X), (Y), and (Z).

X_{ref}, Y_{ref}, Z_{ref} = tristimulus values of the illuminant (or an ideal surface under the illuminant) used in evaluating the tristimulus values X, Y, and Z of a color.

x, y, z = chromaticity co-ordinates of a color in terms of primaries (X), (Y), and (Z).
$x = X/(X+Y+Z)$, and so on.

β = luminance factor.
$\beta = Y/Y_{ref}$

λ = wavelength, in this paper expressed in millimicrons (abbreviated mμ).

Glossary

In preparing this paper, most terms have been used in their colorimetric sense as defined by the Optical Society of America or by the Illumination Engineering Society.[157] These definitions have been copied below for the convenience of the reader. There are included a few new terms which it has been found desirable to introduce in this discussion of color television.

Achromatic Color. Color perceived to have no hue.

Note—Examples of achromatic color perceptions are black, gray, white, silver, and "clear, colorless."

Brightness. The attribute of the color perception of a luminous area that permits it to be classified as equivalent to some member of achromatic color perceptions ranging from very dim to very bright.

[156] In a private communication, Dr. Deane B. Judd advises the author of a trend toward the replacement of the term "Illuminant A" (or B, or C) by the term "Standard Source A" (or B, or C). Examples of the use of this newer terminology are found in bibl. refs. 31 and 40.

[157] See bibl. ref. 62.

Camera Primaries. The set of primary colors for which the color-mixture data for the spectrum are proportional to the camera spectral sensitivity characteristics.

Camera Spectral Sensitivity Characteristics. Curves showing the relations between current (or voltage) outputs of a camera and radiance before the camera as functions of wavelength.

Candle. The unit of luminous intensity. It is based on assigning 60 candles per square centimeter as the luminance of a black body at the temperature of freezing platinum.

Chroma (Munsell). Expression of the degree of departure of an object color from the nearest achromatic color on arbitrary scales defined in terms of its β-value (luminance factor) and its chromaticity co-ordinates (x, y).

Note—The Munsell chroma scales have approximately uniform perceptual steps; under ordinary observing conditions Munsell chroma of a specimen correlates well with the saturation of the color perceived to belong to the specimen.

Chromaticity. The quality of a color specified by dominant wavelength (alternatively, complementary wavelength) and purity, taken together.

Note—Chromaticity is equivalent to the common concept of quality as distinguished from quantity of light. Chromaticity may be specified in other ways than by dominant (alternatively, complementary) wavelength and purity, such as by the chromaticity co-ordinates (x, y) of the standard ICI co-ordinate system.

Chromaticity Co-ordinates. The ratios of each of the three tristimulus values of a sample color to the sum of the tristimulus values.

Chromaticity Diagram. A plane diagram formed by plotting one of any set of three chromaticity co-ordinates against another.

Color. Color consists of the characteristics of light other than spatial or temporal inhomogeneities, light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from stimulation of the retina of the eye.

Color Co-ordinate Transformation. Computation of the tristimulus values of colors in terms of one set of primaries from the tristimulus values of the same colors in terms of another set of primaries.

In color television this computation is performed electrically.

Color Match. Adjustment of three parameters of a radiance distribution until it looks like a sample radiance distribution.

Color-Mixture Data. The amounts of the primaries required to establish a match with the sample, either by addition of all three, or addition of one primary to the sample to match any pair of primaries, or the addition of any pair to the sample to match the remaining primary.

Note—The amounts of the primaries mixed with the sample are recorded as negative quantities. Color-mixture data depend on the choice of primaries and upon the individual observer for whom the match is satisfactory. Individual variations of color-mixture data are considerable.

Synonym—Tristimulus Values.

Color-Mixture Data for the Spectrum. Color-mixture data for spectrally pure samples of various wavelengths.

Color Temperature. The temperature of a black body radiator whose chromaticity is the same as that of the color in question.

Color Triangle. 1. Same as chromaticity diagram. 2. The locus of chromaticities on a chromaticity diagram that can be color-matched by mixtures of positive amounts of a set of primary colors.

Colorimeter. In optics, an instrument in which an equivalent stimulus is set up for the unknown color which is then specified in terms of the equivalent stimulus.

Colorimetry. Expression of color numerically.

Complementary Color. Color that when combined with another color produces a mixture which color-matches some agreed upon achromatic color.

Composition of Radiance (Spectral Composition of Radiance). Radiance per unit of wavelength at each wavelength.

Note—Composition of radiance refers to data expressed in absolute units.

Direct Colorimetry. Color matching in a colorimeter for the purpose of numerical specification of color.

Directional Reflectance. The ratio of the radiance of a surface to the radiance of an ideal, nonabsorbing, perfectly diffusing surface placed in the same position and similarly irradiated.

Distribution of Radiance (Spectral Distribution of Radiance). Relative spectral composition of radiance.

Note—Spectral distribution data may be accompanied by separate statements of the radiance per unit of wavelength at some wavelength, or integrated for all wavelengths.

Dominant Wavelength. The wavelength of a spectrum color that, when combined with achromatic light in suitable proportions, matches a color.

Note—Many qualities of light are considered achromatic under some conditions. Usually the quality of the prevailing illumination is acceptable as achromatic and is used as the achromatic component in the determination of dominant wavelengths of the colors of objects.

Equal-Energy White. An achromatic light corresponding to equal radiance per unit of wavelength at all wavelengths.

Equal-Signal White. The achromatic color produced by a color-television receiver when equal-signal voltages are impressed on the three color-signal channels.

Note—In use, this term should be modified to include a notation of the point of application of the equal signal voltages.

Hue. The attribute of a color perception that determines whether it is red, yellow, green, blue, purple, or the like.

Hue (Munsell). Expression of one aspect of an object color on an arbitrary scale, defined in terms of its luminance factor (β) and its chromaticity co-ordinates (x, y).

Note—The Munsell hue scales have approximately uniform perceptual steps; under ordinary observing conditions Munsell hue of a sample correlates well with the hue of the color perceived to belong to it.

ICI Standard Illuminants[158] for Colorimetry. Three illuminants adopted in 1931 for colorimetric purposes by the ICI: Illuminant *A*, representative of gas-filled tungsten-filament lamps; Illuminant *B*, representative of noon sunlight; and Illuminant *C*, representative of average daylight.

Indirect Colorimetry. Calculation of the color-mixture data for a sample from those of the spectrum and the spectral distribution of radiance of the sample.

Irradiance. Radiant flux incident per unit area of a surface.

Note—The usual unit is the watt per square meter.

Lovibond Numbers. Numbers proportional to the densities of three glass colorants, a yellow, a red, and a blue colorant, required to modify a standard source to produce a color match.

Lumen. The unit of luminous flux. It is equal to the flux through a unit solid angle (steradian) from a uniform point source of one candle, or to the flux on a unit surface all points of which are at unit distance from a uniform point source of one candle.

Luminance. Luminous flux emitted, reflected, or transmitted per unit solid angle and unit projected area of the source.

Note—Usual units are the candle per square meter, the candle per square foot, the lambert, the millilambert, and the foot-lambert. This quantity is sometimes called photometric brightness.

Luminance Factor. The ratio of the luminance of a reflecting or transmitting surface, viewed from a given direction, to that of a perfect diffuser receiving the same illumination.

Luminosity. Ratio of photometric quantity to corresponding radiometric quantity in standard units (lumens per watt).

Luminosity Coefficient of a Primary Color. The luminance of a unit of a primary color.

Note—These coefficients are usually expressed as ratios between the three primaries, and not in absolute units.

Luminosity Curve. Curve of luminosity of spectrally homogeneous lights, plotted relative to the maximum luminosity as a function of wavelength.

Luminous Flux. The time rate of flow of light. When radiant flux is evaluated with respect to its capacity to evoke the brightness attribute of visual sensation, it is called luminous flux and this capacity is expressed in lumens.

Maxwell Triangle. The equilateral-triangular form of chromaticity diagram in which the primaries are represented at the vertices of the triangle.

Mixture. Superposition of two or more radiances. If the mixture is formed by sequential presentation of the radiances, the frequency must be sufficiently high to avoid flicker.

Nonphysical Primary Colors. 1. Primary colors which can be produced only by mixing negative amounts of light with positive amounts of light from physical sources. 2. The hypothetical primaries that correspond to some color co-ordinate transformations.

Photometry. The measurement of luminance.

Primary. *See* **Primary Colors.**

Primary Colors. 1. Three colors of constant chromaticity used to specify an unknown color by the amounts of them required in an additive mixture to match the unknown color.

Note—Any three colors can serve as primary colors provided no one of them can be matched by additive mixture of the other two.

2. Three colors of constant chromaticity, which, when mixed in the proper proportions, can be used to produce all other colors. The three colors most commonly used are red, green, and blue.

Purity. The relative luminances of the spectrum and achromatic components, in the mixtures mentioned in the definition of dominant wavelength, determine and are specified by purity.

Note—Various scales of purity are used, all of which can be expressed as some mathematical function of the ratio of the components.

Radiance. Flux radiated per unit solid angle and unit projected area of surface.

Note—The usual unit is the watt per steradian per square meter. This is the radiant analog of luminance.

[158] In a private communication, Dr. Deane B. Judd advises the author of a trend toward the replacement of the term "Illuminant *A*" (or *B*, or *C*) by the term "Standard Source *A*" (or *B*, or *C*). Examples of the use of this newer terminology are found in bibl. refs. 31, 40.

Receiver Primaries. In color television, the three colors of constant chromaticity produced by the receiver which, when mixed in proper proportions, produce all other colors.

Note—The three colors most commonly used are red, green and blue.

Reference White. The achromatic color, specified by its distribution of radiance with respect to wavelength, which is matched by a mixture of unit amounts of three primaries.

Note—In color television, reference white serves to specifiy the relative gains of the three color-signal channels.

Reflectance. Ratio of reflected to incident flux.

Saturation. The attribute of any color perception possessing a hue that determines its difference from the achromatic color perception most resembling it.

Spectral Color. Color obtainable by mixture of some portion of the spectrum with an adopted achromatic light.

Spectrum Color. Color of some part of the spectrum.

Standard Observer. The characteristics of the color vision of the ICI Standard Observer are defined by the luminosity curve and the chromaticity co-ordinates of the spectrum for a particular set of spectrum colors as primaries. These functions were adopted by the ICI in 1931.

Transmittance. Ratio of transmitted to incident flux.

Tristimulus Values. Same as **Color-Mixture Data.**

Uniform Chromaticity-Scale Color Triangle. A color triangle resulting from a color co-ordinate transformation of standard color-mixture data, in which equal linear distances approximate equally perceptible steps of chromaticity.

Unit of a Primary Color. The amount of a primary color which, in a mixture with two others, matches reference white.

Value (Munsell). Expression of the luminous transmittance or reflectance of an object color on a scale giving approximately uniform perceptual steps under usual conditions of observation.

Note—Munsell value of an opaque surface may be found approximately by taking the square-root of the luminance factor expressed in per cent.

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Subjective Sharpness of Additive Color Pictures*

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Summary—This is a report on the first numerical results to come from a laboratory experiment on the subjective sharpness of additive 3-color pictures. The sharpness factor is isolated by using out-of-focus projection (of slides) instead of actual television transmission.

An observer's acuity for defocus is greatest for the green component and least for the blue component, in an additive 3-color picture. When the same picture is reproduced in monochrome (white, red, green, or blue) at the same brightness, his acuity for defocus is equal to that found for the green component.

DURING the past few years the issue of color television has raised some questions about the ability of the human eye to resolve fine detail in color pictures. In practical terms, we want to know whether the color picture sent by one television system will look sharper than that sent by another. Before this broad question can be answered, it must be resolved into simpler basic questions for which answers can be obtained by suitable experimentation.

We have begun a program of laboratory work aimed at answering some of these basic questions. Observers are put into a viewing situation that might represent, in a rough way, the watching of television at home. Then they are shown a color picture produced on a screen by the additive mixture of three primaries, after the fashion of color television. What makes the experiment possible is that this color picture can readily be adjusted with respect to geometrical resolution and that the adjustment can be made primary by primary. In other words, the color picture may have high resolution in the red component, moderate resolution in the green component, and low resolution in the blue component, or any other combination. The apparatus used will be described below.

This facility for producing additive color pictures with controlled resolution is a useful tool for answering some of the questions about how the eye resolves detail in color pictures. The present experiment is one of the simplest and perhaps one of the most fundamental, and it yields a few numerical results that are probably new. Please remember that this is only a first step; do not expect answers for all of the resolution problems of color television.

In order to describe the results we need to introduce a new concept. We call it "acuity for defocus." This is a threshold quantity which is somewhat like the "visual acuity" used for measuring vision. "Acuity for defocus" is defined here as sharpness of vision in respect to the ability to see blurring, or lack of resolution, in a reproduced picture. The measure of acuity for defocus is the same as the measure of visual acuity, that is, the reciprocal of the visual angle. In this case, the visual angle is the angle subtended at the eye by the diameter of the equivalent circle of confusion on the screen. For numerical purposes, we express it in the conventional minutes of arc so that acuity for defocus is measured in reciprocal minutes.

Fig. 1 is a plot of acuity for defocus against viewing distance, for a picture of a single figure, three-quarter length, against a simple background. The curves marked

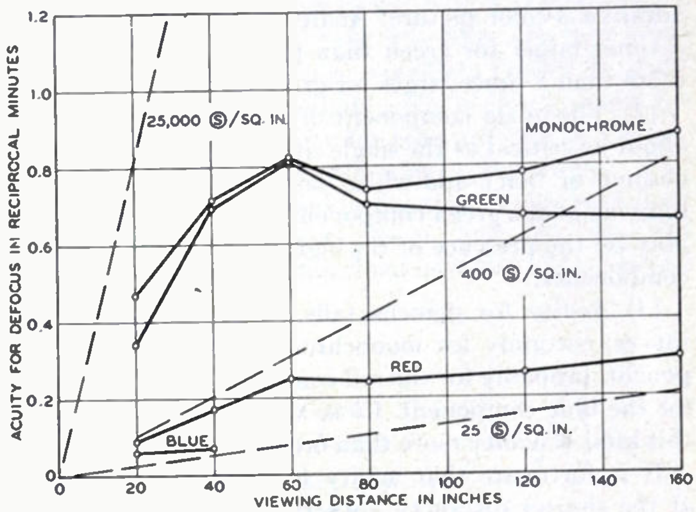

Fig. 1—Single figure, three-quarter length, against a simple background. Screen size 10.0 by 13.3 inches. Average of seven readings, one each by seven observers. Highlight brightness 15 foot-lamberts in the whites, composed 80 per cent of green, 15 per cent of red, and 5 per cent of blue. Highlight brightness of monochrome 15 foot-lamberts.

blue, red, and green tell the story for a 3-color picture in which only one of the colors at a time is made unsharp. The upper curve, marked "monochrome," applies to a black-and-white picture of the same subject. This curve is included merely to show what happens in a more familiar case.

The experimental conditions were as follows: The picture had the size and shape of a 17-inch rectangular television picture, and the viewing distance ranged from 2 to 16 times the picture height. Highlight brightness, in the whites, was 15 foot-lamberts, of which 80 per cent came from the green primary, 15 per cent from the red primary, and only 5 per cent from the blue primary. The brightness range was about 50 to 1. The room had enough ambient illumination to bring the walls up to about a half foot-lambert at eye level.

Seven observers, working one at a time, were used for this test. Three of them were between the ages of 25 and 35, and four were between 45 and 55. They sat at the indicated distances and watched the screen with both eyes and without any optical gadgets except their own glasses. Each observer was required to adjust the picture to the point where he could just distinguish it from a picture of maximum resolution. Since he was asked to be sure on each observation, his indicated acuity is probably lower than a statistical threshold

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value. That is, some accuracy was purposely sacrificed in order to protect the observer from excessive fatigue.

The seven values of acuity derived from the seven individual observers, for a particular distance and color, are averaged and plotted as a single point in Fig. 1. The straight lines connecting these average values together can easily be taken to mean more than the data warrants. Only the larger effects are significant at this early stage because the differences between observers are not too small.

Three major effects are apparent:

(1) The green component is the critical one in the additive 3-color picture. Acuity for defocus is roughly 3 times larger for green than for red, and is probably more than 5 times larger for green than for blue.

(2) The green component of a 3-color picture is just about as critical as the single component is in the monochrome or black-and-white case. That is to say, the blurring of the green component is not masked appreciably by the presence of the high-resolution red and blue components.

(3) Acuity for defocus falls off at the shorter distances, certainly for monochrome and the green component, probably for the red component, but maybe not for the blue component. Close viewing seems to reduce this kind of acuity more than ordinary visual acuity.

It is fortunate that acuity for defocus does fall off at the shorter distances—otherwise we could not have measured it for monochrome and green at 20 inches. The dashed line running steeply upward from the origin marks one of the physical limitations of the equipment. It represents the sharpest image that could be put on the screen. The 25,000 circles per square inch specify the geometrical resolution. It means that the minimum circle of confusion was 1/25,000 of a square inch in area, or about 7 mils in diameter. In television terms, this sharpest image corresponds to about 4,000 scanning lines and a bandwidth of about 250 mc at 30 frames per second for *each* color component.

These television numbers should not be taken for exact equivalents. They are based on a comparative calibration, but the calibration ignored some factors that could make a difference. For example, these pictures had no flicker, no noise, no scanning lines, no moving objects, and no moiré patterns. The sharpness factor was purposely isolated in its most elementary form for the first step.

Another equipment limitation interfered with the measurement of acuity for defocus in the blue primary at distances greater than 40 inches. The lower dashed line in Fig. 1 represents the most blurred image that could be put on the screen without running through a mechanical limit stop. The maximum circle of confusion had an area of 1/25 of a square inch, or a diameter of almost ¼ of an inch. This image was pretty bad; in television terms it would correspond to about 120 scanning lines and a bandwidth of about ¼ mc at 30 frames per second. However, it was not bad enough for the blue component at the longer distances.

It is clear that, in the co-ordinates of Fig. 1, any straight line through the origin represents a constant geometrical resolution on the screen, with the steeper slope corresponding to the higher resolution. The line representing standard black-and-white television may be of interest. The geometrical resolution is reckoned to be 400 circles of confusion per square inch, and this is shown in Fig. 1 as the middle dashed line. It corresponds to about 525 scanning lines and a bandwidth of about 4 mc at 30 frames per second.

This line lies under the monochrome and green curves out to a distance of about 120 inches, or 12 times the picture height. In other words, according to this data, our average observer would have more than enough acuity to distinguish a standard monochrome picture from a much sharper one at any viewing distance up to about 12 times the picture height. He could do just about as well with a 4-mc, 30-frame green component in a color picture, but he would not have enough acuity to make such a distinction with a 4-mc, 30-frame blue component at any distance. In the case of red, he might be able to do it at close range.

This is a good place to recall that we are still talking about one particular picture: a single figure, three-quarter length, against a simple background. Other subject matter will yield different results, and we have

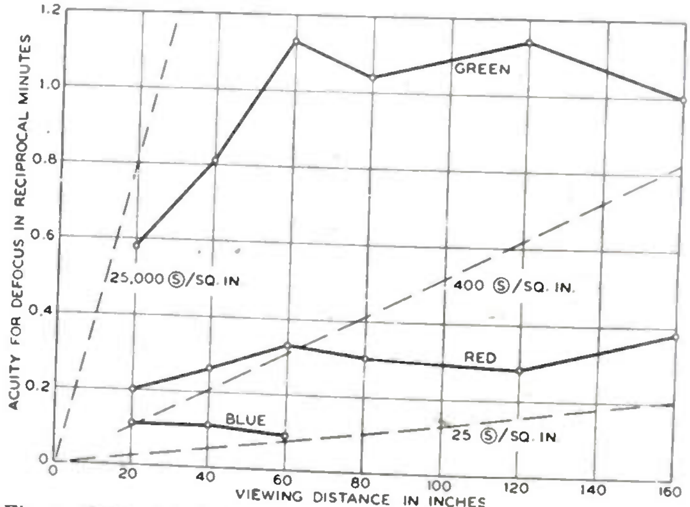

Fig. 2—RMA Resolution Chart (1946). Screen size 10.0 by 13.3 inches. Average of nine readings, one each by five observers plus two each by two observers. Highlight brightness 20 foot-lamberts, composed 80 per cent of green, 15 per cent of red, and 5 per cent of blue.

tried only a few different pictures. The most critical one was the RMA Resolution Chart (1946), which gave the results shown in Fig. 2. This was a black-and-white picture, of course, even though it comprised red, green, and blue components. The highlight brightness was 20 foot-lamberts, composed 80 per cent of green, 15 per cent of red, and 5 per cent of blue, as in the whites in the first picture. The brightness range and the ambient illumination were also the same as before.

The observers were the same seven people, but in this case two of them took the test twice so that in Fig. 2 each point represents the average of nine readings. The more apparent lack of smoothness in these curves shows even better than Fig. 1 that fluctuations of measurement are masking all but the larger effects.

The only significant difference between the test chart and the three-quarter length figure is that the test chart gives a somewhat higher level of acuity. Our average observer can now distinguish a 4-mc, 30-frame green component from a much sharper one at any distance up to at least 16 times the picture height. Indeed, at the 20-inch distance his acuity for the green component begins to approach the limit set by the equipment. The blue component is now measurable out to 60 inches before the mechanical stop interferes.

In Figs. 1 and 2, acuity for defocus and primary brightness in the whites both fall in the same order by color; that is, both are highest for the green component, intermediate for the red, and lowest for the blue. It is reasonable to suppose that acuity for defocus is somehow related to primary brightness in the whites, and this hypothesis will be tested in future experiments.

One of the simpler aspects of the relationship between acuity and brightness and color is illustrated in Fig. 3. When the picture contains only one primary,

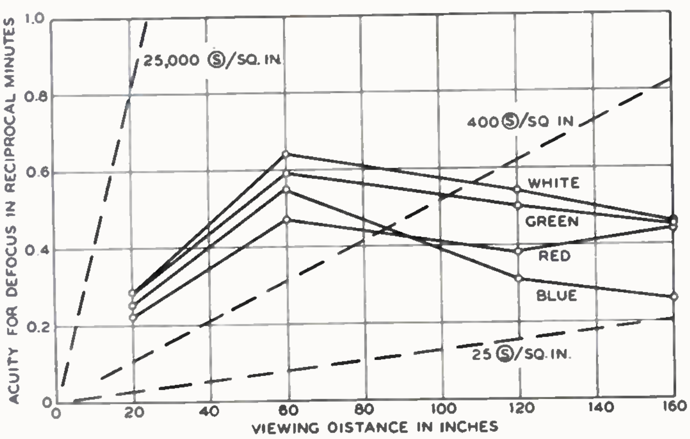

Fig. 3—Single figure, three-quarter length, against a simple background. Screen size 10.0 by 13.3 inches. Average of seven readings by one observer. Each color component viewed separately, not in mixture. Highlight brightness 1 foot-lambert for each color.

that is, when it is all green, all red, all blue, or all white, then acuity for defocus is substantially the same for all these colors, provided their brightnesses are equal. Even this simple rule breaks down outside a limited range of viewing distances.

For the data shown in Fig. 3 we went back to the three-quarter length figure for subject matter. There was only one observer, but he took the test seven times so that each point represents the average of seven readings. The highlight brightness was only 1 foot-lambert, instead of the 15 or 20 used previously, because that was the most that could be produced in the blue picture. Remember that in this test the picture contained only one primary at a time, which is quite different from the mixture of 3 primaries used in the previous test.

At the shorter distances, the most that can be said is that acuity for defocus may be a little lower for red than for the other colors. As the distance increases, red becomes more nearly equal to green and white, but blue begins to fall off. This falling off in blue is probably a consequence of some well-known facts regarding visual accommodation. We know that this particular observer was not color blind, that he was young, and that he had normal vision. We know also that in normal vision distant objects are focused short of the retina in blue light and beyond the retina in red light, and that accommodation works only to shorten the focus, that is, with the aid of accommodation, distant objects can be focused in red light, but cannot be focused in blue light. It might be said that our observer's normal vision made him a little bleary-eyed for these blue images at the longer distances.

There is a small lesson in Fig. 3 for special-effects enthusiasts. If a color system has been designed to save bandwidth in the blue, then the blue primary alone should not be used to create moonlight effects. It might work in theaters, but probably not in living rooms because the observer's acuity for blue will not be low unless there is a mixture of primaries on the screen.

The primary colors used in this experiment have been described simply as blue, green, and red, and the monochrome has been described as white. The spectral

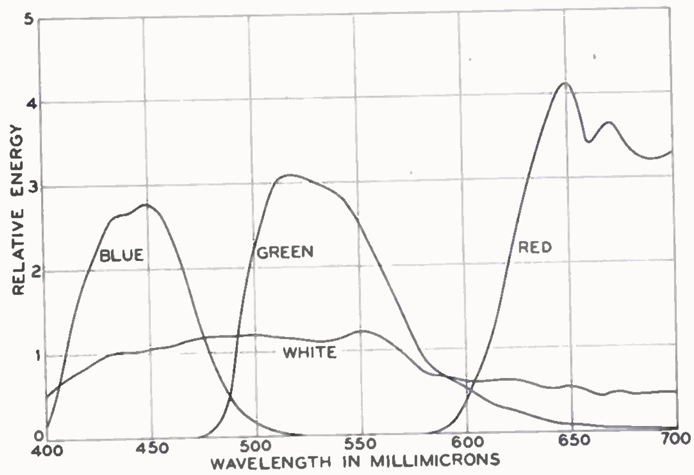

Fig. 4—Spectral distributions of the 3-color primaries and of the monochromatic white.

distributions corresponding to these color names are shown in Fig. 4. The blue and red primaries are non-overlapping on this scale, while the green primary overlaps them both to some extent. The additive mixture of blue, green, and red in approximately the amounts shown produces a chromaticity match with the white.

Fig. 5 shows these same colors plotted on a standard chromaticity diagram as the round dots. The white, because of its wide spectral distribution, shows some variation with lamp voltage (higher voltage toward the left), and so does the green to a lesser extent. For comparison, the reference receiver primaries described in the FCC order of Nov. 20, 1950 are shown by crosses.

Fig. 6 shows the essential features of the mechanism that produces the color pictures. It is an assembly of four special lantern-slide projectors, each one designed for variable focus at constant magnification. The 2.25- by 3.00-inch lantern-slide transparencies are printed from color-separation negatives made in a one-shot color camera. The four individual images can be put into good registry on the 10.0- by 13.3-inch viewing screen,

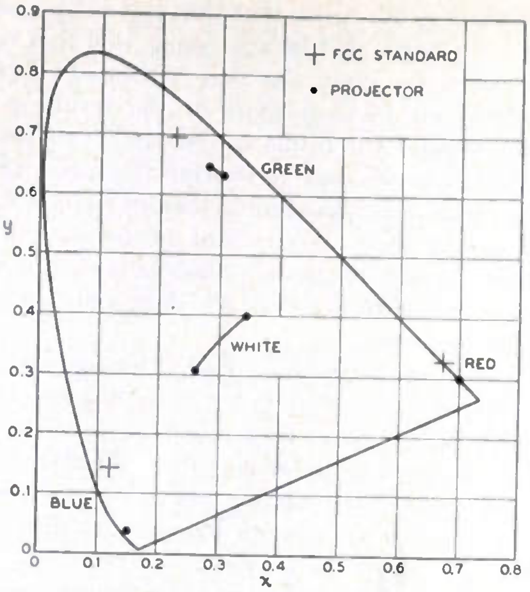

Fig. 5—ICI chromaticity diagram, showing the 3-color primaries, the monochromatic white, and the reference receiver primaries specified in the FCC order of November 20, 1950. White and green show variation with lamp.

and each image separately can then be put way out of focus without any change in its size or in its registry with the other images. The viewing screen is bordered by a 1-inch slot, opening into a black cavity, which absorbs the color fringes resulting from inexact registry of the edges of the projector apertures. Apart from the slot, the picture surround is composed of a 2-foot square of white reflecting material, and outside, the room walls.

The condition for constant magnification is met when both the lantern slide and the projection lens are moved in the same direction (normal to the screen) and by such amounts that the lens always divides the distance between the slide and the screen into two parts whose ratio is the magnification, 4.50 to 1. This is accomplished by means of a simple pantagraph motion, as shown at the lower left. The slide remains parallel with the screen as it moves to and fro in the circular path with the longer radius. Projection lens also remains parallel with screen as it moves in the different circular path with the shorter radius. Registration requires lenses to be closer together than slides, as shown (lower right).

The plan view, at the upper part of Fig. 6, shows that the slide moves a little more than the lens does and that their combined motions serve to pull the sharp image out in front of the screen in order to put a blurred image of the right size on the screen. The plan view shows also that the lamp houses are aimed toward the screen center to secure equality of illumination.

Acknowledgment

The author gratefully acknowledges the valuable co-operation of W. T. Wintringham and G. Nielsen, in the design and performance of this experiment.

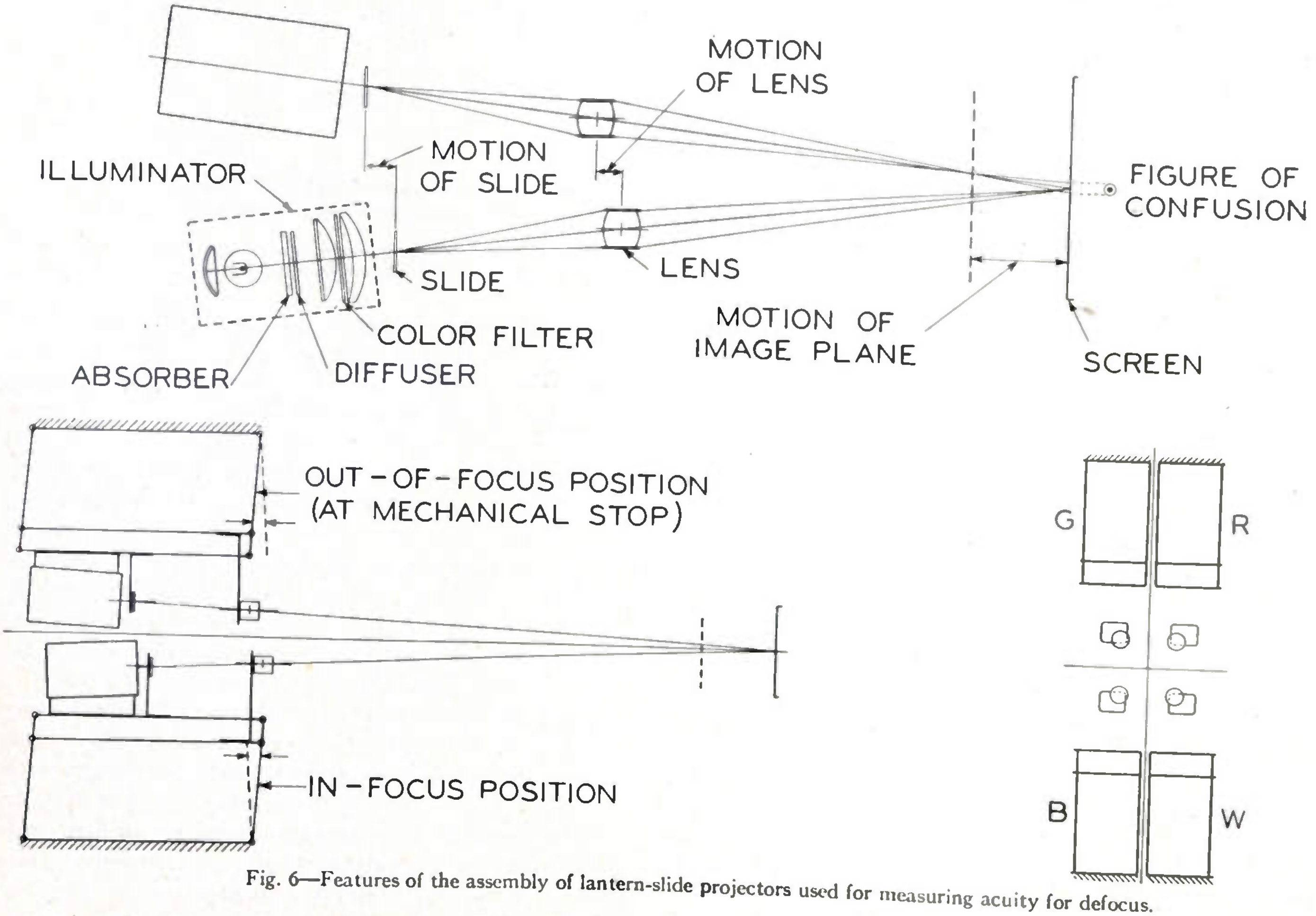

Fig. 6—Features of the assembly of lantern-slide projectors used for measuring acuity for defocus.

DIRECT-VIEW COLOR KINESCOPES

A series of eleven papers.

Methods Suitable for Television Color Kinescopes*

E. W. HEROLD†, FELLOW, IRE

Summary—**This paper is the first of a series which covers Radio Corporation of America work on color-television cathode-ray picture reproducers (color kinescopes) for the home. Minimum reproducer requirements are here considered to be high-light brightness and resolution equal to or exceeding that achieved in the present United States black-and-white television system and large-area three-color fidelity which encompasses the major part of the horseshoe-like area of the chromaticity diagram of the International Commission on Illumination (ICI). Color phosphors with electron-beam excitation meet the requirements.**

One color-kinescope method, which requires the beam to be accurately positioned at all times during scanning on a screen of adjacent subelemental color-phosphor areas, has practical disadvantages. In a second method, using a similar type of kinescope, the beam position controls the color signal; although accurate scanning is not required, some of the disadvantages are the same. A third method, which uses adjacent complete picture images, optically combined, has little to offer over the use of three separate color tubes. A phosphor screen, whose color can be changed by a difference in electron-beam velocity or current density, has attractive features, but is not available in practical form. Methods of considerable interest are those whereby either the electron beam is electrically controlled at the phosphor screen for changing color or whereby shadowing techniques are employed to produce a direction-sensitive color screen. All these methods were investigated; subsequent papers of the series will describe some of the tubes which were built and give information as to their design and operation.

INTRODUCTION

INVENTORS AND SCIENTISTS have been concerned with television reproduction in color ever since the late 1920's when a number of color-television demonstrations were given using scanning-disk techniques.[1,2] Although the patent literature and occasional publications indicate that thought was being given to all-electronic means for color reproduction, the most successful work of the 1930's continued to use mechanical methods. This work reached its ultimate about 1940 when the field-sequential color-television system using a rotating color disk was extensively demonstrated and publicized.[3] Although the color-disk method, by adding the cathode-ray tube, eliminated some of the more complex moving parts of the mechanical scanning system, there were inherent limitations in reproduction, namely, the inability to provide color sequences at a sufficiently rapid rate for other than frame or field-sequential methods and the inherently small-size picture which resulted from any practical direct-view receiver.

Recognition of these limitations stimulated efforts toward electronic solutions. Work in this direction by the Radio Corporation of America led, early in 1940, to a demonstration to the Federal Communications Commission (FCC) of color reproduction using three optically superimposed images from three cathode-ray tubes, thereby eliminating all moving parts.[4] By 1942, Baird, in England, also demonstrated all-electronic color pictures, but by means of a single cathode-ray tube producing two adjacent images, optically combined to give a two-color effect.[5] His British patent application of 1942 and 1943[6] showed that he had more ingenious tubes in mind. One of these, using a two-sided phosphor screen for a two-color picture, was actually demonstrated in principle by Baird in 1944. At the same time he described a more complex tube suitable for three colors.[7] RCA engineers also continued to study the single-tube color reproducer during this period, but it was not until after World War II that such factors as improved high-voltage and deflecting systems, metal kinescopes, aluminized phosphors, and the like provided the key to some of the problems. As a result of this progress, it finally became possible, early in 1950, to demonstrate a satisfactory and practicable single-tube, three-color reproducer for the home.[8,9]

The purpose of this paper is to present some of the problems of a three-color reproducer and to show how they may be solved in all-electronic form using cathode-

* Decimal classification: R583.6×535.6. Original manuscript received by the Institute, August 15, 1951.

† RCA Laboratories Division, Radio Corporation of America, Princeton, N. J.

[1] J. L. Baird; July, 1928. See R. F. Tiltman, "Television in natural colors demonstrated," *Radio News*, vol. 10, p. 320; October, 1928.

[2] H. E. Ives, "Television in color," *Bell Lab. Rec.*, vol. 7, pp. 439–444; July, 1929.

[3] P. C. Goldmark *et al.*, "Color television," Pt. I, PROC. I.R.E., vol. 30, pp. 162–182; April, 1942. Also Pt. II, PROC. I.R.E., vol. 31, pp. 465–478; September, 1943.

[4] "See Television in color—members of F.C.C. visit plants of RCA and Philco," *N. Y. Times*, p. 18; February 6, 1940. Also, "Television in color demonstrated by RCA," *Philadelphia Inquirer*, p. 18; February 6, 1940.

[5] "J. L. Baird's improved colour television," *Electronic Eng.* (London), vol. 15, p. 327; January, 1943. See also, *Wireless World*, vol. 49, p. 41; February, 1943.

[6] J. L. Baird, British Patent 562,168 (provisional spec. left July 25, 1942, complete spec. left July 23, 1943).

[7] "J. L. Baird's Telechrome," *Jour. Telev. Soc.*, vol. 4, pp. 58–59; September, 1944. See also, *Electronic Eng.* (London), vol. 17, pp. 140–141; September, 1944; *Electronics*, vol. 17, p. 190; October, 1944; and *Wireless World*, vol. 50, pp. 316–317; October, 1944.

[8] T. R. Kennedy, Jr., "RCA shows all-electronic tube as key to color television," *N. Y. Times*, p. 1; March 29, 1950; "New color television tube seen bringing color programs to the home," *Radio Age*, vol. 9, pp. 3–5; April, 1950.

[9] RCA Laboratories Div. "General description of receivers which employ direct-view, tri-color kinescopes," *RCA Rev.*, vol. 11, pp. 228–232; June, 1950.

ray beams and luminescent screens. This paper is the first of a series of articles; subsequent papers will present technical information on some of the color kinescopes which have been developed by RCA and the techniques necessary for their utilization.

Requirements of a Color Reproducer

Some of the requirements of a color reproducer are apparent from black-and-white television experience. The picture should have a large area, preferably equal to or larger than that of a 16-inch kinescope (14⅝ inches diagonal). For color, the picture brightness should be not less than, and perhaps exceeding, that of black-and-white home-television reproduction. It is important, of course, that good contrast range be achieved; it must be noted that the effect of ambient white-light illumination, which reduces contrast in black-and-white pictures, has the additional effect of reducing chromaticity in color reproduction.

An additive color system, such as one produced by electron-beam excitation of phosphors, with or without color filters, requires only three primary colors, red, green, and blue, for good color reproduction of large-area detail.[10] More recently, it has been established[11] that the normal human eye is much less sensitive to color in small detail, the color defection resembling that known as tritanopic vision (blue blindness). Thus, a color reproducer must have good three-color primaries for the larger areas, but needs only a limited two-color, or even monochrome, reproduction for fine detail. Although this characteristic of the eye is utilized in television systems employing "mixed-highs,"[12] the application of the principle in a color-reproducer system is not yet a matter of public knowledge. (The color kinescopes to be considered later will be capable of equal resolution in each of the primary colors and, hence, will provide more color fidelity than the eye can use.)

Colorimetry makes use of the ICI chromaticity diagram shown in Fig. 1.[10] The entire range of colors observable by the normal eye is found within the horseshoe-shaped figure, whose periphery bears numbers to indicate pure spectral wavelengths in millimicrons. Any color has x and y coordinates which specify the fraction of red and green components of a fictitious and physically unrealizable set of primary colors. A three-color television reproducer must use realizable primary colors which, in an optimum case, would lie so that lines joining their ICI coordinates encompass the most important part of the area of the horseshoe of Fig. 1. Suitable primary color points, as suggested by Hardy and Wurzburg,[13] are shown by the circled points in Fig. 1.

[10] R. M. Evans, "An Introduction to Color," John Wiley and Sons, Inc., New York, N. Y.; 1948.

[11] W. E. K. Middleton and M. C. Holmes, "The apparent colors of surface of small subtense," *Jour. Opt. Soc. Amer.*, vol. 39, pp. 582–592; July, 1949. Also, other references given therein.

[12] A. V. Bedford, "Mixed highs in color television," Proc. I.R.E., vol. 38, pp. 1003–1009; September, 1950.

[13] A. C. Hardy and F. L. Wurzburg, Jr., "The theory of three-color reproduction," *Jour. Opt. Soc. Amer.*, vol. 27, pp. 227–240; July, 1937.

The resolution, or fineness of detail, which a color reproducer must achieve, depends on the capabilities of the system with which it is to be used. Present 525-line black-and-white television, with 60 interlaced fields through a 4.25-megacycle channel, is capable, under ideal conditions, of about 340-line resolution in each direction. If it is assumed that there is no deterioration of

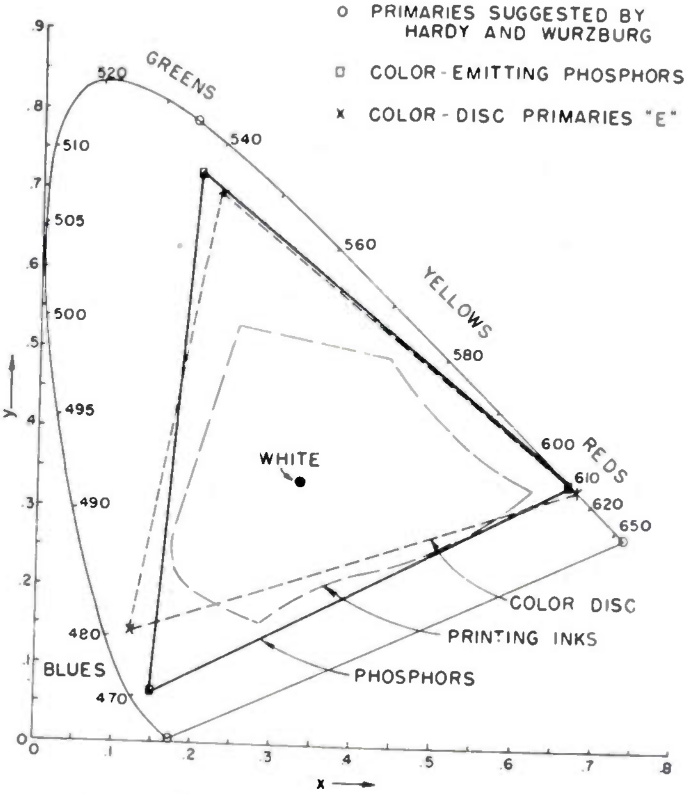

Fig. 1—The ICI color diagram includes all visual colors. The three color primaries achieved by unfiltered phosphors are compared with the color disk and with the idealized primaries of Hardy and Wurzburg. The area possible with modern color printing (according to MacAdam) is shown by the dashed-line figure.

standards and that no use is made of the above-discussed dichromatic vision for small detail, the color reproducer should also have at least 340-line resolution in each direction and should have the appropriate number of picture-element groups, each one of which must be capable of light emission in any one of the three primary colors.

A color reproducer need not operate with all of the possible color-television systems although most all-electronic reproducer methods can be made to operate on any known color system, with more or less difficulty. Although color systems have been classified as field-sequential, line-sequential, dot-sequential, and simultaneous,[14] the distinction is not straightforward. The system, sometimes called "dot-sequential," which was successfully field tested by RCA in 1949 through 1950,[15]

[14] Report of the Senate Advisory Committee on Color Television, "The present status of color television," Proc. I.R.E., vol. 38, pp. 980–1002; September, 1950.

[15] RCA Laboratories Division, "A 6-mc. compatible high-definition color television system," *RCA Rev.*, vol. 10, pp. 504–524; December, 1949.

is also a simultaneous system with brightness information which amplitude-modulates the main carrier, color-hue information which phase-modulates a subcarrier (the so-called "sampling frequency"), and color-saturation information which amplitude-modulates this same subcarrier.[16] The nature of the color system—simultaneous or sequential—is an important consideration in the color reproducer. A truly sequential system is one in which the colors appear one at a time in sequence and are reproduced by the reproducer only one at a time; in a cathode-ray reproducer the electron beam or beams share the time of use between the colors. For this reason, in a color-kinescope reproducer, no matter whether one or three electron beams are used, the brightness of the sequential picture is inherently limited to one-third of that of simultaneous reproduction with three beams. A television system which permits *either* sequential or simultaneous presentation, such as the aforementioned RCA color system, is advantageous because the choice of reproducer tube and reproduction method can be made on purely economic grounds.

Regarding the requirements imposed by the color system on the reproducer, it is clear that a purely sequential system requires time-switching of colors and there is, therefore, an advantage in a reproducer in which switching can be done by the application of sine waves, especially if it is necessary to change color at a rapid rate. With cathode-ray reproduction, when three electron beams are used (one for each color) simultaneous reproduction has no such problem of color switching. A reproducer with one electron beam, used for simultaneous presentation, must have some means of changing colors, but the problems are quite different from those with sequential presentation. For the inventor of new color kinescopes, a color system which allows either simultaneous or sequential presentation again has the advantage of permitting greater flexibility of design.

Color Phosphors

The requirements for a color reproducer can be well fulfilled by a cathode-ray device, provided that suitable color-emitting phosphors or color filters are used. Most luminescent materials have characteristic colors other than white, and the "white" phosphors of the black-and-white kinescope are actually mixtures of phosphors of two complementary colors, or three-color mixtures which give white. In view of this, it is clear that use of such a "white," with a color filter, as is done in the color-disk method of reproduction, makes inefficient use of the electron beam since the beam energy must divide itself among two or three color phosphors, with only one portion of the light going through the filter at a time. The best use of cathodo-luminescence, then, is to eliminate filters as much as possible by choice of phosphors with high light output and ICI points close to the ideal ones of Fig. 1.

The art of preparing cathodo-luminescent materials is an extensive one,[17] in which many varieties are available. For the color tubes demonstrated by RCA in March, 1950, willemite (Zn_2SiO_4:Mn) was used for the green and another silicate [$CaMg(SiO_3)_2$:Ti] for the blue. The third phosphor was a readily-available cadmium borate ($2CdO \cdot B_2O_3$:Mn), which has a red-orange color which many observers judged to be not close enough to the optimum red. At the suggestion of G. C. Sziklai of RCA Laboratories, a didymium-glass filter was used which has a sharp rejection band at the yellow sodium lines; at other wavelengths it is very much like a neutral filter with 40- to 50-per cent absorption. This filter made the color reproduction satisfactory.[18] Although a substantial loss of light resulted, there was a slight compensating advantage in the improved contrast due to the neutral-filter action. However, the borate red left much to be desired in efficiency and the output of the more efficient green and blue phosphors had to be reduced to achieve a color balance.

As a result of much careful work, an improved red-emitting phosphor has been synthesized.[19] When the same green willemite phosphor, a sulphide blue (ZnS:Ag) of improved efficiency,[20] and the new red material, $Zn_3(PO_4)_2$:Mn, are used, ICI points which form the solid-line triangle in Fig. 1 are achieved, together with improved visual efficiency. A comparison is made in Fig. 1 with the primaries achieved by the color-disk television reproducer, on which considerable effort has been expended over a number of years. The comparison is made with the result of this work, the so-called primaries "*E.*"[21] A second comparison is made with the range achieved with modern printing inks shown by MacAdam.[22] It is evident that the phosphor primaries are superior to the others and sufficiently close to the optima for excellent color reproduction. Further improvement in efficiency of the red component is, of course, still desirable.

To obtain a very desirable increase in brightness, the color phosphors can be operated at high voltages. This is readily possible provided aluminizing is used, a technique which has other advantages as well.[23]

It is now appropriate to examine the different ways

[16] When a black and white picture is transmitted by this compatible system, the amplitude of the subcarrier is zero and the transmission is identical with that of a black-and-white system.

[17] H. W. Leverenz, "An Introduction to Luminescence of Solids," John Wiley and Sons, Inc., New York, N. Y.; 1950.

[18] Exhibit 392, "Color Characteristics of the RCA Tri-Color Kinescopes," Radio Corporation of America, F. C. C. Dockets 8736, 8975, 9175, and 8976; 1949–1950 hearings.

[19] A. L. Smith, "Luminescence of three forms of zinc orthophosphate: manganese," *Jour. of the Electrochem. Soc.;* vol. 98, pp. 363–368, September, 1951.

[20] Developed by H. W. Leverenz and the Chemico-Physics group at RCA Laboratories, Princeton.

[21] Exhibit 210, Columbia Broadcasting System, F.C.C. Dockets 8736, 8975, and 9175; 1949–1950 hearings.

[22] D. L. MacAdam, "On the geometry of color space," *Jour. Frank. Inst.*, vol. 238, pp. 195–210; September, 1944. Also see, *Life*, vol. 17; July 3, 1944.

[23] D. W. Epstein and L. Pensak, "Improved cathode-ray tubes with metal-backed luminescent screens," *RCA Rev.*, vol. 7, pp. 5–10; March, 1946.

in which such phosphors can be used for a color kinescope.

Accurate Beam-Scanning Method

The earliest proposals for a color kinescope were an extension of the black-and-white technique, specifying that the white phosphor screen should be covered by a "checkerboard" of color filters,[24] or should be replaced by one of ruled phosphor lines of the three colors in succession.[25,26] Although, with the line screen, scanning by the single electron beam could be either parallel or transverse to the phosphor lines, scanning accuracy was easier to achieve with the former. Fig. 2 illustrates this method. Obviously, extreme scanning accuracy in one direction is required if color dilution or error is to be avoided and a high-definition system seems very difficult to achieve. The "checkerboard" color screen, or dot screen, requires accuracy of scan in both directions; it was once considered difficult to make[25] and would certainly be difficult to operate; nevertheless, it has been revived in a very recent patent.[27] The colors may be sequentially presented when only one electron gun and beam are used and, of course, are controllable by slight shift in beam position. If the beam is controlled to excite more than one color strip or spot at a time, simultaneous presentation with a single beam is possible. A beam may also be split into three or more parts, separately controlled, but through a common deflecting system, to achieve simultaneous presentation.[28,29]

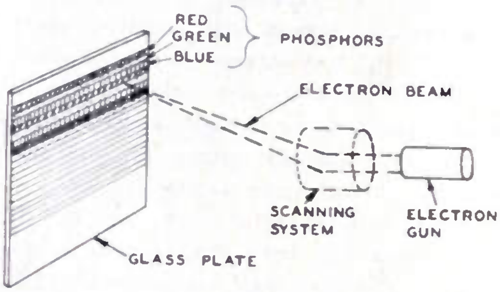

Fig. 2—Example of line-screen color kinescope using one electron beam. To assure correct colors, beam scanning must be highly accurate. No automatic registry means are shown.

Line or dot screens with this method require phosphor lines or dots which are of size less than one-third of the distance between scanning lines (when scanned parallel) or less than one-third of a picture-element size (when scanned transversely). The making of the screen is only one of the difficulties, since the scanning beam must also have a correspondingly reduced minimum spot size.

The achievement of high scanning accuracy is aided by automatic control and registry by feedback methods, of which a large variety have been devised during the past decade. Some of the proposals have been published as patents,[30,31,32] but many are still being worked on in the laboratory. Although the achievement of automatic registry by control signals or feedback may lead to complex circuitry, it seems clear that a single-beam, line-screen, color kinescope can be made with relatively little complexity since it would require few more parts than the black-and-white conventional kinescope. Among the line-screen tube disadvantages are the color error when the beam is misregistered, or incorrectly focused.

Over a number of years, experiments with line screens were made by D. W. Epstein at RCA Laboratories by a three-step phosphor-settling process through a movable mask. Subsequently, suitable screens were made by a development of the RCA Victor Division at Harrison, N. J., in which the three color-phosphor line-groups were printed, using the silk-screen process.[33] A demonstration of the principle of a line-screen tube was shown by RCA to the FCC on October 10, 1949. At RCA Laboratories, color pictures were achieved both with accurate scanning linearity alone and with associated feedback circuits to lock the beam in its correct position at all times.[34]

Signal Control by Beam-Scanning Position

The method of the previous section requires extreme scanning accuracy because the scanning and the color signals are essentially independent phenomena. If, however, the color signals can be made dependent on the scanning, the latter need be no more accurate than in black-and-white practice since the scanning now controls the colors. This may be done by use of a color-sensitive photo device, or other special signal-generating means built into the screen, by which the kinescope control grid is automatically switched to the correct primary color signal, depending on the instantaneous beam position. The method has been suggested for transverse scanning of line screens,[34,35,35a] but, because of the need for an extremely small focused spot, it is subject to some of the same disadvantages as the accurately controlled scanning method of the previous section.

[24] V. K. Zworykin, U. S. Patent 1,691,324 (applied for July 13, 1925).
[25] R. Rüdenberg, U. S. Patent, 1,934,821 (convention date May 5, 1931).
[26] M. vonArdenne, British Patent 388,623 (convention date June 19, 1931).
[27] H. Kasperowicz, U. S. Patent 2,508,267 (applied for October 26, 1945).
[28] Fernseh Akt. Ges., British Patent 434,868 (convention date March 6, 1933).
[29] B. T. Hewson and A. Locan, British Patent 533,993 (complete spec. left June 17, 1940).
[30] V. K. Zworykin, U. S. Patent 2,415,059 (applied for October 13, 1944).
[31] W. H. Stevens, British Patent 803,080 (complete spec. left July 4, 1945).
[32] C. E. Huffman, U. S. Patent 2,490,812 (applied for January 3, 1946).
[33] N. S. Freedman and K. M. McLaughlin, "Phosphor-screen application in color kinescopes," Proc. I.R.E., pp. 1230–1236; this issue.
[34] D. S. Bond, F. H. Nicoll, and D. G. Moore, "Development and operation of a line-screen color kinescope," Proc. I.R.E., pp. 1218–1230; this issue.
[35] P. K. Weimer, U. S. Patent 2,545,325 (applied for January 30, 1948).
[35a] Alfred N. Goldsmith, U. S. Patent 2,431,115 (applied for August 5, 1944).

Adjacent Image Method

Hardly far behind the accurate beam-scanning method in point of time were proposals for a color kinescope involving two or more complete television images, in different colors, which were optically combined by mirrors or by projection. The method can be used with three beams[36,37] allowing simultaneous presentation, or with one beam[38] which, in this case, is restricted to sequential presentation. Fig. 3 illustrates the method in one form. Although either field-sequential or line-sequential systems are well suited for the one-beam tube, the latter system has received particular attention[38,39] because a single line scan can be made to traverse all three areas. Because of the optical registration, which is very similar to that needed for three separate color kinescopes, the combination of the three images in one tube is not a sufficient advantage to make the method attractive. For a direct-view kinescope, furthermore, the front face area is very inefficiently used. Although good performance is difficult to achieve,[40] such an all-electronic picture reproducer device has been frequently demonstrated,[5,41,42] probably because the tube is so easily constructed.

The Baird two-color tube,[6,7] using one color phosphor

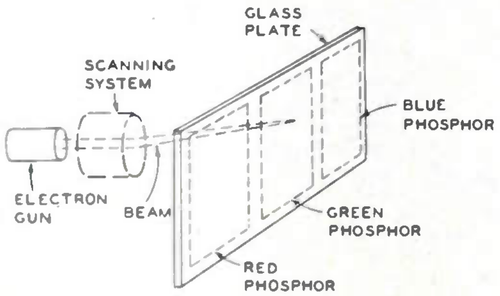

Fig. 3—Kinescope with adjacent color images. Optical combining means for direct view or projection are required.

on one side of a mica sheet and the second phosphor on the opposite side, with two electron guns at opposite sides and at an angle to permit viewing, is to be classified as in the adjacent-image group but requires no optical registry. However, a two-color system is severely handicapped in comparison with a three-color one.

Multiple-Color Phosphor Screen

A superficially attractive possibility for a color kinescope uses a single phosphor or a combination of phosphors in which color is responsive to either electron velocity or current density. Considering the former, it is possible to build up a three-layer screen so that electrons of one velocity penetrate only the first layer, producing one color, whereas faster electrons will penetrate to the second layer and the fastest electrons reach the third layer, so producing three colors, as shown in Fig. 4(a).[43]

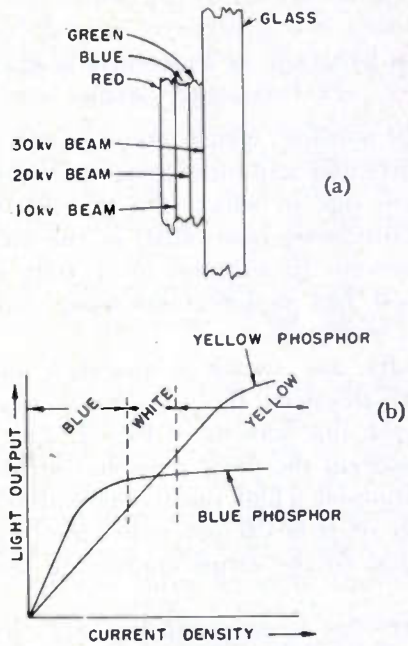

Fig. 4—Multicolor phosphor screen: (a) shows a multiple-layer screen with color depending on beam velocity, and (b) shows how saturation in a two-component screen makes color dependent on current density.

A variation of the method uses barriers of different thickness on the beam side of the color phosphors.[44] Either a single gun, in which the cathode potential is varied to change the electron velocity, or three guns of differing cathode potentials can be used for color rendition. Unfortunately, it appears unlikely that such screens can be made to operate with electron-velocity differences of less than around ten kilovolts, so that sequential switching is very difficult at best. There may be inherent color dilution, as well, so as to affect color fidelity. Use of three electron sources at such large velocity differences has other difficult problems, such as scanning amplitude differences.

A change of color with current density has often been observed[45] when saturation of one or more of the phosphor components sets in (See Fig. 4(b)). This effect has been proposed for a color kinescope by using variable-frequency pulses for brightness modulation and changes in current density for color.[46] The color change in the usual two- or three-component phosphors due to satura-

[36] K. Schlesinger, U. S. Patent 2,083,203 (convention date October 1, 1932).
[37] J. C. Wilson, U. S. Patent 2,294,820 (applied for April 29, 1941).
[38] Fernseh Akt. Ges., British Patent 432,989 (convention date March 6, 1933).
[39] R. Lorenzen, U. S. Patent 2,200,285 (applied for June 22, 1937).
[40] C. S. Szegho, "Color cathode-ray tube with three phosphor bands," *Jour. Soc. Mot. Pic. Eng.*, vol. 55, pp. 367–376; October, 1950.
[41] Color Television, Inc. Exhibits 237, 259, 260, F.C.C., Dockets 8736, 8975 and 9175; 1949–1950 hearings.
[42] Exhibit 210, Item 8 and Item 9b, Columbia Broadcasting System, F.C.C., Dockets 8736, 8975, and 9175; 1949–1950 hearings.
[43] C. S. Szegho, U. S. Patent 2,455,710 (applied for December 21, 1943).
[44] G. C. Sziklai and A. C. Schroeder, U. S. Patent 2,543,477 (applied for July 29, 1948).
[45] A. Bril and F. A. Kroger, "Saturation of fluorescence in television tubes," *Philips Tech. Rev.*, vol. 12, pp. 120–128; October, 1950.
[46] C. S. Szegho, U.S. Patent 2,431,088 (applied for December, 3, 1943).

tion is slight, and high-chroma colors are difficult to achieve. However, a color effect has been observed in certain *single* phosphors which have high-chroma emission of two widely separated colors, depending on current density.[47] If such a phosphor can be made with light efficiencies comparable to those now widely used, a new technique for color reproduction will become practical.

Beam Control at Phosphor Screen for Changing Color

A general method, which offers an extremely fertile field for particular and interesting variations in a color kinescope, is one in which the electron beam is deflected, or otherwise controlled, in the vicinity of the phosphor screen. In simplest form, only one electron beam is used, but modifications using multiple beams can also be employed.

Historically, the switching-at-screen approach was first used to eliminate the need for accurate scanning with the color-line screens of Fig. 2. The method involved insulating the color phosphor strips from each other and applying a high positive potential to the strips whose colors are to be excited, with a low or even a negative potential to the strips containing the other colors.[48–52]

An illustration is shown in Fig. 5(a), in which the phosphors are deposited on the surface of metal strips, the electron beam coming in at an angle to permit viewing. In view of the closeness of the color strips, as required for high definition, the electric field needed for deflection to the correct color is confined to a region very close to the screen and high-voltage differences are required. The color-changing circuits must, therefore, operate with voltages of many kilovolts, and are difficult to make in practical form. With a sequential presentation, the difficulties increase rapidly as the switching rate is increased, which makes switching least difficult for field or frame color sequencing. There are even greater practical disadvantages when a magnetic field is used for switching color.[53]

One modification of the high-voltage switching method[54,55] eliminates the line nature of the screen by using three closely-spaced, phosphor-coated grids. This makes the phosphor screen easier to fabricate, but the high-voltage color-changing and insulation problems remain. In addition, there is now parallax because the three color phosphors are no longer in the same plane; this can be overcome by projection rather than direct viewing, provided depth of focus is sufficient in the projection optics.

The impracticality of such high color-changing voltages suggests actual deflection electrodes at the phosphor screen, so that a single beam can be deflected to the correct color with much lower voltage differences than needed with Fig. 5(a). One such device is shown in Fig. 5(b), indicating deflection plates aligned with the rows of color-phosphor lines.[48,56] It is seen that, when there is no potential difference between deflection plates, the beam strikes the green-emitting phosphor. Since alternate deflection plates are connected, a potential difference causes the beam to be bent toward either the red- or blue-emitting lines, depending on which group of plates is more positive. A simple calculation shows that, with deflection plates of 1 cm or more in width, spaced by about one picture element, only some tens of volts are required to change colors, in distinction to Fig. 5(a) which requires from 100 to 500 times more voltage.

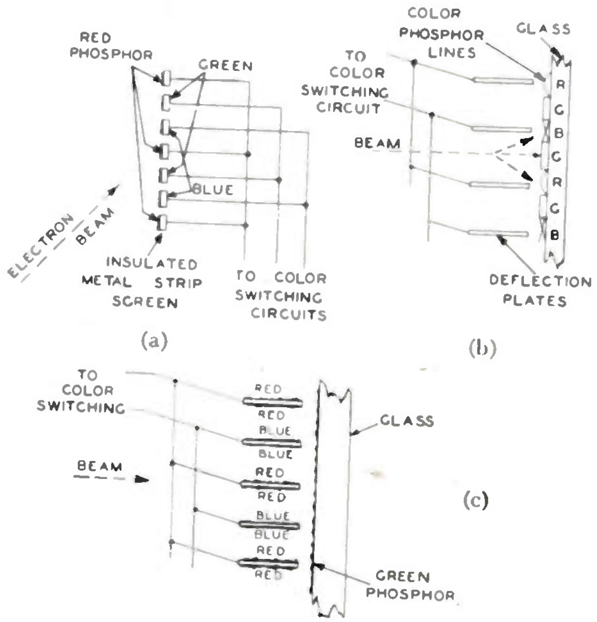

Fig. 5—Beam control at phosphor screen for changing color. (a) simple line-screen color switching. (b) Deflection switching of colors with line screen. (c) Deflection switching without requiring registry.

The capacitance of the two groups of plates since there are of the order of 150 to 300 of them in each group, is sufficiently high to pose serious difficulty when rapid color changes are needed. For sequential presentation, correct gating signals applied to the electron gun permit a sine wave to be applied to the color-deflection plates, and this permits tuned circuits to be used, thus reducing the power as compared with square-corner switching wave forms.

[47] Unpublished work of O. Schade, RCA Victor Division, Harrison, N. J., and F. H. Nicoll, S. M. Thomsen, and others, RCA Laboratories, Princeton, N. J.; and R. C. Bitting and L. M. Seeburger, RCA Victor Division, Camden, N. J.

[48] L. C. Jesty, British Patent 443,896 (complete spec. left November 5, 1935).

[49] A. V. Bedford, U. S. Patent 2,307,188 (applied for November 30, 1944).

[50] H. E. Kallmann, U. S. Patent 2,416,056 (applied for February 21, 1944).

[51] L. E. Swedlund, U. S. Patent 2,446,440 (applied for January 28, 1947).

[52] L. W. Parker, U. S. Patent 2,498,705 (applied for July 2, 1947).

[53] T. W. Chew, U. S. Patent 2,529,485 (filed October 9, 1945).

[54] A. B. Bronwell, U. S. Patent 2,461,515 (applied for July 16, 1945).

[55] A. B. Bronwell, "A new viewing tube for color television," *Tele-Tech*, vol. 7, pp. 40–41 and 60–65; March, 1948. Also in *Electronic Eng.* (London), vol. 20, pp. 190–191; June, 1948.

[56] A. C. Schroeder, U. S. Patent 2,446,791 (applied for June 11, 1946).

The registry of such a large number of deflection plates with the phosphor lines is a mechanical difficulty of the Fig. 5(b) method, which has been overcome by epositing two of the color phosphors directly on the deflection plates, as proposed by R. L. Snyder and constructed and improved by H. B. Law, both at RCA Laboratories, Princeton, N. J. An illustration is shown in Fig. 5(c). This simplifies tube construction but prevents use of aluminizing over the phosphors since the red and blue light must pass through the green phosphor, which acts as a diffusing screen to reduce undesired directivity of the red and blue colors. When aluminizing is not used, care must be taken to prevent differences in charging up of the phosphors, which cause nonuniform deflection. Special techniques, of course, are also required for use of anode potentials on the kinescope above the "sticking potential" of the phosphors. Improved phosphor conductivity and transparent conducting coating under the green phosphor are methods which may be used but, in general, much more care must be taken in such a tube than in black-and-white tubes because three different and unmixed phosphors are involved. There is also limited red and blue definition, due to a finite number of deflection plates in the one direction and the diffusion of the red and blue light through the green-emitting phosphor in the other direction. On the other hand, the tube requires comparatively little mechanical registration (chiefly tilting of plates to keep them parallel to the deflected electron beam).

The use of fine-meshed control grids at the phosphor screen assembly for overcoming high color-changing voltages was developed by S. V. Forgue.[57] In such tubes, the light-emitting area is composed of a set of parallel, closely spaced, phosphor screens, which are separated by color control grids operated near cathode potential. When one of the color control grids is slightly positive in potential, the electron beam can pass through a subsequent phosphor screen. When the grid is negative in potential, the beam is turned back to strike a preceding phosphor screen. In a two-color tube, one control grid separates two phosphor screens. In a three-color tube, two control grids interleave with three phosphor screens. When such kinescopes are used for a sequential color-picture presentation, sine-wave switching can be used for high-sequence rates, and the capacitance is considerably less than the deflection-plate methods of Figs. 5(b) and 5(c). There is, however, parallax between the color images which either limits the viewing angle or suggests projection optics as with the other tube using grids.[54,56]

P. K. Weimer developed a switching-at-screen color kinescope which uses a single electron beam at an angle of 45 degrees with the viewing screen.[58] All three color-emitting phosphors are now placed on the front surface of a perforated metal sheet in adjacent line-like areas. By varying the voltage on a nearby and parallel transparent conducting coating, the electron beam is reflected back in a path which can be slightly altered to strike one, or another, color. The phosphor areas and the openings in the sheet are so located that the same color is emitted no matter at what point on the raster the beam is deflected, assuming a fixed reflecting-electrode potential. To obtain a rectangular raster, keystone-correction is applied to the deflection circuits. This device has a mechanical requirement, namely, accurate parallelism of the perforated sheet and the transparent reflecting electrode, but in other respects it has many advantages, among which is an effectively perfect superposition of the three color images. A sine wave can be used for sequential color switching, when this need be done at a rapid rate, using circuits developed by N. Rynn.

Each of the color kinescopes in this section has been described with a single electron beam; for sequential color presentation only one beam is needed. For a simultaneous presentation, brighter pictures are often obtained by use of three separate electron beams. With the kinescopes using a color control mechanism at the screen, one may use three separate electron guns by operating them at different cathode potentials. The three guns are located as closely together as possible (if a single deflecting system is to be employed). In the methods of Fig. 5(a), or the Bronwell gridded tube,[54,55] the differences in cathode potentials are so large that a single deflecting system would be impracticable. However, for the Forgue grid-controlled color tube, or the Weimer 45-degree reflection tube, only a small cathode-potential difference is required for the three electron guns to cause the fixed-potential color control system at the screen to act differently on each beam. With the type of operation using a transverse control field, as in Fig. 5(b) and 5(c), the analogous procedure (i.e., three guns at slightly different cathode potentials) would not be applicable, and one is led to a separation of the electron guns in space, with no control field. This becomes a direction sensitive color screen (treated in the next section) which depends on shadowing.

Direction-Sensitive Color Screens Using Electron Shadowing

Because electrons in a field-free region move in substantially straight lines, one can make use of shadow techniques to produce a color-emitting phosphor screen in which color depends on the direction of arrival of the impinging electron beam. An early proposal using color-phosphor lines shadowed by an aligned grid is shown in Fig. 6.[59] It is seen in Fig. 6(b) that a single beam may be deflected and reconverged so as to appear to come from three positions in time sequence. Alternatively, three separate and spaced electron guns may be used

[57] S. V. Forgue, "A grid-controlled color kinescope," Proc. I.R.E., pp. 1212–1218; this issue.

[58] P. K. Weimer and N. Rynn, "A 45-degree reflection-type color kinescope," Proc. I.R.E., pp. 1201–1212; this issue.

[59] W. Flechsig, German Patent 736,575 (applied for July 12, 1938); see also, corresponding French Patent 866,065.

as in Fig. 6(a). The mechanical difficulties in such a structure are great and the use of the line screen requires a nonsymmetrical deflecting voltage for normal color sequencing in a one-beam tube; for this reason, a color screen with dots instead of lines has particular advantages.

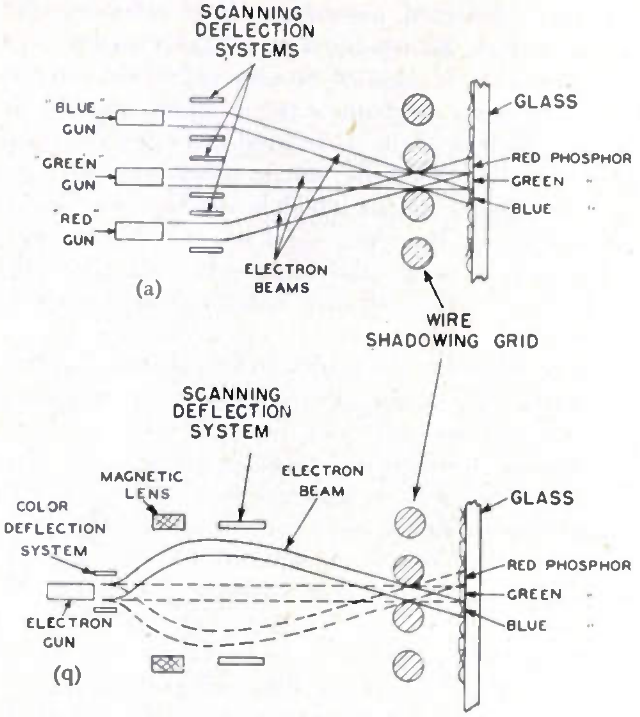

Fig. 6—Proposal by Flechsig using color phosphor lines shadowed by wire grid. (a) With three beams. (b) With one beam deflected at the gun.

The first direction-sensitive method to receive considerable publicity made use of a nonplanar surface, and was proposed by Baird for a three-color kinescope.[6,7]

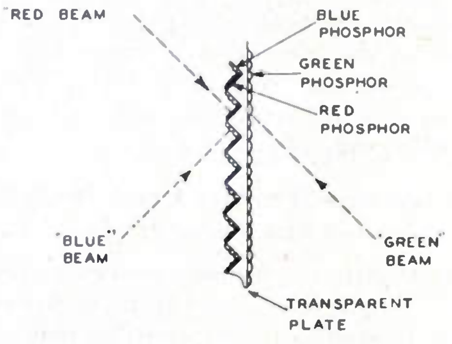

Fig. 7—Baird three-color nonplanar color screen, in principle.

Shown in Fig. 7, it used a ridged transparent plate with the color phosphors deposited as strips along the ridges. The third color was produced on the opposite side. Modified nonplanar color screens using all three beams on the same side were devised by Geer[60] and others,[61,62] for which a typical illustration is shown in Fig. 8. The major problems of such a tube, aside from fabrication, lie in obtaining good color directivity and in the complex deflection problems. It is necessary to produce a rectangular raster with three off-axis, keystone-corrected guns, in which not only the edges but each scanning line should be registered with those of the other two guns. Although these problems have not yet been overcome practically, they are now receiving serious consideration in at least one laboratory. A few years ago, R. R. Law and D. A. Jenny, at RCA Laboratories, Princeton, N. J., studied means for reducing the angle of separation of the three beams by using very steep pyramids on the nonplanar surface, and also by constructing alternative nonplanar surfaces, two varieties of which are shown in Figs. 9(a) and 9(b). Unfortunately, the deposition of phosphors so nearly parallel to the direction of viewing leads to so large a light loss that widely spaced guns, with their attendant deflection problems, may be essential.

There is, of course, a very substantial advantage in a direction-sensitive color screen with such a narrow angle between electron beams that a single deflection yoke can be used. Although it is possible to do this with the line-screen shadow device of Fig. 6,[63] it appears to be

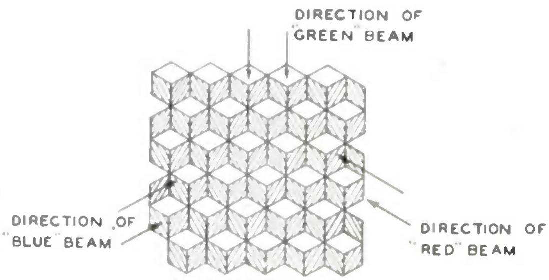

Fig. 8—Cubical-pyramid nonplanar color screen. Sides of cubes facing in different directions are coated with different color phosphors.

much easier to adopt proposals of Alfred N. Goldsmith, consulting engineer to the Radio Corporation of America, and A. C. Schroeder, of RCA Laboratories. Special techniques developed by H. B. Law, of RCA Laboratories, showed the practicality of the arrangement and permitted successful tubes to be made using three beams, one for each color.[64] This screen uses color phosphors arranged in groups of three dots in an equilateral triangle; close to the phosphor screen and between it and the electron guns is an aperture mask which produces the shadowing. For each group of three phosphor dots, there is a hole in the shadow mask of

[60] C. W. Geer, U.S. Patent 2,480,848 (applied for July 11, 1944).

[61] Alfred N. Goldsmith, U. S. Patent 2,481,839 (applied for August 5, 1944).

[62] Developments of A. B. Dumont Laboratories, "Experimental cathode-ray tubes for television," *Electronics*, vol. 20, pp. 113–115; March, 1947. See also, U.S. Patent 2,544,690 (applied for December 26, 1946).

[63] C. S. Szegho, "Experimental tri-color cathode-ray tube," *Tele-Tech.*, vol. 9, pp. 34–35; July, 1950.

[64] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

about the same size as one dot. An electron beam approaching the scanning mask at a slight angle (of the order of 1 degree) from the line to the center of deflection, will land only on a single color in any one of three rotational positions, 120 degrees apart. Thus, by placing the three guns at an appropriate distance from the axis of the tube and at the correct azimuthal orientation, the three beams may be converged to a point on the screen, and each beam is able to excite only a single color. Use of a very large number of dot groups prevents discernment by the viewer of the picture structure, just as in color printing.

The technique for making the mask and dot screen and their registry is described in another paper.[64] Deposition of the hundreds of thousands of accurately located phosphor dots presented a major problem which

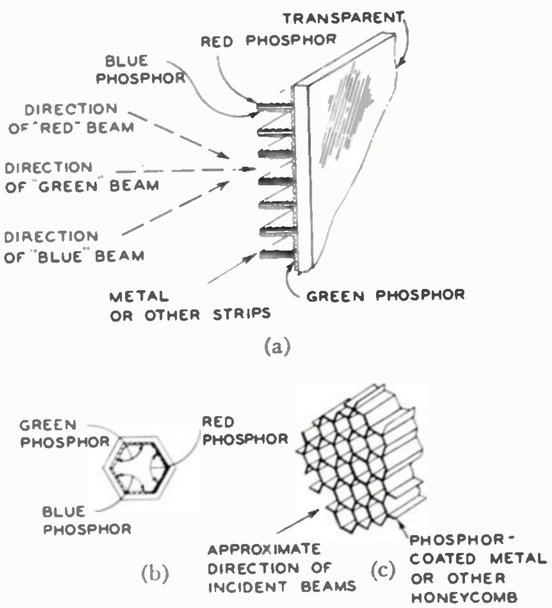

Fig. 9—Two forms of nonplanar direction-sensitive color screen.

was overcome by the use of printing techniques developed by N. S. Freedman and K. M. McLaughlin.[33] Other details of the three-gun shadow-mask color kinescope are discussed in accompanying papers.[65,66,67] The three beams are converged to a single point on the screen, even through wide angles of deflection, by using an anastigmatic deflection yoke and convergence system.[68]

A modification of the shadow-mask color kinescope is attainable by use of an ingenious development of R. R. Law of RCA Laboratories.[69] In this development only a single electron beam is used; prior to the normal scanning deflection, a small additional deflection at the gun and subsequent convergence moves the beam to different azimuth positions so as to cause any desired color to be emitted. When this is done in time sequence, so as to display each primary color in turn, a sequential color presentation is achieved, and it appears possible to use simple circuit components even at very high sequence rates. Alternatively, by correct control of the beam deflection at the gun, space-sharing of the color phosphors by the beam allows a simultaneous presentation.[69]

Both the one-beam and the three-beam shadow-mask kinescopes, using the RCA color television system, were publicly demonstrated[8] in March, 1950, in Washington, D. C.

[65] H. C. Moodey and D. D. Van Ormer, "Three-beam guns for color kinescopes," Proc. I.R.E., pp. 1236–1240; this issue.

[66] D. D. Van Ormer and D. C. Ballard, "Effects of screen tolerances on operating characteristics of aperture-mask, tri-color kinescopes," an accompanying paper. Proc. I.R.E., pp. 1245–1249; this issue.

[67] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask, tri-color kinescopes," Proc. I.R.E., pp. 1241–1245; this issue.

[68] A. W. Friend, "Deflection and convergence in color kinescopes," Proc. I.R.E., pp. 1249–1263; this issue.

Acknowledgment

The development of all-electronic color-television reproducers at RCA encompassed the entire range of methods surveyed in this paper, as well as methods not described. The accompanying papers describe a limited part of the work and reflect appropriate credit on the authors; in other instances, contributions are mentioned in footnote and text references. There are additional individuals and groups who made major contributions to engineering aspects of the color-tube work. These include, at RCA Laboratories, Princeton, N. J., A. Rose, F. H. Nicoll, D. W. Epstein, H. Rosenthal, P. Messineo, J. Rajchman, and L. Pensak; the tube-making group under S. W. Dodge and the model shop personnel under F. H. Creager; also the engineers in R. D. Kell's group with their expert knowledge of color television and systems; and L. E. Flory, W. Pike, J. Dilley, V. Landon, and J. Eckert, who designed circuits and receivers for testing the color kinescopes. In the RCA Victor Division, credit is due G. S. Briggs, H. R. Seelen, L. B. Headrick, and others, the men in the Lancaster tube shop under C. P. Smith, and those in the Harrison tube shop under K. M. McLaughlin. The Buckbee, Mears Company of St. Paul, Minn. supplied many photoengraved parts during the later stages of the work, and the active and enthusiastic co-operation of their staff is gratefully acknowledged.

Acknowledgment is due F. J. Darke, of the Patent Department of RCA Laboratories, whose researches into early patents uncovered many of the references. Mr. Darke is also responsible for the classification of color-tube methods.

A final acknowledgment is made here on behalf of all the authors of this series to Brig. General David Sarnoff, Drs. C. B. Jolliffe, E. W. Engstrom, and V. K. Zworykin, and to the others in the management of the Radio Corporation of America whose encouragement and resoluteness were essential to the final successful results.

[69] R. R. Law, "A one-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1194–1201; this issue.

A Three-Gun Shadow-Mask Color Kinescope*

H. B. LAW†, SENIOR MEMBER, IRE

Summary—A three-gun shadow-mask color kinescope is described as well as construction techniques. The beams, from three guns mounted together in a 2-inch diameter neck, are deflected by a single deflection yoke. The guns are pointed so that the electron beams converge to a spot on a thin, perforated metal sheet that acts as a mask and is located a short distance away from a viewing screen composed of many phosphor dots. Associated with each hole in the mask is a trio of phosphor dots capable of emitting the three primary colors, red, blue, and green. The dots are so placed that each electron beam as it scans can "see" only one dot of the trio. Each of the three beams is thus capable of exciting one color only, and when all three beams are modulated with the appropriate primary color information, a picture in full color can be reproduced.

An apparatus called the "lighthouse" is used to record the locations of the phosphor dots on a photographic plate placed behind the mask and in the plane of the phosphor screen. A point source of light, at the position from which the deflection of one of the beams appears to take place, is used to simulate the electron beam in recording the phosphor dot positions. The pattern for one color of phosphor is the same as for the other two colors, and the geometry of the hole system in the mask is such that the three phosphor patterns nest together perfectly. The phosphor screens may be made by using various processes such as, electrostatic printing, offset printing, photoprinting processes, silk screening, and settling. The latter two methods have been used in the tubes described in the text. Experimental tubes have shown the principles of operation and construction to be sound.

I. Introduction

IN THE PAST, a number of ideas for all-electronic television picture tubes have been proposed that allow both the brightness and color of individual picture elements to be displayed. Progress toward a practical reproducer has been slow, primarily because of the technical difficulties involved. In the last few years, however, many of the difficulties have been resolved by new techniques for black-and-white kinescope production such as metal-cone construction and aluminized phosphor screens. Other developments described below make the production of a color kinescope feasible.

A resumé of color-tube proposals has been given in an accompanying paper by Herold.[1] Some of these proposals may be compared with techniques used in color photography and color printing. For example, color photography by layer emulsion, such as Kodachrome, has a counterpart in the proposal to use three different layers of phosphor for the screen, each phosphor element being capable of emitting one of the three primary colors when selected to do so in some manner by the scanning beam. The proposal to superimpose optically three rasters in the primary colors, to form a color picture, is similar to color photography employing separation negatives. As for color printing, a great many of the color-reproducer proposals have incorporated a structure at or near the viewing screen to produce small elements of color that may be likened to the color dots of a printed picture.

Although a change of color can be obtained with layer phosphors, no commercial tube for the production of color pictures by this method has yet appeared. The optical superposition of three pictures in the primary colors has performed satisfactorily when three separate kinescopes have been used, and this method has served well for system experimentation. A single screen, made up of enough controllable color elements to give a good picture, seems, at first thought, complex. However, should complexity be unavoidable, a color-reproducer tube may still be useful if, by confining the complexity to the fabrication of the tube itself, the tube is made simple to operate. Whether such a reproducer tube is practical then depends on the solution of manufacturing problems. The color-reproducer tube to be considered here attempts to place the complex features into the tube itself so that the user finds it nearly as simple to operate as black-and-white kinescopes.

The shadow-mask color kinescope is based on the fact that electrons, moving in a field-free region, travel in straight lines. By use of the geometry of the color phosphor screen, it is possible to cast shadows on certain portions of the screen whose color one does not wish to excite. When the direction of arrival of the impinging beam is shifted, the shadows are shifted in position and the beam is permitted to illuminate only the desired color on the screen. The form of shadow geometry employed in the present tube incorporates proposals by Alfred N. Goldsmith, consulting engineer to The Radio Corporation of America, and A. C. Schroeder, of the RCA Laboratories Division.

This paper describes a color-kinescope shadow-mask viewing screen comprising a shadow mask placed in correct alignment with a phosphor screen consisting of a multiplicity of color-emitting phosphor dots. The shadow-mask screen is discussed in connection with a kinescope using three guns while the application of the same shadow-mask screen to a one-gun three-color kinescope is covered in a companion paper by R. R. Law.[2] Later work pertaining to the problems involved in producing the tube in metal cones with printed phosphor screens is presented by members of the RCA Vic-

* Decimal classification: R583.6×535.6. Original manuscript received by the Institute, August 15, 1951.

† RCA Laboratories Division, Radio Corporation of America, Princeton, N. J.

[1] E. W. Herold, "Methods suitable for television color kinescopes," Proc. I.R.E., pp. 1177–1185; this issue.

[2] R. R. Law, "A one-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1194–1201; this issue.

tor Division in companion papers.[3-6] Work undertaken at RCA Laboratories Division on the development of a suitable deflection yoke also appears in this series of papers.[7]

The first public demonstration of single-gun and three-gun shadow-mask color tubes incorporating this work was made in March, 1950.[8] In December, 1950, a triple-gun tube was demonstrated, which had improved phosphors and a greater number of color elements.[9]

II. Principle of Operation

In the three-gun shadow-mask color kinescope three electron beams are used, one for each primary color. The beams strike a phosphor screen composed of a regular array of red-, green-, and blue-emitting phosphor dots as shown in Fig. 1. Between the electron gun position and the phosphor screen, there is placed a thin perforated metal sheet for the purpose of partially masking the electron beams. That is, the electron beam which is to contribute the red part of the picture is prevented, by the mask, from striking those areas of the screen containing blue and green emitting phosphors. Likewise, the green and blue beams can strike only the green- and blue-emitting phosphor dots, respectively.

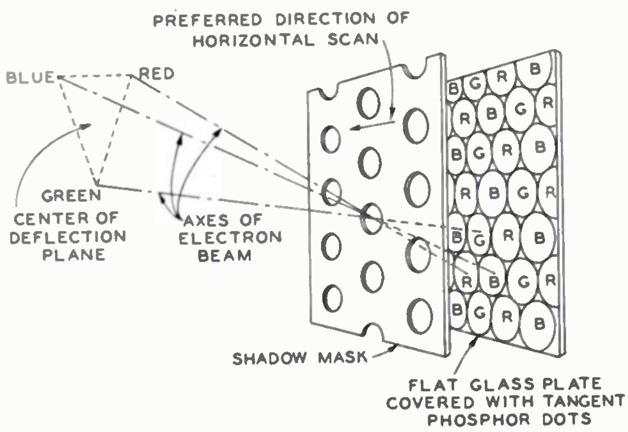

Fig. 1—An illustration of the geometrical relation between the electron beams, shadow mask, and phosphor screen, in the color kinescope.

The viewing screen is made up of closely spaced phosphor-dot trios on a flat glass plate (Fig. 1). Each trio consists of a red-, green-, and blue-emitting phosphor dot with the centers of the dots lying at the corners of an equilateral triangle. The trios themselves lie at the corners of an equilateral triangle of larger size. Associated with each of the trios is a hole in the shadow mask; these holes are also located at the corners of an equilateral triangle.

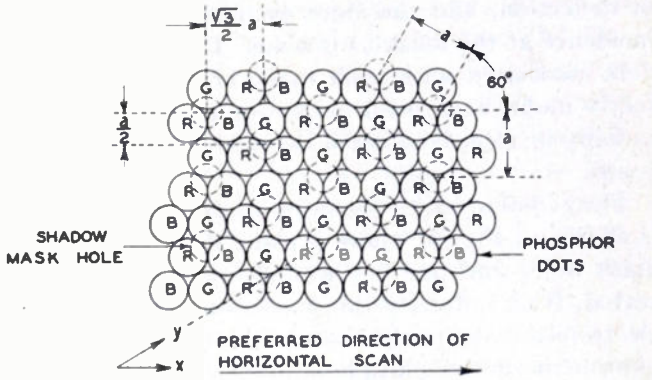

Fig. 2—Phosphor-dot array used in the color kinescope. The relation between the shadow-mask holes and the phosphor dots is shown for a region near the axis of the tube.

The phosphor pattern and shadow mask have a number of geometrical properties that may be more clearly seen in Fig. 2. The shadow mask hole associated with each trio is shown as a dotted circle.

The three beams, located 120 degrees apart about the tube axis, are converged to a point on the mask (Fig. 3) either by pointing the guns or by a lens system.[3] If the convergence angle, or angle between each of the beams and the tube axis, is made large, it is necessary to provide three separate deflecting systems capable of producing accurately registered rasters on the screen. Alternatively, if the angle of convergence is made small enough, the three beams can be included in the same neck and a single deflecting system can be used. In three-gun tubes described in this and companion papers,[3-5] it has been found possible to reduce the convergence angle to less than 2 degrees so that the three guns may be built into a two-inch diameter neck. In the one-gun tube, a single gun on the tube axis is used but the beam is deviated from the axis, bent back again, and rotated to give virtual origins equivalent to the three guns.

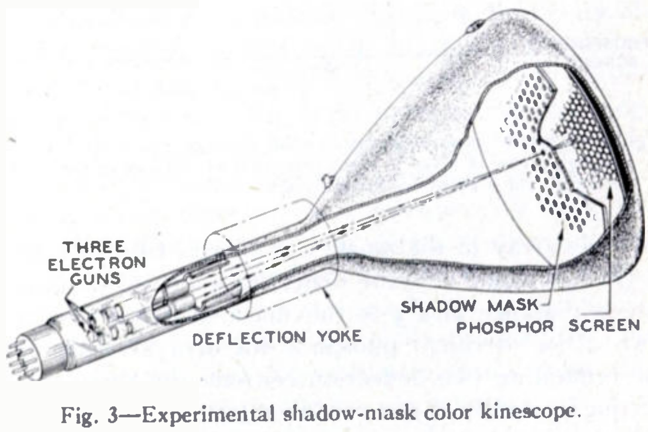

Fig. 3—Experimental shadow-mask color kinescope.

[3] H. C. Moodey and D. D. Van Ormer, "Three-beam guns for color kinescopes," Proc. I.R.E., pp. 1236–1240; this issue.
[4] D. D. Van Ormer and D. C. Ballard, "Effects of screen tolerances on operating characteristics of aperture-mask, tri-color kinescopes," Proc. I.R.E., pp. 1245–1249; this issue.
[5] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask, tri-color kinescopes," Proc. I.R.E., pp. 1241–1245; this issue.
[6] N. S. Freedman and K. M. McLaughlin, "Phosphor-screen application in color kinescopes," Proc. I.R.E., pp. 1230–1236; this issue.
[7] A. W. Friend, "Deflection and convergence in color kinescopes," Proc. I.R.E., pp. 1249–1263; this issue.
[8] T. R. Kennedy, Jr., "RCA shows all-electronic tube as key to color television," *N. Y. Times;* March 29, 1950.
[9] Jack Gould, "Improved RCA color is shown," *N. Y. Times;* Dec. 6, 1950.

The three beams go through the deflection yoke off axis, and each beam has its own center of deflection that is approximately a point. The three points for the three beams define a plane normal to the tube axis that may be called the center-of-deflection plane (Fig. 1). Each beam may be considered as originating from its center of deflection, and therefore each changes its angle of incidence at the mask as it scans. The trio of phosphor dots associated with each mask hole must not lie directly under each mask hole, but should be displaced radially in accordance with the angle of incidence of the beam.

The geometry of the positioning of the phosphor dots is shown in Fig. 4, where a plane defined by a row of mask holes and one of the deflection centers is illustrated. If an infinitely thin mask and a point source of electrons are assumed, it can be seen that the radial displacement of the phosphor dots, required for correct alignment, results in a phosphor dot array similar to

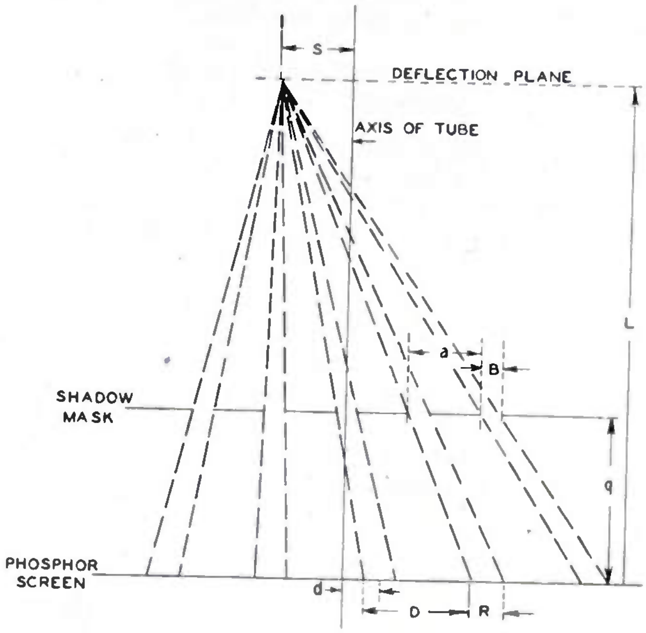

Fig. 4—A plane perpendicular to the shadow mask and passing through a row of holes in the y direction as defined in Fig. 2. The geometry for a point source is shown.

the hole array in the mask, but enlarged by the factor $L/(L-q)$, where L is the deflection-plane-to-phosphor-screen distance and q is the mask-to-screen distance. Two other identical phosphor-dot arrays result from the remaining two deflection centers, the three arrays nesting perfectly if the correct relation exists between L and q for a given spacing between mask holes. The implication for manufacturing is that, if a stencil can be made for depositing phosphor of one color with all the dots in the right place, then the proper shift of the stencil will result in accurate positioning of the second and third colors.

Various processes may be used to place the phosphor in the desired position on the phosphor plate. These processes include electrostatic printing, offset printing, photoprinting processes, silk screening, and settling. The latter two methods will be discussed in this and in another paper.[6]

III. Shadow-Mask Design

Regardless of the geometrical pattern of holes chosen for the shadow mask, the electron beams in scanning the mask will trace patterns on the phosphor screen that are similar to the mask pattern but slightly enlarged. In general, one gun is required for each color that is to be displayed on the phosphor screen. The design of the pattern of holes in the mask then consists of finding an arrangement of holes and a placement of beam deflection centers such that the patterns scanned by the beams on the phosphor screen will nest together without voids or overlap. One such pattern of holes in the shadow mask that would be satisfactory for any number of colors is a system of parallel slots with the deflection centers on a line normal to the slots. Another arrangement suitable for three colors is to place the holes in the mask at the corners of equilateral triangles (Fig. 2). The deflection centers also occur at the corners of an equilateral triangle. The orientation of this triangle, with respect to the mask, must be correct or voids and overlap will result; the correct orientation is illustrated in Fig. 1.

The triangular pattern was chosen for the shadow mask in experimental tubes primarily because of its mechanical properties. A thin piece of metal perforated with the pattern can be stretched taut on a frame and will resist the tension about equally in all directions. Each hole in the pattern is well supported and may be expected to maintain its position better than, for example, a shadow mask made up of a grill where support is confined to the ends of the strips in the grill.

Having chosen the triangular-array dot pattern for the shadow mask, one must determine the fineness of the pattern required to realize in the reproducer the full capabilities of the transmitting system. This may be done by experimentally relating the number of holes in the mask to the maximum possible horizontal and vertical resolutions due to the structure of the mask alone. An expression giving the number of holes in the mask may be found as follows: If the width divided by the height of the picture, or aspect ratio, is A, then a mask of height h has a width Ah. When the mask is oriented as in Fig. 2, and the distance between holes is a, there are $2h/a$ horizontal rows of holes with $Ah/a\sqrt{3}$ holes in each row. Every hole is associated with a trio of red, green, and blue dots, so that if one wishes N such trios in the phosphor screen,

$$N = \frac{2A}{\sqrt{3}}\left(\frac{h}{a}\right)^2.$$

Now, if R_H and R_V are the horizontal and vertical limiting resolutions expressed in lines per picture height, then

$$R_H = k_H\sqrt{N}; \qquad R_V = k_V\sqrt{N}$$

where k_H and k_V are the proportionality factors to be determined.

The subjective resolution of a kinescope employing a combination of a conventional scanning-line raster, together with triangular arrays of phosphor groups, has not yet been determined by a method analogous to that already employed for the scanning process alone.[10] Preliminary observations were made, however, with a high-definition-monochrome scanning raster on a shadow-mask screen assembly. Observations also were made of the resolution that can be seen when wedge patterns are placed in direct contact with a mask and viewed by transmission. The results for a number of observers were between $k_H=0.67$ to 0.82, and $k_V=0.72$ to 0.93. As an example of the use of these values, the shadow-mask color kinescopes, which were publicly demonstrated in December, 1950[9] had 195,000 mask holes, corresponding to $N=215{,}000$[11]; using the resolution factors above, a horizontal resolution between 325 and 400 lines and a vertical resolution between 350 and 450 lines is indicated.

Complete experiments, such as those in E. W. Engstrom's[12] study of scanning line structure visibility, can be performed to determine the dot structure needed for negligible visibility over a wide range of viewing distances. At normal viewing distances, the dot structure of the color kinescopes demonstrated in December, 1950, was unobjectionable.

For the triangular array of holes in the shadow mask, a hexagonally-shaped hole would allow the patterns traced out on the phosphor screen to cover 100 per cent of the area and nest perfectly. However, if the diameter of the hole is only a factor of two or three greater than the thickness of the metal, the shape of the hole obtained will depend largely on the method of fabrication. One of the best ways of making the holes, to be described later, is to etch them through the thin mask metal. Round holes of the size required are most easily made by this process and are quite satisfactory because it is possible for about 90 per cent of the area on the phosphor screen to be struck by the beam. Etched holes have a further advantage in that they may be made to have sloping sides so that the masks are extremely thin from an operational standpoint, i.e., mask holes as viewed from the deflection center do not appear to close up near the edge of the mask because of the thickness of the mask.

Another factor to be considered is a possible color dilution in the picture caused by secondary electrons from the mask striking the phosphor screen. Since the shadow-mask is at the same potential as the aluminized screen, high-velocity secondaries (reflected electrons) from the shadow-mask apertures may strike the phosphor screen. When one of the three guns is turned on and the direct beam strikes a phosphor of a single color, slight color dilution could result if these electrons, scattered from the shadow-mask, fall on phosphors of all three colors. Assuming equal efficiency for the phosphors, the effect would be a white dilution. If, as is true of currently available phosphors, the red is not as efficient as the other two, the dilution of the red would be slightly greater than that of the other colors because of the larger beam current needed in the red gun. The dilution caused by scattering is a minimum, as a result of the tapered holes. As the beam strikes the sharp edge of the taper, a smaller fraction of the high-velocity secondaries can be scattered through the hole than if the hole had straight sides like a punched hole. Using tubes made in this way, colorimetry measurements by W. F. Davidson of RCA Laboratories indicated the dilution is not an important factor, since it was only 3 per cent or less.

As a further step in the design of the mask, the preferred orientation of the mask array with respect to the horizontal scan must be determined. The shadow mask contains a regular array of holes through which the three beams pass to reach the phosphor screen. Because of the regularity of the array, the holes fall into rows in certain directions. If the scanning beams travel parallel to a row of holes, then the raster will be modulated normal to the direction of scan, unless the scanning line separation is an exact multiple of the separation between rows of holes. If the scan lines are not parallel to the rows of holes, the modulation will take place at some angle other than normal to the raster. Modulations of these types, if noticeable, may produce an effect called moiré.

Experimentally, it was found that noticeable moiré could be eliminated by scanning the mask in the x direction (Fig. 2), but that considerable moire resulted from scanning at an angle approaching either plus or minus 30 degrees from the x direction. The experiments were confirmed in a theoretical study by E. G. Ramberg of RCA Laboratories, in which the maximum deviation from the average transmission of the mask was determined as a function of the angle between the scanning lines and the optimum scanning direction. In the calculations a bell-shaped density distribution in the electron spot was assumed. For a picture with approximately 470 *visible* scanning lines, corresponding to present United States' 525-line black-and-white standards, with a scanning spot small enough to resolve these lines easily, and a shadow-mask of $N=215{,}000$, the calculations showed that intensity variations from the average (moiré) were negligible, being only 1 per cent when the mask was scanned in the x direction of Fig. 2. Within an angle of 2 degrees from this optimum direction, variations were still under ± 2 per cent, a tolerable value. Again checking observation, a 30 degree deviation, i.e., horizontal scanning along the y direction of Fig. 2, was shown to lead to intensity variations of ± 35 per cent from the average. For shadow masks with larger numbers of holes, of course, the allowable deviation from the favored direction is increased. The effects are also greatly decreased when the scanning spot size

[10] M. W. Baldwin, Jr., "The subjective sharpness of simulated television images," Proc. I.R.E., vol. 28, pp. 458–468; October, 1940.

[11] The actual number of holes in the mask is about 10 per cent less than those computed for a rectangular picture because of the rounded sides of the picture displayed.

[12] E. W. Engstrom, "A study of television image characteristics," Proc. I.R.E., vol. 21, pp. 1631–1651; December, 1933.

is increased to the point at which the scanning lines are just resolved.

Although of rare occurrence, another source of moiré is possible with certain types of signal. A strong intermittent signal of high video frequency can combine with the dot structure in the tube to form a "beat" pattern. When a sufficiently large number of mask holes is used, or with scanning spots which cover more than one hole, the effect is also of small magnitude.

IV. Design Geometry

Thus far, in discussing the geometry of the tube, each electron beam has been considered as originating from a point source at its center of deflection, which implies that the holes in the mask may be nearly equal in size to the phosphor dots. Since the electron beam at the center of deflection is far from a point, its diameter will require a reduced mask-hole size to obtain proper shadowing action at the phosphor screen. To study the effect, a simple approximation is to assume that electrons

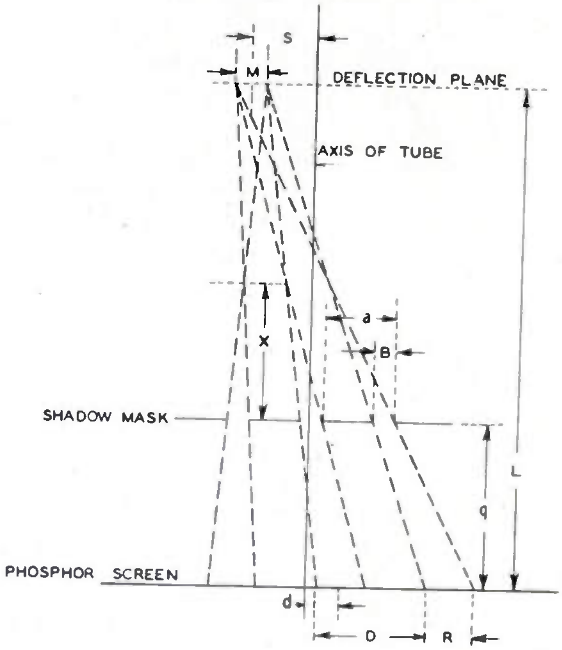

Fig. 5—A plane perpendicular to the shadow mask and passing through a row of holes in the y direction as defined in Fig. 2. The geometry for a source of diameter M is shown.

originate and travel in straight lines from a disc that represents the crossection of the beam at the center of deflection. Peripheral rays would then define the electron beam as it goes through the shadow mask to the phosphor screen.

Fig. 5 represents a plane through the axis of the tube and one of the deflection centers; the beam cross section disc diameter is M and the distance from its center to the axis is S. The geometry will be discussed for only one of the beams and its associated phosphor dots because the other two colors have identical geometry. Fig. 2 shows a view of the phosphor dots in the plane of the phosphor plate and indicates by the y axis the row of single phosphor dots considered.

The centers of adjacent phosphor dots making up a trio lie at the corners of an equilateral triangle. As shown in Fig. 5, let R be the phosphor dot diameter when the three-color array consists of tangent dots, D the minimum distance between dots of the same color, and d the distance from the center of a trio to the center of one of the dots of the trio. Then

$$D = R\sqrt{3} = 3d. \quad (1)$$

In Fig. 5, similar triangles may be used to get the relations

$$\frac{d}{q} = \frac{S}{(L-q)}; \quad \frac{D}{L} = \frac{a}{(L-q)} \quad (2)$$

where S is the separation of the axis of the electron beam from the tube axis in the deflection plane, a is the distance between holes in the mask, L is the deflection-plane-to-phosphor-screen distance, and q is the mask-to-phosphor-screen distance. By eliminating $(L-q)$ and using (1), the following relations may be found.

$$q = \frac{La}{3S}; \quad \frac{1}{D} = \frac{1}{a} - \frac{1}{3S}; \quad \frac{1}{R} = \sqrt{3}\left(\frac{1}{a} - \frac{1}{3S}\right). \quad (3)$$

Again from similar triangles,

$$\frac{\frac{B}{2}}{x} = \frac{\frac{M}{2}}{L-(q+x)}; \quad \frac{\frac{B}{2}}{x} = \frac{\frac{R}{2}}{q+x} \quad (4)$$

where x is the crossover point of the peripheral rays, B is the mask hole diameter, and M the diameter of the electron beam in the deflection plane. Eliminating x and using the above relations, the mask hole diameter B is related to the hole spacing a by

$$B = \frac{a}{3}\left(\sqrt{3} - \frac{M}{S}\right). \quad (5)$$

The ratio of the open area of the mask to the total area is an important variable in determining picture brightness. From the above relations this ratio in terms of M and S is

$$\frac{\text{Hole area}}{\text{Total area}} = \frac{\pi B^2}{2a^2\sqrt{3}} = \frac{\pi}{18\sqrt{3}}\left(\sqrt{3} - \frac{M}{S}\right)^2. \quad (6)$$

The open area becomes zero when $M = \sqrt{3}S$, or when the cross sections of the beams are tangent disks in the deflection plane. If the beams originate from point sources in the deflection plane, i.e., when $M = 0$, then the open area would be a maximum of $\pi/6\sqrt{3} = 30.3$ per cent.

V. Design for Maximum Efficiency of Operation

From (6) the beam striking the phosphor screen will be

$$I_S = I_m \frac{\pi}{18\sqrt{2}}\left(\sqrt{3} - \frac{M}{S}\right)^2, \quad (7)$$

where I_m is the current arriving at the mask. To evaluate

I_m, a simple approximation is to assume that the cross section of the beam in the deflection plane is a geometrical enlargement of the cross section in the final limiting aperture of the gun. As a result of this assumption, there is effectively an aperture of diameter M in the deflection plane with a beam centered in the aperture. Now assume that in this aperture there is a current density distribution

$$\rho = \rho_0 e^{-r^2/b^2} \tag{8}$$

where r is the radial distance from the center of the beam, ρ_0 is the current density on the beam axis, and b is the radius at which the current density has fallen to ρ_0/e.

The current arriving at the mask is then

$$I_m = 2\pi\rho_0 \int_0^{M/2} re^{-r^2/b^2}dr = \pi\rho_0 b^2[1 - e^{-M^2/4b^2}], \tag{9}$$

and the total current in the beam is

$$I_0 = \pi\rho_0 b^2. \tag{10}$$

The current to the phosphor screen from (7), (9), and (10) is then

$$I_S = I_0[1 - e^{-M^2/4b^2}]\frac{\pi}{18\sqrt{3}}\left(\sqrt{3} - \frac{M}{S}\right)^2. \tag{11}$$

An inspection of (11) shows that the larger S the more efficiently the beam is used, i.e., I_S/I_0 becomes larger. Also, from the equation it can be seen that the smaller b the larger I_S/I_0. However, since the total beam current I_0 increases with b (10), the optimum value of b for maximum beam current involves gun design that is considered beyond the scope of this discussion. Accordingly, conditions for maximum beam utilization and not maximum beam current will be investigated. Further inspection of (11) shows that $I_S/I_0=0$ for both $M=0$ and $M=\sqrt{3}S$, which indicates there is an optimum M. It is the purpose of the discussion to find this value of M.

From (11) the value of M for maximum efficiency of operation I_S/I_0 may be found by setting $d(I_S/I_0)/dM = 0$. The result is

$$\frac{S}{M} = \frac{1}{\sqrt{3}}\left[1 + \frac{4b^2}{M^2}(e^{M^2/4b^2} - 1)\right]. \tag{12}$$

Equation (12) enables the value of M for maximum I_S/I_0 to be calculated when any combination of S and b have been chosen. By expanding $e^{M^2/4b^2}$ in (12), it can be shown that S/M approaches $2/\sqrt{3}$ as b approaches infinity, i.e., when there is a uniform current density across the diameter M. In this case the open area of the mask is 7.5 per cent. To find M graphically from (12) for other values of b, it is convenient to plot S/b against S/M. This has been done in Fig. 6.

It is of interest to find the open area of the mask as well as how efficiently the beam is used, for the optimum values of M, when combinations of S and b have been chosen. Equation (7) for the open area of the mask I_S/I_m, and (11) for the efficiency in use of the beam I_S/I_0, have been plotted in Fig. 7. In the latter plot, the optimum value of M from (12) was used by eliminating b between (11) and (12).

In Fig. 7 it may be seen that the beam efficiency goes to zero for $S/M=2/\sqrt{3}=1.15$. The efficiency becomes zero because b becomes infinite when $S/M=2/\sqrt{3}$, and

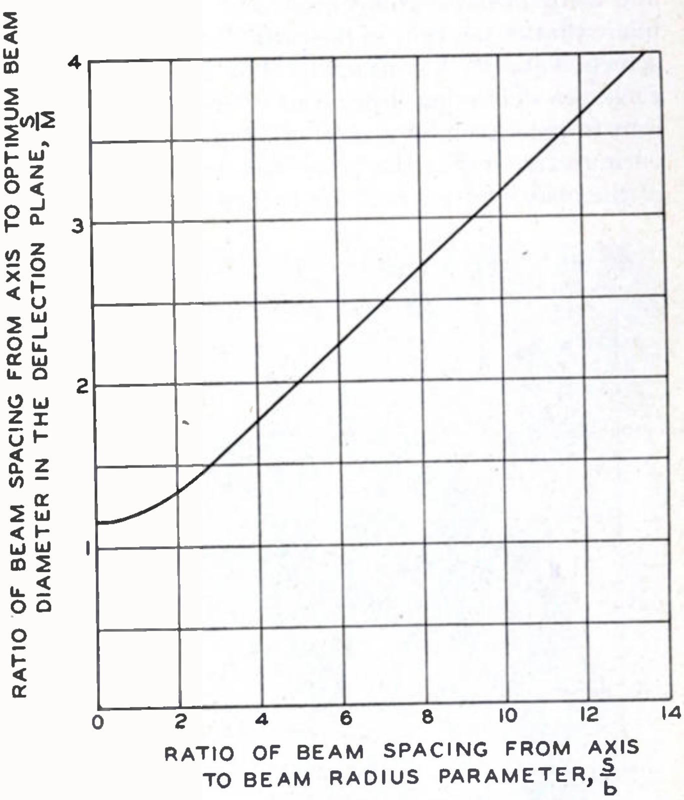

Fig. 6—Plot of the relation between b, S, and the corresponding optimum value of M. S is the distance between the axis and the center of each beam in the center-of-deflection plane, M is the diameter of the electron beam in the center-of-deflection plane, and b is the radius of the beam in that plane at which the current density in the beam has reduced to $1/e$ of its maximum value.

infinite b means that the beam current is infinite. If at $S/M=2/\sqrt{3}$ the current density were uniform over the area of the beam diameter M, but zero elsewhere, the efficiency in use of the beam would be simply the transmission of the mask at $S/M=2/\sqrt{3}$ or 7.5 per cent.

As an example of the way the curves in Fig. 6 and Fig. 7 may be used, suppose the current density distribution in the deflection plane is as postulated, and a typical gun is used that results in 80 per cent of the cathode current passing through a disc of 0.200-inch diameter in the deflection plane, then the b value may be found from (9) as follows:

$$0.8 = 1 - e^{-0.200^2/4b^2}; \qquad b = 0.0786 \text{ inch.}$$

Having found b, S may be chosen and the optimum value of M found. The 0.200-inch assumed for M in the example above was only for the calculation of b and is not necessarily the optimum value for the S to be chosen. Proceeding with the example, if $S=0.300$ inch, then $S/b=3.82$ and $S/M=1.72$ for optimum M, as found from the curve in Fig. 6. For the chosen value of S, then, $M=0.174$ inch. From Fig. 7 the proper transmission for the mask is 13.3 per cent, and the beam is used with an efficiency of 9 per cent.

The current to the phosphor screen for a black-and-white and for a three-gun color tube may be compared, using the typical gun data mentioned above. For black and white, a single gun is used, and the assumption was made that 80 per cent of the cathode current reaches the screen. Three such guns are used for the color tube, with each gun delivering 9 per cent of its own cathode current to the screen for a total of 27 per cent. The ratio of current arriving at the black-and-white screen to that of the color-phosphor screen is then $80/27 \approx 3$. Because

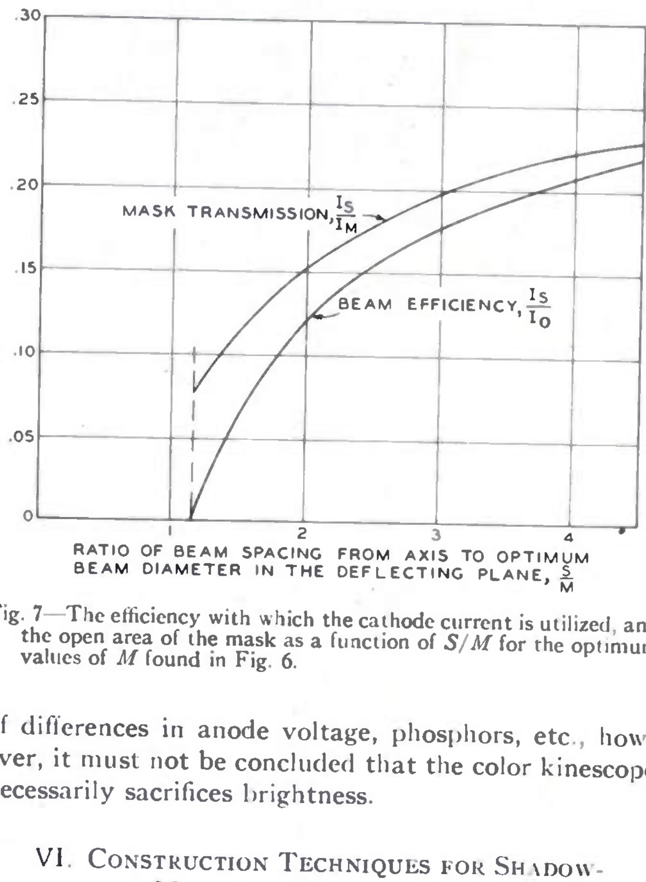

Fig. 7—The efficiency with which the cathode current is utilized, and the open area of the mask as a function of S/M for the optimum values of M found in Fig. 6.

of differences in anode voltage, phosphors, etc., however, it must not be concluded that the color kinescope necessarily sacrifices brightness.

VI. Construction Techniques for Shadow-Mask Screen Assemblies

A vital part of the complete tube is the screen assembly which consists of a shadow mask, spacer frame, and phosphor-dot screen. Experimental shadow masks were made with the appropriate array of holes in thin copper sheet by using photoengraving techniques. The master-dot pattern for photoengraving was made by contact printing a grill twice on the same photographic plate, the second time after the grill had been rotated through 60 degrees. A pattern of properly positioned diamond-shaped spots results from the shadowing effect of the opaque part of the grill. Subsequent printing steps, with shaped light sources and a spacer between the negative and the photographic plate to be exposed, make it possible to transform the diamond dots into approximately circularly shaped black dots.

Having obtained a suitable negative, the steps in producing the holes in the shadow mask are as follows: the thin copper is coated with engravers enamel, exposed through the negative with ultraviolet light, and developed. The exposed enamel is insoluble but the unexposed enamel washes away to uncover the metal underneath. Ferric-chloride etching solution is then applied to etch holes where the metal is exposed. Shadow masks with spacings between holes of from 0.018 inch to 0.030 inch were made for experimental tubes.

The shadow masks were mounted on cold-rolled steel frames designed to be of the right thickness to act also as a spacer between the shadow mask and the glass plate on which the phosphor-dot pattern was placed. Because the shadow-mask to phosphor-screen distance must be held uniform over the screen area, it was found necessary to stretch the shadow mask on the spacer frame. The required tension was produced by placing the mask between heated metal blocks while screws clamping it to the frame were still loose. The mask expands but the frame remains relatively cool so that when the clamps are tightened and the hot blocks removed, the mask quickly draws tight.

The glass plate for the phosphor-dot screen is fastened to the other side of the spacer frame. It was necessary to fix the position of the glass plate with respect to the shadow mask at room temperature and yet allow for differential expansion of the glass and metal during tube processing. The required result was obtained by an alignment hole on one end of the spacer frame and an alignment slot in line with the hole on the other end. Two corresponding holes were drilled in the glass and close fitting pins served to locate the glass accurately.

In order to position correctly the phosphor dots on the glass plate, each beam may be considered as originating from its center of deflection with electrons traveling in straight lines from the deflection center to the mask. Using an apparatus that has been called the "lighthouse," a point-light source placed at the center of deflection of the beams was used to simulate the electron beam. A photographic plate placed in the plane of the phosphor screen was used then to record the correct position of the phosphor dot of one color under every shadow-mask hole. It was not necessary to make an exposure from the remaining two deflection centers to locate the other two-color dot arrays since, as shown above, the patterns would be the same, except for a shift of position. A reference for making the shift, as well as locating the pattern on the spacer frame, was obtained by recording the hole and slot positions on the photographic plate at the time the dot pattern was exposed.

With the photographic plate it was possible to make a settling mask of thin copper by again using photoengraving techniques. A single mask that was shifted after each color was deposited was used in settling early experimental screens, as were three masks made from plates exposed from all three beam positions. Settling was done with the masks in contact with the glass plate. The masks were then removed before pouring off

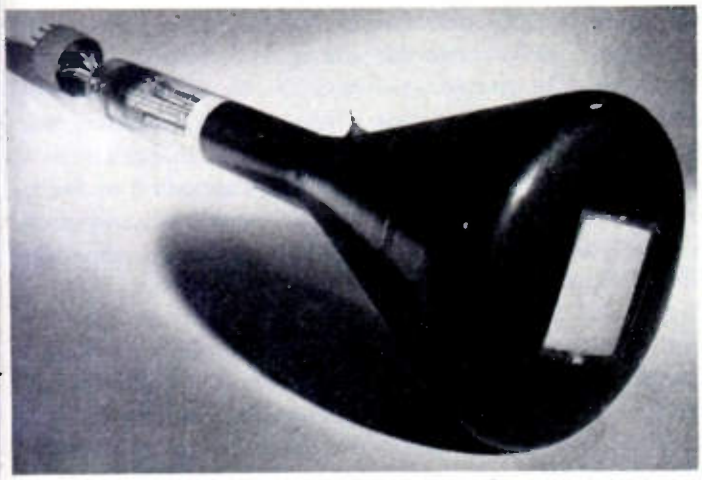

Fig. 8—Experimental shadow-mask color tube containing a test sample of dot screen.

the settling solution. Later, phosphor screens printed by the silk-screen process were also made.[6]

The three phosphors used were green willemite (Zn_2SiO_4:Mn), blue silicate [$CaMg(SiO_3)_2$:Ti], and red-orange borate ($2CdO \cdot B_2O_3$:Mn). After all three colors had been laid down, the alignment was checked by

Fig. 9—Unassembled parts for an experimental shadow-mask color kinescope.

assembling the phosphor plate on the spacer frame with the mask in position and by illuminating the phosphor screen from one of the centers of deflection. Diffusion of light in the phosphor dots makes it easy to observe with a microscope the individual beams, as defined by the holes in the shadow mask. The phosphor screen was then disassembled and aluminized, both to increase the light output of the screen and to insure a field-free region between the shadow mask and the phosphor screen.

VII. Experimental Shadow-Mask Color Tubes

Experimental tubes were made by mounting the assemblies already described in glass kinescope bulbs having 2-inch necks to provide room for the three guns. One of the first such tubes for testing a small portion of a full size screen is shown in Fig. 8. The screen assembly in this tube, 3 inches × 3 inches in size, has a mask with spacings between holes of 0.030 inch for a total of 11,500

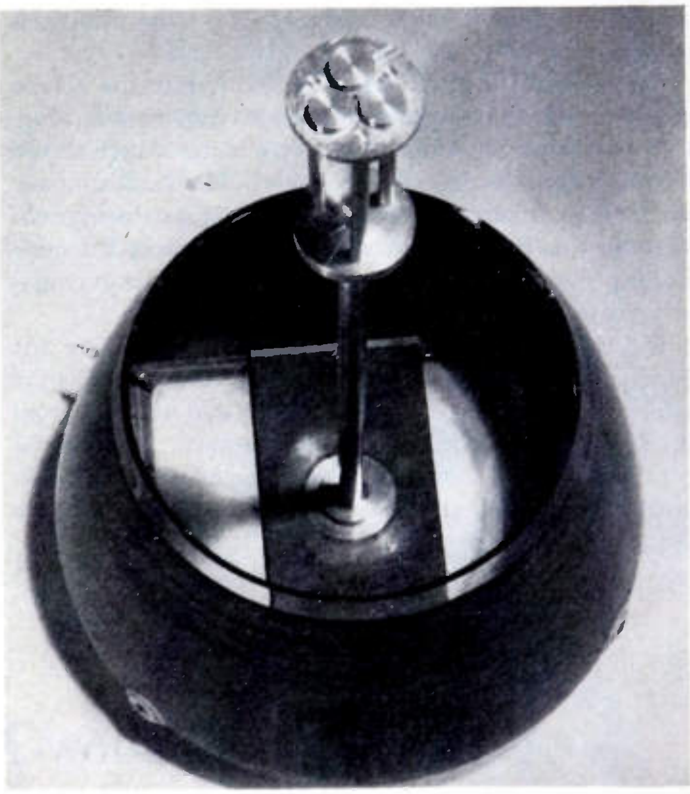

Fig. 10—Jig for locating the electron guns with respect to the phosphor-screen assembly in an experimental shadow-mask color kinescope.

holes. The three guns mounted in the neck all point to a spot on the mask with a convergence angle of about 2 degrees.

In operating the tube it was found necessary, because of slight gun misalignment, to use very small permanent magnets mounted on the outside of the neck adjacent to the individual guns in order to bring the spots accurately together. A correction was also required for the earth's field to keep the beams from being bent away from their respective color centers. If the tube was set up for good color fields, a rotation of the tube in the horizontal plane would cause dilution of the pure fields. One remedy was to place Helmholtz coils around the tube and adjust them so that the earth's field was neutralized. Since the coils required readjustment when the tube was rotated, however, a Mu-metal shield was used to eliminate the earth's field inside the tube, as well as any stray fields that might be present.

Even with all magnetic fields in the tube eliminated, the beam did not accurately go through the color centers because of a misalignment of the guns with respect to the phosphor-screen assembly. It was possible, however, to place a permanent magnet in such a position that its effect was to produce pure color fields. If, at the same time, a Mu-metal shield was used, then rotation of the tube and the permanent magnet in the earth's field produced no change in the pure color fields. Color pictures shown on the tube were bright with the colors cleanly separated. Even though this early tube was crude and contained only a small portion of a full screen, experiments with it showed that the principles of operation and construction were sound.

Tubes with finer masks were built, but the screen size was limited because of glass-tube construction. Fig. 9 shows the parts for a tube with a 4 inch ×6 inch screen having a hole spacing of 0.018 inch in the shadow mask, the total number of holes being 85,500. The convergence angle in this tube was reduced to a little over 1 degree. Color pictures obtained showed a marked improvement in texture.

Fig. 10 shows the jig arrangement for locating the guns. The fixture protruding from the tube contains the information on the proper orientation and distance from the mask for the guns. By placing the glass cone and the gun press in position, the correct location of the gun press was spotted, and then the jig was removed before the glass seals were made.

Improved tubes, making use of the techniques and principles herein discussed, are described elsewhere.[5]

VIII. Conclusion

It has been demonstrated experimentally that a single kinescope can be made to present color pictures of good color purity when the principle of electron shadowing is used in the construction of the viewing screen. Although classed as a "structure" screen, its construction has proven to be less difficult than some. Its successful fabrication depends, in a large measure, on techniques whereby the screen and its mask are handled as a whole, as contrasted to the construction and assembly of individual elements. Of equal importance is the fact that it was found practical to reduce the angle between guns to the point where the deflection of all three beams could be accomplished with one deflection yoke instead of three. The result of this work has been the demonstration of a direct-view color kinescope, with good resolution capabilities and a nondirectional viewing screen of large size and very good color separation.

IX. Acknowledgment

Sincere thanks are due to the many people mentioned in the first paper of this series for their valuable contributions, particularly F. H. Nicoll who designed the electron guns that were used in experimental tubes, L. E. Flory and his group for their co-operation in testing sample tubes, and E. W. Herold who co-ordinated the work being reported in this series of papers, and who has been very helpful and given much time to the reading of this manuscript.

A One-Gun Shadow-Mask Color Kinescope*

R. R. LAW†, SENIOR MEMBER, IRE

***Summary*—A direct-view shadow-mask three-color kinescope employing a single electron gun is described. Color selection in this tube is accomplished by controlling the direction of approach of a single electron beam to a direction-of-approach sensitive color screen. For sequential presentation the beam is shared in time sequence between the three primary colors. For simultaneous presentation the beam is shared continuously among the three primary colors. The new problems presented by the one-gun shadow-mask color kinescope arise from the special requirements placed on the electron optical system, from the need for deflecting the beam into different color positions, and in the case of sequential presentation, from the necessity for blanking-off the beam as it is switched from one color position to the next. Practical solutions to these and other problems are presented.**

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Introduction

This one-gun shadow-mask color kinescope is an outgrowth of the RCA work on all-electronic color television. It makes use of a single electron gun and a direction-of-approach sensitive color screen which emits light of any combination of the three primary colors, depending upon the direction of arrival of the impinging electrons. Because an electron beam has very little inertia and its direction of approach can readily be changed, a single beam from a single electron gun can be shared in time sequence between the three primary colors to reproduce a color-television picture from any color-television signal capable of sequential[1] presenta-

[1] Report of the Senate Advisory Committee on Color Television, "The present status of color television," Proc. I.R.E., vol. 38, pp. 980–1002; September, 1950.

tion; alternatively, by the use of appropriate color-signal circuits, the single beam can be shared continuously among the three primary colors to achieve simultaneous reproduction from signals which so permit. In each case the brightness signal is applied to the electron gun control grid, but the method of color selection depends upon the mode of presentation. In the case of field-sequential or line-sequential presentation, step-wise switching from color to color is desired. In the case of dot-sequential presentation, sine-wave switching by circular deflection with uniform angular velocity is preferred. In the case of simultaneous presentation, the color signals determining hue and saturation are applied to the color-selection deflection system to vary the direction of approach continuously.

In one successful application,[2] the direction of approach of a single electron beam is changed from picture element to picture element as it is made to scan a screen which employs a multiplicity of color dots and an apertured shadow-mask[3] registered therewith. Thus the electrons approaching from a particular direction can strike only a single color phosphor no matter which part of the raster is being scanned. In this manner it is possible to reproduce a color-television signal[4] in which a line on the raster consists of dots of the three primary colors arranged from left to right in the sequence red, blue, and green.

The concept of the one-gun tube is understood as follows: Electrons may be "colored-tagged" as they leave the electron gun by imparting to them a desired direction. This is possible because in an axially symmetric electron optical system, within the limits imposed by aberrations, electrons emerging from a common source-point at the gun may be reconverged to a common image point at the screen, carrying intact their original direction-of-approach "color tag." Control of current to represent brightness is accomplished in the conventional manner.

The operation of the one-gun color kinescope is different from the operation of the three-gun color kinescope[3] in that the beam from the single gun may be deflected away from the axis by any amount and in any direction so that it will return to the axis with any desired direction and angle of approach. In case a dot-sequential presentation is employed, the beam is deflected so that, in effect, it occupies in time sequence the three positions of the three guns in the three-gun kinescope. If a simultaneous presentation is employed, the direction of deflection is changed continuously to vary the angle of approach in accord with the hue and saturation information. The problems unique to the one-gun kinescope arise in part from the differences in electron optics, the need for deflecting the beam into the different color positions, and, in the case of sequential presentation, the necessity for blanking off the beam as it is switched from one color position to the next.

First, the electron optics of the one-gun color kinescope are analyzed in regard to both the basic optical principles and the fundamental limitations imposed by space charge. Second, the problem of "sampling", as used in a sequential presentation, is examined with particular regard to the color purity to be expected when the beam is keyed on and off in synchronism with the changes in direction of approach to provide automatic sampling. Third, these findings are compared with the performance of practical tubes working in accord with these principles.

Electron Optics of the One-Gun Color Kinescope

As is well known, in an axially symmetric electron optical system, in the absence of space charge and within the limits imposed by aberrations, electrons emerging from a common source point may be reconverged to a common image point.[5] Thus, in the electron

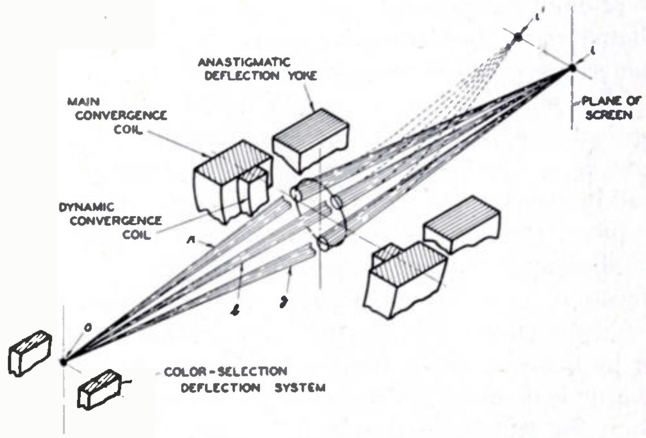

Fig. 1—Electron optics of the one-gun color kinescope.

optical system of Fig. 1 the three separate beam pencils *r*, *b*, and *g* emerge from a common object point *o* on the axis of symmetry. They may be reconverged to a common image point *i*, also on the axis of symmetry, with direction-of-approach angles so that they may excite the red, blue, or green phosphors of a direction-of-approach sensitive color screen. Furthermore, within the same basic limitations, and if the current through the dynamic convergence coil is adjusted to compensate for the fact that less convergence is required as the beam is deflected from the center, the three-pencil beam will still reconverge at a common image point *i'* on a flat screen even after it has been caused to trace out a raster by the anastigmatic deflection yoke. When an individual beam pencil is traced through the system, it will be found that the direction of approach of the beam

[2] RCA Laboratories Division "General description of receivers for the dot-sequential color television system which employ direct-view tri-color kinescopes," *RCA Rev.*, vol. 11, pp. 228–232; June 1950.

[3] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

[4] RCA Laboratories Division, "A 6-mc compatible high-definition color television system," *RCA Rev.*, vol. 10, pp. 504–524; December, 1949.

[5] Bruche und Scherzer, "Geometrische Electronoptik," Julius Springer, Berlin; 1934.

pencil at the image is related to the direction of emergence of the beam pencil from the object. Thus, a single beam pencil may be used to give any one of the desired primary colors by deflecting the beam pencil into any one of the positions r, b, or g. It should be emphasized that the functions of the color-selection deflection system and the anastigmatic deflection yoke are quite independent: The color-selection deflection system serves to "color-tag" the electrons as they leave the gun; the anastigmatic deflection yoke serves to deflect the beam over the raster. As a result, the "color-tagged"

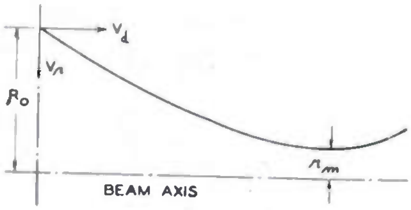

Fig. 2—Diagram of a half-longitudinal section of a beam of circular cross section beyond an electron lens.

beam may be focused on the screen and deflected over a raster in much the same manner as the beam in a conventional cathode-ray tube, except for the greater diameter of the composite beam which necessitates a wider aperture electron optical system.

The requirements on the elements of this electron optical system will become less stringent as the beam pencils are crowded closer and closer together. But it will be seen from Fig. 1 that as the angle-of-approach is reduced the individual beam pencils must be made smaller and smaller if they are not to overlap. The question now arises whether space-charge mutual-repulsion effects will permit the individual beam pencils to be made as small as desired. This problem of space charge is of much greater concern for the one-gun tube than for the three-gun tube because of the different current requirements. When the one-gun color kinescope is used to reproduce a color-television picture sequentially,[2] the single electron beam is shared in time sequence between the three primary colors and blanked off as it is switched from one color position to the next. As a result, the average beam current to any particular color phosphor can only be a small fraction of the peak current capability of the single electron gun. When allowance is made for this low duty factor and the loss of electrons on the shadow-mask, peak beam currents of several milliamperes may be required to give a picture of adequate brightness.

A rigorous analysis of space-charge effects is beyond the scope of this presentation, but a simple approximate analysis suffices to give a satisfactory indication of the point where space-charge effects may become important. In terms of the geometry of Fig. 2, by making certain simplifying assumptions, Thompson and Headrick[6] have shown that for a beam of circular cross section the minimum radius is given by

$$r_m = R_0 \epsilon^{-(V_d m / 4eI) V_r^2} \qquad (1)$$

where

R_0 = initial radius of outer beam surface, cm,
r_m = minimum radius of beam, cm,
V_r = initial inward component of velocity of outer electrons, cm/sec,
V_d = axial component of velocity of the beam, cm/sec,
I = electron beam current, esu,
e = electronic charge, esu,
m = electron, mass, grams.

The following assumptions may be made in developing this relationship: First, the radial component of the velocity of the electrons as they leave the electron lens is assumed to be proportional to their distance from the beam axis; second, the beam is assumed to be a uniform cylinder of electrons moving in a field-free space, except for the field due to the electron-charge density of the beam; and third, the axial velocity of the electrons in the beam is assumed to be constant. In practice the deviations from the assumptions will tend to increase the size of the focused spot. For the purpose of this analysis, this relation will be construed as setting a lower limit to the beam size obtainable in a high vacuum rather than being a measure of the spot size.

In a practical design of the one-gun shadow-mask color kinescope, the lens-to-screen distance is 14 inches, the angle of approach is 1.2 degrees, and the second-anode voltage is 18 kv.[2] In this case, a simple computation based on the geometry of Fig. 1 will show that if the beams are not to overlap the diameter of the individual beam pencils in the plane of the converging lens cannot exceed 0.52 inch. Translated in terms of the geometry of Fig. 2, R_0 cannot be greater than 0.26 inch. Furthermore, if the converging lens is adjusted so that the beam comes to a point focus in the absence of space charge corresponding to low levels of beam current, V_r cannot be greater than 0.0187 V_d. Under these specific conditions, the variation of r_m with I as computed by (1) is shown in the following Table I.

TABLE I

I (milliamperes)	r_m (inches)
15	0.035
9	0.009
6	0.002

The practical tube for which the above calculations were made gives a picture approximately 9 inches high.[2] For 500-line vertical resolution the spot should not be more than 0.009 inch radius. If space-charge effects are to be unimportant, r_m as computed above, must certainly be less than 0.009 inch. If the point where space-charge effects limit the performance is arbitrarily taken to be that point were r_m equals 0.009 inch, Table I shows that the beam current should not exceed 9 milliamperes.

[6] B. J. Thompson and L. B. Headrick, "Space charge limitations on the focus of electron beams," Proc. I.R.E., vol. 28, pp. 318–324; July, 1940.

By a similar calculation one may determine the limiting beam current corresponding to other beam-approach angles. The results of these calculations are shown in the following Table II. As is to be expected, the limiting beam current varies as the square of the beam-approach angle.

TABLE II

Maximum beam current that can be focused in spot (milliamperes)	Beam-approach angle (degrees)
9	1.2
3	0.7
1	0.4

In the preceding calculation for a tube with a lens-to-screen distance of 14 inches and an angle-of-approach of 1.2 degrees, we saw that the individual beam pencils might approach one-half inch in diameter at the plane of the converging lens. By similar reasoning, it is easily shown that the composite beam may exceed 1 inch in diameter. It has been possible to provide an electron optical system which will handle this relatively large diameter beam. As already pointed out in connection with Fig. 1, this system includes a large aperture primary converging lens, an auxiliary dynamic convergence lens to compensate for the fact that less convergence is required as the beam is deflected from the center, and an anastigmatic deflection system. Some of these problems have been encountered in the design of projection-tube systems. It is known that a large

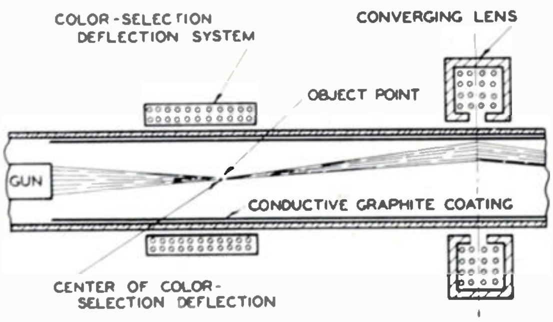

Fig. 3—Electron optics of a developmental one-gun color kinescope.

aberration-free aperture can be obtained with a sufficiently large magnetic lens located outside the tube envelope.[7] When such a primary magnetic converging lens is used, dynamic convergence is conveniently accomplished by an auxiliary coil inside the main lens. The solution of dynamic convergence and anastigmatic deflection problems are similar in both the three-gun and one-gun color kinescopes, and are discussed in detail elsewhere.[8]

An electron source which meets the requirements schematically indicated in Fig. 1 was suggested and developed by D.A. Jenny of RCA Laboratories. As indicated in Fig. 3, it includes a standard 5TP4 projection-type electron gun, a color-selection deflection system which serves to deflect the beam into the successive color positions, and a converging lens which bends the beam pencils back toward the axis to form the image. The voltages applied to the electrodes of the gun are

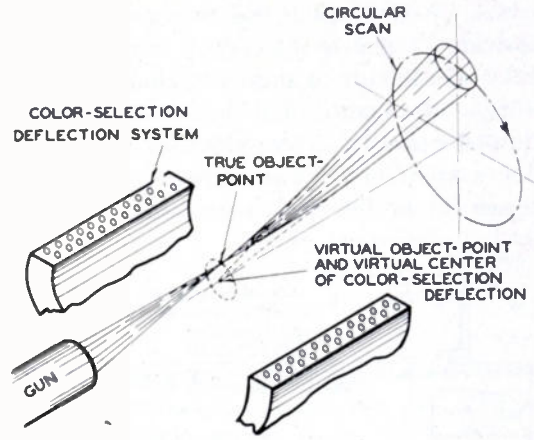

Fig. 4—Electron trajectories in the region of the color-selection deflection system.

so adjusted that the beam comes to a focus at the object point. The electron optical requirements are met when the longitudinal position of the object point is so adjusted that the virtual object point coincides with the virtual center of deflection of the color-selection deflection system. This relationship is shown in greater detail in Fig. 4. In the field-free region beyond the deflection system the electrons are assumed to travel in straight lines. Insofar as the converging lens is concerned, the electrons appear to have originated from a virtual source at the apex of the dashed-outline cone formed by tracing the straight-line trajectories back into the deflection system. Because of the finite length of the deflection system, the virtual center of deflection lies somewhat ahead of the geometric center of the color-selection deflection system. Also, because the beam is bent somewhat before it reaches the virtual center of deflection, the true object point traces out a circle around the virtual object point.

Such a system was used with the one-gun color kinescope in the March, 1950 demonstrations.[2] The standard 5TP4 projection-type electron gun was used to form the object point. This gun, itself, is unnecessarily long for this application. Also, as the first-anode voltage is lowered to move the object point in close to the gun, less than normal beam current for the gun is obtained. By placing an auxiliary magnetic-type electron lens over the electrostatic electron lens formed by the first-to-second-anode transition, as shown in Fig. 5, it is possible to raise the first-anode voltage and increase the beam current several fold. This arrangement was suggested by F. H. Nicoll of RCA Laboratories. To reduce the length of the tube further, the simplified shortened electron gun, shown in Fig. 6, was developed.

[7] R. R. Law, "High current electron gun for projection kinescopes," Proc. I.R.E., vol. 25, pp. 954–976; August, 1937.
[8] A. W. Friend, "Deflection and convergence in color kinescopes." Proc. I.R.E., pp. 1249–1263; this issue.

The electron optics of this arrangement are of course similar to those encountered in the system of Fig. 5. The details of the performance of these several practical designs are reported in a later section.

Color Selection in the One-Gun Color Kinescope

Color selection in the one-gun color kinescope is accomplished by deflecting the beam into appropriate color positions. Because the energy stored in a magnetic field makes it difficult to suddenly change the direction of deflection, the choice of magnetic deflection or electrostatic deflection for color selection will depend upon the color system under consideration. In the case of field-sequential or line-sequential color systems, step-

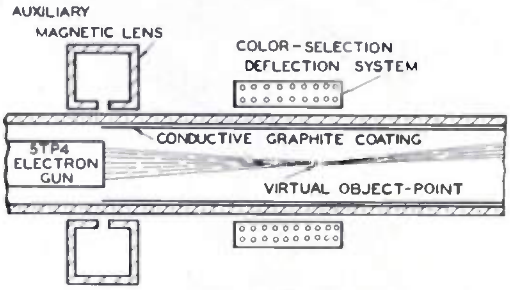

Fig. 5—Developmental electron gun with auxiliary magnetic lens.

wise switching from color to color is desired. This problem is no more difficult than the raster scan, and it should be possible to accomplish the switch by magnetic means during the beam-retrace time. If the direction of approach is to be changed from picture element to picture element to provide a dot-sequential presentation of the color signal, magnetic-deflection color selection with sine-wave switching by circular deflection with uniform angular velocity is preferred since it leads to considerable circuit simplification. In the case of simultaneous presentation of the three primary colors with the brightness signal applied to the gun-control

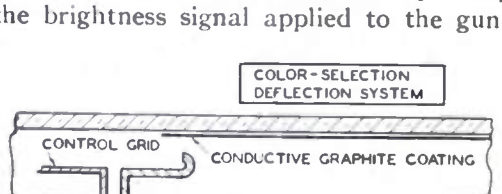

Fig. 6—Developmental simplified short electron gun.

grid and the color signals determining hue and saturation applied to the color-selection system, the ability to change continuously is desired. The rate of change of direction of approach required will be determined by the bandwidth of the hue and saturation information. Ordinarily, this bandwidth will be great enough to make electrostatic color-selection deflection desirable.

In the receiver previously described,[2] dot-sequential presentation of the color signal is employed and color selection is done magnetically. The required circular deflection is provided by a small deflection yoke having two sets of coils which are fed with quadrature currents at color-subcarrier frequency to produce a rotating field. Service adjustment of color phasing is provided by mechanical positioning of this yoke. The amplitude of the circular deflection is adjusted to produce the proper convergence angle as required by the mask and phosphor-dot screen. The duty factor of the beam is controlled by a signal having a frequency three times the color-subcarrier frequency which is injected into the kinescope cathode circuit. The amplitude and phase of this signal are determined by the alignment of a filter circuit which utilizes the third harmonic of the circular-deflection driver tube.

The performance of the one-gun color kinescope under the above operating conditions is well illustrated by analyzing the case of a large-area single primary color at various relative brightness levels. The essential features of such an analysis are illustrated in Figs. 7, 8,

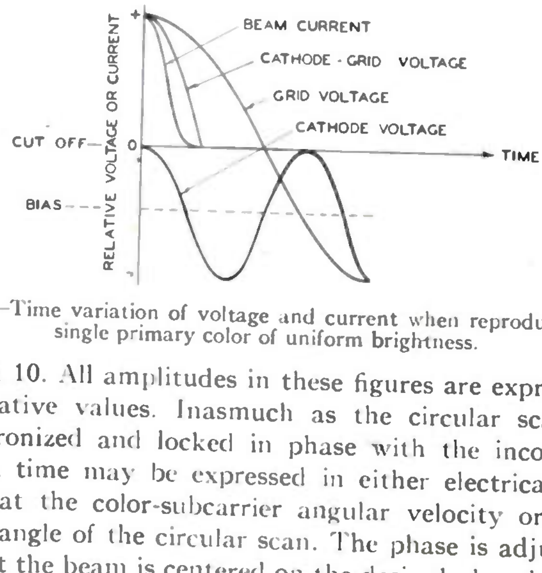

Fig. 7—Time variation of voltage and current when reproducing a single primary color of uniform brightness.

9, and 10. All amplitudes in these figures are expressed as relative values. Inasmuch as the circular scan is synchronized and locked in phase with the incoming signal, time may be expressed in either electrical degrees at the color-subcarrier angular velocity or azimuth angle of the circular scan. The phase is adjusted so that the beam is centered on the desired phosphor at the moment the desired single-primary-color signal is a maximum. In the present analysis time arbitrarily starts at this instant.

Proceeding now to the detailed analysis, the voltage arriving at the grid is a sine wave of fundamental frequency whose amplitude is proportional to the brightness of the desired monochrome area. In keeping with the requirement that the current must be zero with zero signal, this sine wave is plotted in Fig. 7 about a voltage axis corresponding to the cutoff voltage. It is indicated by the curve labeled "grid voltage." As already mentioned, the duration of the beam pulse is controlled by a signal which is injected into the kinescope cathode circuit, and which has a frequency three times the color-subcarrier frequency. This signal is represented in Fig. 7 by the curve labeled "cathode voltage," and is plotted about a voltage axis marked "bias voltage" equal to the peak third-harmonic voltage amplitude. The algebraic sum of these voltages is the resultant signal between the cathode and the grid. It is represented in Fig. 7 by the curve labeled "cathode-grid voltage." In the particular case portrayed, the third harmonic amplitude is one-half the fundamental am-

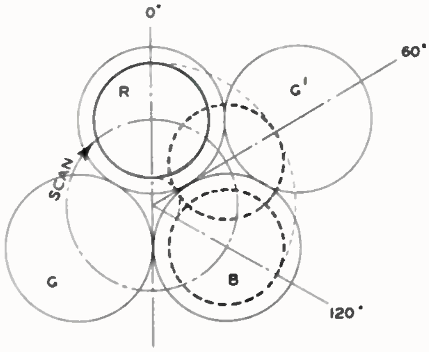

Fig. 8—Diagram of beam positions assumed during circular color scan.

plitude. When the kinescope is operated in the space-charge-limited region of its characteristic, the beam current is very nearly proportional to the five-halves power of the cathode-grid voltage. It is represented here by the curve labeled "beam current."

The shadow-mask screen is described elsewhere.[3] Two features are of importance in the present analysis: First, the phosphor dots of contrasting colors occupy adjacent tangent circles; second, to provide a factor of safety for errors in mechanical alignment, the openings in the shadow mask are of such size that the electron beam transmitted by each opening arrives at the phosphor plate in a spot smaller than the individual phosphor dots. Because of the circular deflection of the beam, the electron spot scans the trio of contrasting

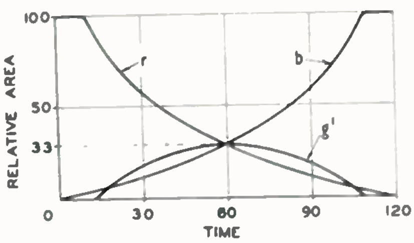

Fig. 9—Time variation of area of each color bombarded by beam with uniform angular-velocity circular scan.

phosphor dots with a uniform circular motion, as shown in Fig. 8. The position of the hole in the mask, the mask to phosphor-dot-screen distance, and the convergence angle are so related that the spot traverses a circular path from the center of the desired phosphor dot through the centers of each of the undesired phosphor dots and returns to the center of the desired phosphor dot. Thus in Fig. 8, at zero electrical degrees or zero angle of scan, it is centered on the desired phosphor dot *R*. At 60 degrees it impinges equally on the desired phosphor dot *R*, and the undesired phosphor dots *G'* and *B*. *G'* will be recognized as one of the phosphor dots of an adjacent trio. In a similar manner, the remainder of the cycle may be traced out in detail. In the following analysis, the relative area of the spot on each of the phosphor dots has been computed for the case where the diameter of the electron spot is 80 per cent of the diameter of the phosphor dots. The results of this analysis are indicated in Fig. 9. The relative areas at various angles of scan are shown by the curves *r*, *g'*, and *b*. The analysis has been carried out for the remainder of the scanning cycle, but for reason of simplicity it is not reproduced here.

The instantaneous relative excitation of the several phosphor dots is now, of course, the product of the relative instantaneous values of current and area. The variation of instantaneous excitation with scanning angle for one-third cycle is shown by the curves *R*, *G'*, and *B* in Fig. 10. Finally, the relative light output of each color is numerically equal to the relative area under each of these curves. When the complete cycle

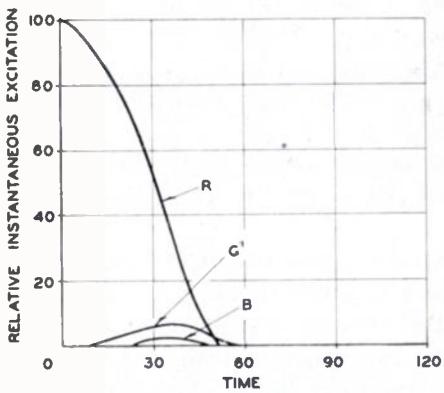

Fig. 10—Time variation of relative instantaneous excitation of each color due to single primary-color signal.

is traced out in this manner, it can be shown that light of the two undesired colors is produced in equal small quantities. Since an equal small portion of the desired color may be combined with the undesired colors to produce white, the net contaminating effect may be expressed as a slight dilution. For the purpose of this analysis, dilution is arbitrarily defined as

$$\text{Dilution} = \frac{\sum \text{Light output of undesired colors}}{\text{Light output of desired color}}.$$

The foregoing analysis gives the dilution and the light output for one particular operating point. During modulation corresponding to changes in the brightness level of the monochrome area, the signal on the grid changes but the third-harmonic signal applied to the cathode does not. By repeating the analysis using a fixed third-harmonic signal with various relative amplitudes of the fundamental, it is possible to deduce a transfer characteristic and the dilution at corresponding points. The effect of using other relative values of the third harmonic may be computed in the same manner.

The results of these computations are shown in Fig. 11. As is to be expected, the dilution decreases as the relative amplitude of the third harmonic is increased. Of particular interest from a practical standpoint is the fact that dilution can be substantially eliminated by the addition of a third-harmonic component. For example, the introduction of a 20-per cent relative amplitude third harmonic reduces the dilution to about 6 per cent.

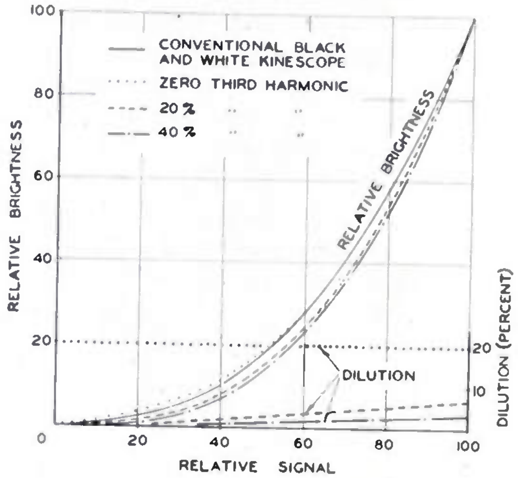

Fig. 11—Kinescope transfer characteristic and dilution for various values of third harmonic.

Also, the relative transfer characteristic is observed to change very little as the third-harmonic content is changed.

To translate relative brightness into true brightness, it is necessary to know the duty factor, i.e., the ratio of average beam current to peak beam current. Inasmuch as high-light brightness is measured in the "whites" of the picture, the duty factor of greatest interest is that for a white field. The duty factor for a white field is readily determined from Fig. 7; it is simply the ratio of the area under the desired beam-current-versus-time curve to the area possible if the beam current remains at peak amplitude throughout the cycle. Fig. 12 shows the results of such a graphical analysis for various third-harmonic-amplitude ratios. To better show the relation of dilution to duty factor, the dilution data of Fig. 11 are replotted in Fig. 12, with relative third harmonic as the independent variable. It will be observed that the introduction of a 20-per cent relative third harmonic which reduces the dilution by a factor of more than three reduces the duty factor, and consequently the brightness, by less than one-third.

It should be pointed out that the foregoing questions of dilution and duty factor do not arise when appropriate means of simultaneous reproduction are employed. In one method of simultaneous presentation, proposed by G. C. Sziklai of RCA Laboratories, the rest position of the beam is on the axis of the electron optical system. In the rest position the beam strikes the three phosphor dots equally to produce white; as the current is varied, a black-and-white picture is reproduced so long as the beam remains on the axis. Color information is imparted by deflecting the beam from the axis to vary the direction of approach: the direction of deflection in azimuth serves to determine the hue of the color, and the amplitude of deflection serves to determine the saturation of the color.

This method can take advantage of the principle of mixed highs since the relative beam direction need only be changed as color changes are required. Furthermore, because of the symmetry of the three phosphor dots with respect to both the electron optical axis and the hole in the shadow mask, off-axis excursions of the beam are large only for high saturation. On this account, less accurate convergence may be tolerated. It should be emphasized, however, that stringent requirements are made upon the accuracy of the shadow-mask screen assembly in any system where hue and saturation are directly dependent on direction of approach. Thus, deviations in the shape and uniformity of the phosphor dots and in alignment of the shadow-mask holes with respect to the phosphor dots may lead to less faithful color rendition.

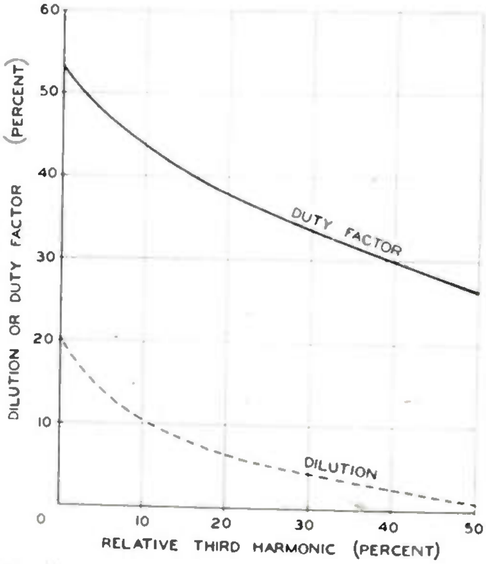

Fig. 12—Duty-factor and dilution as a function of relative amplitude of third harmonic.

Performance of Practical One-Gun Shadow-Mask Color Kinescope

As already indicated, to move the object point in close to the gun the first anode of the standard 5TP4 projection-type electron gun, used in the tube for the March, 1950 demonstrations,[2] was operated with a lower than normal first-anode potential. Instead of the normal 6 kv, it was necessary to operate the first anode at about 3 kv. Under this condition, tests indicate that the peak beam current is less than 0.5 milliampere.

Although a detailed correlation of peak beam current and observed high-light brightness involves details of colorimetry beyond the scope of this paper, an approximate analysis is of interest because it indicates the influence of the several operational factors. The details of colorimetry may be incorporated in an assumed value for the "white" visual output in lumens per watt. For the present calculation, assume that the tube is operated under the following conditions:

"White" visual output	7 lumens/watt
Shadow-mask transmission factor[3]	0.20
Relative third-harmonic sampling voltage	0.20
Duty-factor (from Fig. 12)	0.40
Peak beam current	0.5 ma
Anode voltage	18,000 volts
Picture size	9×12 inches.

Under these conditions, a high-light brightness of 7 foot-lamberts is to be expected. When allowance is made for the 0.6 transmissivity of the "minus-yellow" filter employed for color correction of the phosphors in use at that time,[9] the high-light brightness is reduced to 4 foot-lamberts. This checks the observed value.[10]

With the improved phosphors presently available, no filter is required. Also, as already indicated, the performance of the tube is greatly improved by adding an auxiliary magnetic-type electron lens over the electrostatic lens, as shown in Fig. 5. By this means it is possible to increase the useful beam current several fold. Tests of this by V. D. Landon and associates of RCA Laboratories indicate that peak beam currents of 1.5 milliamperes may be used. Under these conditions pictures with good fidelity and color rendition and with 20 foot-lamberts high-light brightness are obtained. Substantially the same result is obtained with the simplified shortened electron gun of Fig. 6. This gun makes possible an improved tube, for not only is the first-anode voltage obviated but the shorter gun makes it possible to reduce the tube length by approximately 7 inches.

[9] *Telev. Dig.*, vol. 6, no. 13; April 1, 1950.
[10] *Telev. Dig.*, vol. 6, no. 14; April 18, 1950.

A further improvement is brought about by using a shadow-mask with reduced angle of approach. As already indicated, when the beam pencils are crowded closer together, the requirements on the electron optical system become less stringent. Tubes of this design were built using a shadow-mask screen with 0.7-degree angle of approach. The most noticeable difference is simplification of dynamic convergence.

Acknowledgments

Although space does not permit recognition of the many individuals who contributed to the development of the one-gun shadow-mask color kinescope, in addition to those already mentioned in the text of this and the companion papers, acknowledgment is made of the help of the RCA Victor Division Lancaster and Harrison groups, who built the demonstration tubes, as well as that of F. H. Norman, J. E. Eckert, E. O. Keizer, and G. A. Olive of RCA Laboratories, who carried out much of the experimental work.

A 45-Degree Reflection-Type Color Kinescope*

PAUL K. WEIMER†, SENIOR MEMBER, IRE, AND NATHAN RYNN†, MEMBER, IRE

Summary—The 45 degree reflection-type color kinescope is an experimental tube of the single gun type in which the color is changed by applying a control voltage directly to the screen assembly. The screen assembly consists of a multi-apertured metal plate coated on the front side with red, green, and blue phosphor strips and mounted parallel to a glass plate coated with a transparent conductive film. An electron beam scans the back of the metal plate at an angle of incidence of approximately 45 degrees. The portion of the beam passing through the slots is reflected by the electric field between the plates, causing it to fall back on one set of phosphor strips. By varying the potential of the glass "reflector" plate, the beam can be shifted from one color phosphor to another. The scanning beam is not required to follow the aperture pattern and the color purity is independent of beam focus.

A feature of this tube is the automatc registry of the three colors over all parts of the screen. The screen is not difficult to construct; the power required to switch colors at megacycle frequencies is small. Other characteristics of this tube which should be noted are: the unconventional shape of the bulb, and the need, in some forms of the tube, for a "keystoning" correction of the scanning.

Experimental one-gun tubes having screens seven inches in diameter have been built and operated with the RCA color system. Tests have shown that the 45-degree reflection-type color kinescope is capable of good quality, high definition pictures. A complete evaluation of tubes of this type, in which advantages and disadvantages are weighed against those of other color kinescopes, cannot be made at this time.

Associated circuits for operating the tube with the RCA color signal are outlined. Variations of the tube including a three-gun version are also described.

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Introduction

A NUMBER of proposals for color kinescopes have been outlined in a paper by Herold.[1] The 45-degree reflection-type kinescope falls into the class of tubes in which the emitted color is controlled by deflection of the beam in the immediate vicinity of the phosphor screen. A desirable feature of this class of

[1] E. W. Herold, "Methods suitable for television color kinescopes," Proc. I.R.E., pp. 1177–1185; this issue.

tubes is that the color control is entirely independent of the scanning process and of the beam focus. A color picture inherently free from misregistry of the three colors may be obtained using a single gun with conventional scanning techniques. The three primary components of the color signal may be presented sequentially at any rate, depending upon the color system employed.

The screen arrangement for the "beam deflection" type of color kinescope usually consists of a beam-defining structure in registry with an array of red-, green-, and blue-emitting phosphor strips or dots, plus some means of bending the beam from one strip to the next. An important advantage of tubes that have a beam-defining structure near the color screen is that the color purity is insensitive to beam focus. This is to be contrasted with the "line-screen" arrangement[2] wherein the beam must be aimed and focused by the gun onto a thin strip of color; here even a slight defocusing tends to dilute the colors.

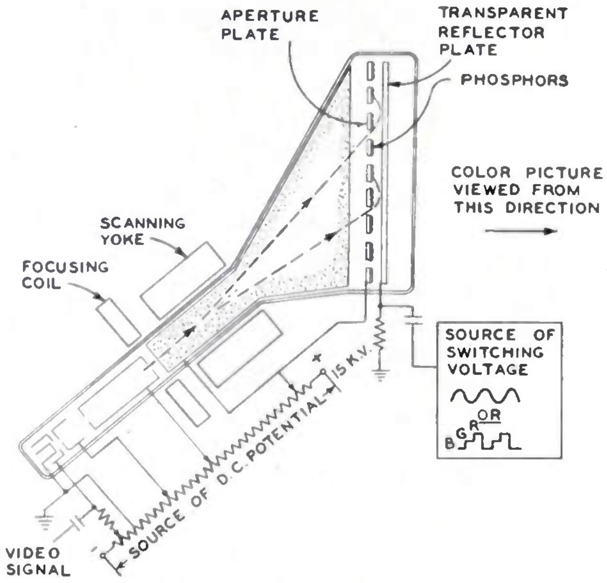

Fig. 1—Cross-sectional diagram of the 45-degree reflection-type three-color kinescope. Although the beam scans the screen at approximately a 45-degree angle, the picture is viewed in a normal manner.

Pairs of minute deflection plates mounted in front of each set of color strips have been proposed[3] as a means of switching the beam from one color to another. Such structures are difficult to build on a fine enough scale to give a high-quality color picture. Furthermore, the switching voltages required and the capacitance to be driven are likely to be inconveniently high.

The 45-degree reflection-type kinescope employs a relatively simple method of controlling the beam in the neighborhood of the screen. This paper will describe some of the early experimental tubes with 7-inch screens having a line structure sufficiently fine to give about 180 black-and-white lines resolution (540 color lines). This size screen was chosen for convenience and was a part of a larger screen capable of 360 black-and-white lines resolution and filling a 16-inch envelope. The 7-inch experimental tubes were tested with the RCA color television signal and were found to give color pictures of pleasing quality, judged on the basis of the limited number of picture elements available.

Principle of Operation

Fig. 1 shows a cross sectional diagram of the 45-degree reflection kinescope. The screen assembly which is shown in greater detail in Fig. 2 consists of two parts: a metal aperture plate and a transparent reflecting electrode. The beam approaches the aperture plate at an angle of incidence of approximately 45 degrees and a fraction of the beam passes through the slots. An electric field between the aperture plate and the reflector electrode causes the transmitted portion of the beam to be reflected and to return in a parabolic path to the aperture plate, where the beam strikes one of the phosphor strips deposited on the front side of the aperture plate.

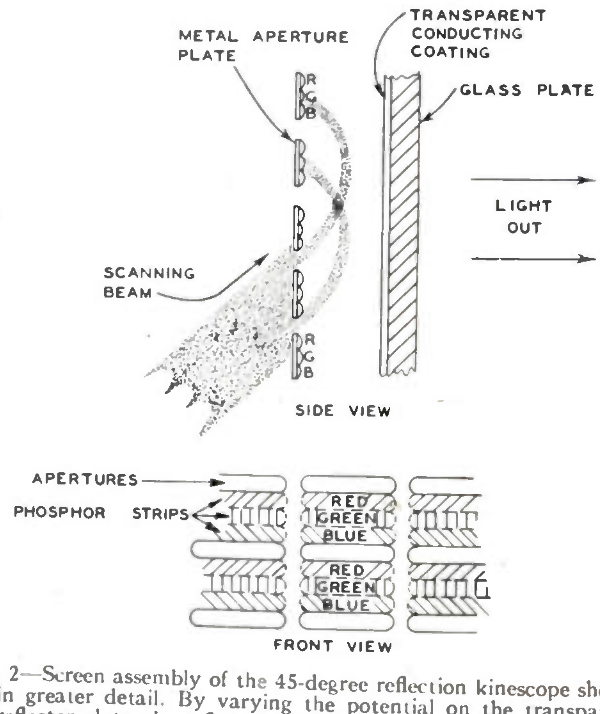

Fig. 2—Screen assembly of the 45-degree reflection kinescope shown in greater detail. By varying the potential on the transparent reflector plate, the reflected portion of the beam can be switched from one color phosphor to another.

The color picture is viewed directly through the transparent reflector electrode. The phosphor is deposited on the plate in the form of strips so that a group of three strips emitting red, green, and blue light, respectively, is laid between each pair of apertures. The width of each of the phosphor strips within the group is approximately the same as that of the aperture, so that the reflected beam can be made to fall on any one of the three colors selectively. When the voltage on the reflector electrode is varied, the point of impact of the reflected beam can be shifted from one color to another. The voltage change

[2] D. S. Bond, F. H. Nicoll, and D. G. Moore, "Development and operation of a line-screen color kinescope," Proc. I.R.E., pp. 1218–1230; this issue.

[3] L. C. Jesty, British Patent 443,896.

required to switch colors is inversely proportional to the distance between the aperture through which the beam passes and the corresponding bombarded spot. In some experimental tubes, the strength of the reflecting field was so chosen that the reflected beam actually jumped across about thirty slots before returning to the plate. Under these conditions less than 100 volts change in voltage of the reflector plate shifted a 12,000 volt beam from one color to another. A still finer pattern would require less power to switch colors. The capacitance to be driven by the color-control voltage need not exceed 50 to 100 micromicrofarads.

It must be noted that the color reproduction is entirely independent of the scanning raster and of the focus of the beam. The beam is not required to follow any particular pattern of slots on the aperture plate. A conventional gun and deflection yoke are entirely adequate with no possibility of misregistry of the three colors, assuming, of course, that the pattern is sufficiently fine.

The 45-degree angle of incidence of the beam requires a tube envelope of unconventional design. However, as a compensating feature, it permits a more compact cabinet design. In the tubes tested, a keystoning correction has to be added to the scanning to give a rectangular picture. Tests of the tube with the RCA color television signal are described below.

ELFCTRON OPTICS

Basic Equations—Color Switching

In the experimental 45-degree reflection-type kinescopes described herein, the aperture plate and the reflector plate are accurately flat and parallel. The electron motion in such a uniform field is similar to that of a projectile in a gravitational field and is readily calculable. It is found that the distance between the point where the beam passes through an aperture and the point where it returns to the aperture plate is given by:

$$S = \frac{2V_B D}{V_B - V_R} \sin 2\theta \qquad (1)$$

where:

- S is the range of the reflected beam (see Fig. 3),
- D is the distance between the reflector plate and the aperture plate.
- V_R is the potential of the reflector plate in volts,
- V_B is the potential of the aperture plate in volts,
- θ is the angle of incidence of the beam with respect to the aperture plate.

In order to shift the beam from one color to another, the rate of change of S with respect to a change in the reflector plate potential is of interest. From (1) the differential displacement is:

$$dS = \frac{2V_B D \sin 2\theta dV_R}{(V_B - V_R)^2}, \qquad (2)$$

where dS is the displacement of the point of impact of the reflected beam produced by a change of reflector voltage of dV_R.

In the operation of these kinescopes, it was found convenient to keep the mean potential of the reflector plate at ground. Setting $V_R = 0$ in (1) and (2),

$$S = 2D \sin 2\theta \qquad (3)$$

and

$$dS = \frac{2D}{V_B} \sin 2\theta dV_R. \qquad (4)$$

Experimental tubes were made with a spacing D = approximately 0.44 inch, giving $S_{max} = 0.88$ inch. In the approximate center of the picture where $\theta = 45$ degrees, the center-to-center spacing of the color strips was approximately 0.007 inch. Substituting these values in (4), the voltage change required to deflect a 12 kilovolt beam from one color to the next is

$$dV_R = \frac{V_B dS_{max}}{2D} = \frac{12{,}000 \text{ volts} \times 0.007 \text{ inch}}{2 \times 0.44 \text{ inch}} = 95 \text{ v.}$$

The 95 volts required to switch from one color to another were readily obtainable with sine-wave color switching

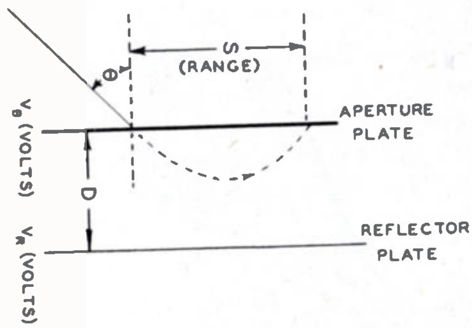

Fig. 3—Parabolic electron trajectory in the reflecting field between the aperture plate and the reflector plate.

at 3.58 mc, the color-sequence rate in use during tests with the RCA color television system. By (2), the required switching voltage could have been reduced to approximately 50 volts for the same target structure if V_R, the average potential of the reflector plate, had been run at 3,000 volts instead of at ground. Under these conditions the beam will skim much closer to the reflector plate but not strike it because its energy at the instant of closest approach will be directed parallel to the plate.

It is noted from (4), that the shift of the reflected beam produced by a change in voltage of the reflector plate is proportional to the spacing D between the reflector and aperture plates. The spacing of 0.44 inch was chosen as a compromise, giving adequate voltage sensitivity without sacrificing resolution. A very much larger spacing would allow the use of still less power for switching but would require a beam of exceedingly narrow angle of convergence to avoid objectionable spreading in a direction parallel to the slots. (The reflecting field provides focusing of the beam but only in a direction perpendicular to the slots.) On the other hand, if extra power for switching is available, a further reduction in spacing would be desirable in order to make the tube still less susceptible to misalignment and to stray magnetic fields.

Color Uniformity

An electron-optical problem connected with the 45-degree kinescope is that of making the reflected beam fall on the proper color phosphor over all parts of the

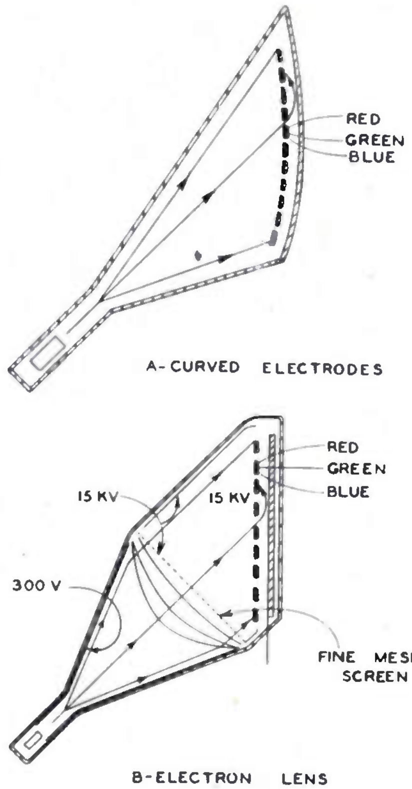

Fig. 4—Two alternative methods of achieving color uniformity by causing the beam to strike the entire screen at 45 degrees. The electrodes in (A) are nonspherical surfaces whose vertical cross-section is a spiral and whose horizontal cross-section is a circle. The electron lens method in (B) permits plane electrodes to be used and eliminates the need for a "keystoning" correction in the scanning.

screen. Three possible approaches were considered.

(a) Curving the aperture plate and reflector plate so that the beam approaches the aperture plate at exactly 45 degrees over all parts. Fig. 4 (a).

(b) Using plane electrodes but providing an electron lens between the gun and the front of the aperture plate so the 45-degree angle of incidence is preserved over the whole screen. Fig. 4 (b).

(c) Using plane electrodes but arranging the position of the apertures and phosphors to compensate for the different angles of approach over the target (Figs. 1 and 5).

The greater simplicity of constructing plane electrodes as compared to the curved electrodes ruled out (a) for the initial experiments. The electron lens method mentioned in (b) is a promising approach but requires a longer tube with some loss in brightness due to the fine mesh screen. The third approach was used and gave very satisfactory results. Equations (1), (2), (3), and (4) show that the maximum values of the range S and the displacement dS occur in the center of the picture, where the angle of incidence θ is exactly 45 degrees. At the top and the bottom of the picture, where θ approaches 60 degrees and 30 degrees, the range may decrease as much as 20 per cent. To compensate for this effect, a particular pattern of apertures has been devised for the aperture plate.

Fig. 5 shows the particular arrangement of apertures used in the 45-degree reflection-type kinescope. The insert shows an enlarged view of the slot-like apertures. These apertures are formed on concentric arcs of circles,[4] the centers of which lie on a common point O obtained by dropping a perpendicular from the center of deflection to the plane of the target. The phosphors are laid on arcs about the same center, with three rows of phosphor between each two rows of apertures (Fig. 2). Along each arc the beam approaches the aperture plate at the same angle. Thus, for a constant voltage on the reflector plate, the beam will excite the same color phosphor all along the arc.

The color uniformity from top to bottom was achieved by arranging the spacing between adjacent concentric arcs to take into account the fact that the range S is a maximum for a 45-degree angle of incidence,

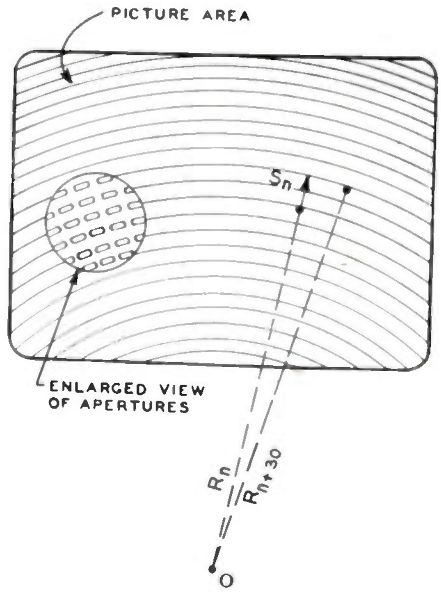

Fig. 5—Circular pattern of apertures used in experimental 45-degree reflection kinescopes. Plane electrodes are made feasible by arranging the position of the apertures and phosphor strips to compensate for the varying angle of incidence across the screen (Fig. 1). The insert shows an enlarged view of a small section of the aperture plate.

as indicated by (equations (1), (2), (3), and (4)). For a 16-inch kinescope employing a picture 9 inches high, the spacing between rows may be approximately 20 per cent greater in the center of the picture than at the top and the bottom.

[4] The circular pattern of apertures was suggested by E. G. Ramberg, RCA Laboratories Division, Princeton, N. J.

The radii of the arcs along which the apertures were to be formed were calculated in a step-wise manner from (3). The plane of the target was set 8.5 inches from the center of deflection, and the angle of incidence varied between 30 degrees at the bottom of the picture to 60 degrees at the top. It was decided arbitrarily that the range should span thirty rows of apertures over all parts of the target and that the maximum range in the center of the picture (45-degree incidence) should be 0.8854 inch. The radii of successive arcs were then given by

$$R_{n+30} = R_n + 0.8854 \sin 2\theta_n,$$

where

$$\theta_n = \arc\tan\left(\frac{R_n}{8.5}\right).$$

The radii were calculated for 393 arcs covering a vertical distance of 10¾ inches. This pattern would permit a useful picture about 9½ inches high having approximately 1,000 color-phosphor strips. The experimental tubes described herein used an aperture plate based on the central part of these calculations, giving a screen diameter of 7 inches.

The Focusing Action of the Reflecting Field

The preceding discussion has assumed that the angle of incidence of the beam over all parts of the aperture screen is specified exactly by a line connecting the bombarded aperture with the center of the deflection coil. This is, of course, true only for the central core of the beam and then only in the absence of perturbing fields or possible misalignments of the screen. The dependence of the range S on the angle of incidence was given by (3).

Inasmuch as a variation in the range of one part in 120 in the present screen moves the beam from one color phosphor to another, the rate of variation S with a small change in θ is of interest. Differentiating (3) with respect to θ, one obtains

$$\frac{dS}{d\theta} = 2S_{\max} \cos 2\theta. \quad (5)$$

It is noted that $dS/d\theta$ is small in the neighborhood of 45 degrees. This means that the electric field between the aperture plate and the reflector plate has a focusing action in the plane of incidence of the beam. Thus, the fraction of the beam passing through each aperture may actually diverge and still be brought together by the reflecting field to strike a single-color strip without appreciable excitation of adjacent color strips. The relaxation of the requirements on alignment of the target and on the shielding of the beam from stray magnetic fields are further advantages of this focusing effect.

Equation (5) shows that if the angle of incidence is greater than 60 degrees or less than 30 degrees, $dS/d\theta > S$, which is equivalent to defocusing. This would appear to limit the total angle of scan to 30 degrees if the benefits of the focusing action are to be obtained. Such a limitation is not a severe restriction on tube dimensions or receiver cabinet design since a 30-degree total angle centered about a 45-degree angle of incidence would permit a shorter cabinet for the same size picture than a conventional tube with a total angle of 60 degrees.

The tapering off of the focusing effect of the reflecting field at the top and the bottom of the picture makes some magnetic shielding desirable to prevent stray fields, such as the earth's magnetic field, from shifting the beam from the proper color. The focusing of the reflecting field in these areas does not appear to be essential for color purity since the convergence angle of a high velocity beam is a very small fraction of one degree.

It may be noted that the two alternative methods of achieving color uniformity illustrated in Fig. 4 profit by having a 45-degree angle of incidence over the entire screen.

Alternate Forms of the 45-Degree Color Kinescope

Transmission-Type Kinescope

A variation of the 45-degree reflection-type kinescope is the transmission-type tube operating by the method illustrated in Fig. 6. The beam strikes the phosphor strips on the second plate at high velocity. The color is switched by applying an ac voltage to the second plate.

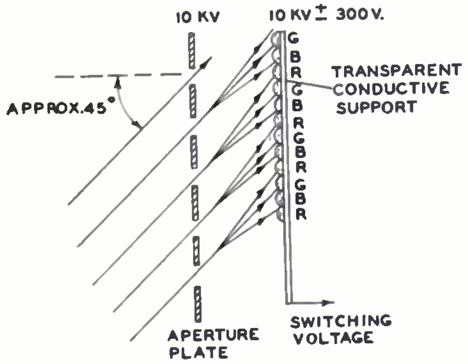

Fig. 6—An alternate form of 45-degree color kinescope. This "transmission type" tube was considered less attractive than the reflection type on the grounds that it was more difficult to construct, required more power to switch colors and lacked the desirable focusing features of the reflecting field.

Simple calculations show that the transmission-type tube at 45 degrees requires four to eight times as much switching voltage as the reflection-type tube for the same beam voltage and target spacing. There is no focusing action of the field, and the target is very sensitive to stray magnetic fields. Unlike the reflection-type tube, this form requires accurate mechanical registry of the two plates. A satisfactory solution to the uniformity problem would have to be worked out before a useful tube could be built. It may be noted that the circular pattern of apertures used to achieve uniformity extra power for switching is available, a further reduction in spacing would be desirable in order to make the tube still less susceptible to misalignment and to stray magnetic fields.

Color Uniformity

An electron-optical problem connected with the 45-degree kinescope is that of making the reflected beam fall on the proper color phosphor over all parts of the screen. Three possible approaches were considered.

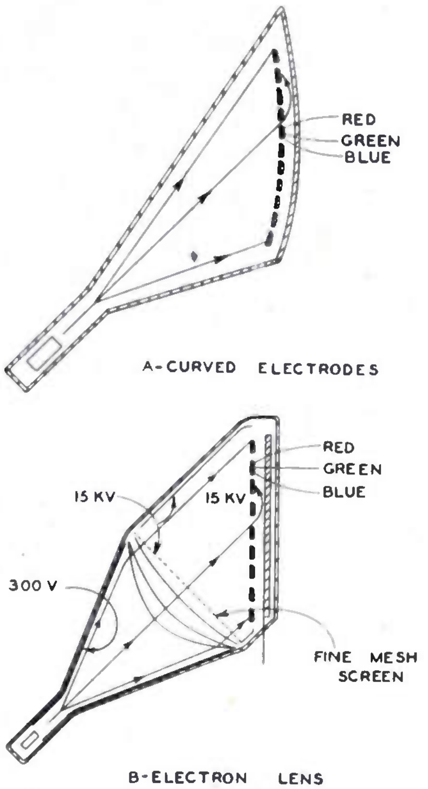

Fig. 4—Two alternative methods of achieving color uniformity by causing the beam to strike the entire screen at 45 degrees. The electrodes in (A) are nonspherical surfaces whose vertical cross-section is a spiral and whose horizontal cross-section is a circle. The electron lens method in (B) permits plane electrodes to be used and eliminates the need for a "keystoning" correction in the scanning.

(a) Curving the aperture plate and reflector plate so that the beam approaches the aperture plate at exactly 45 degrees over all parts. Fig. 4 (a).

(b) Using plane electrodes but providing an electron lens between the gun and the front of the aperture plate so the 45-degree angle of incidence is preserved over the whole screen. Fig. 4 (b).

(c) Using plane electrodes but arranging the position of the apertures and phosphors to compensate for the different angles of approach over the target (Figs. 1 and 5).

The greater simplicity of constructing plane electrodes as compared to the curved electrodes ruled out (a) for the initial experiments. The electron lens method mentioned in (b) is a promising approach but requires a longer tube with some loss in brightness due to the fine mesh screen. The third approach was used and gave very satisfactory results. Equations (1), (2), (3), and (4) show that the maximum values of the range S and the displacement dS occur in the center of the picture, where the angle of incidence θ is exactly 45 degrees. At the top and the bottom of the picture, where θ approaches 60 degrees and 30 degrees, the range may decrease as much as 20 per cent. To compensate for this effect, a particular pattern of apertures has been devised for the aperture plate.

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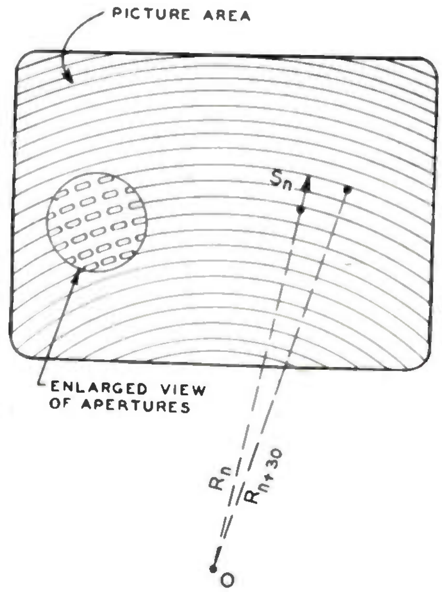

Fig. 5—Circular pattern of apertures used in experimental 45-degree reflection kinescopes. Plane electrodes are made feasible by arranging the position of the apertures and phosphor strips to compensate for the varying angle of incidence across the screen (Fig. 1). The insert shows an enlarged view of a small section of the aperture plate.

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$$R_{n+30} = R_n + 0.8854 \sin 2\theta_n,$$

where

$$\theta_n = \text{arc tan}\left(\frac{R_n}{8.5}\right).$$

The radii were calculated for 393 arcs covering a vertical distance of $10\frac{3}{4}$ inches. This pattern would permit a useful picture about $9\frac{1}{2}$ inches high having approximately 1,000 color-phosphor strips. The experimental tubes described herein used an aperture plate based on the central part of these calculations, giving a screen diameter of 7 inches.

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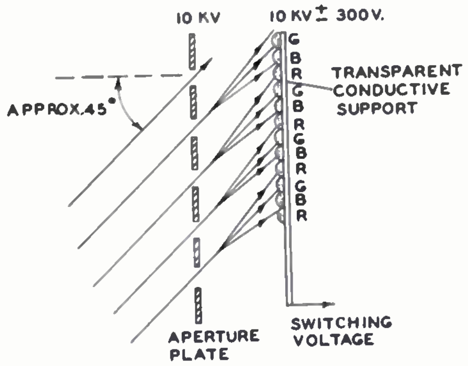

Fig. 6—An alternate form of 45-degree color kinescope. This "transmission type" tube was considered less attractive than the reflection type on the grounds that it was more difficult to construct, required more power to switch colors and lacked the desirable focusing features of the reflecting field.

Simple calculations show that the transmission-type tube at 45 degrees requires four to eight times as much switching voltage as the reflection-type tube for the same beam voltage and target spacing. There is no focusing action of the field, and the target is very sensitive to stray magnetic fields. Unlike the reflection-type tube, this form requires accurate mechanical registry of the two plates. A satisfactory solution to the uniformity problem would have to be worked out before a useful tube could be built. It may be noted that the circular pattern of apertures used to achieve uniformity in the reflection-type tube does not appear attractive here because of the lack of focusing.

Electron Mirrors for Compactness and Simplification of Bulb Design

The electric field between a flat plate and a fine mesh screen can be used as a plane mirror for electrons. Fig. 7 shows how such a mirror might be used to simplify or shorten the bulb design of the 45-degree tube. The target would be aligned for the apparent center of deflection instead of the actual center of deflection. The principal disadvantage is the loss in beam strength produced by the double transit through the screen *S*. With available high-transmission screens, this loss might be reduced to about 50 per cent.

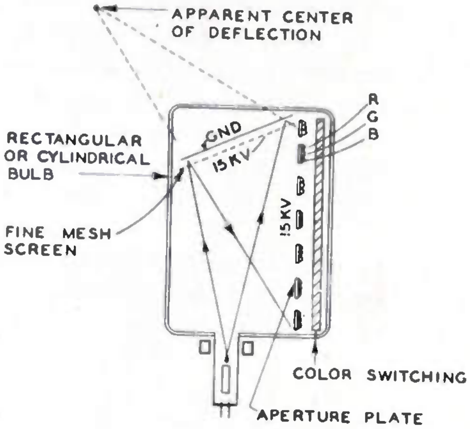

Fig. 7—The use of an electron mirror to shorten or simplify the bulb design of the 45-degree color kinescope.

Three-Gun 45-Degree Kinescope

An alternative 45-degree kinescope arrangement which does not require a color switching signal consists of three guns mounted as close together as possible with a 45-degree reflection-type target. With a 12-kv beam, color separation can be achieved by operating the cathodes of the red and blue guns approximately 95 volts above and below the potential of the green gun. For each color the electrons pass through the apertures with slightly different velocities, thus falling on different colors. See (4).

The beams should be as nearly superimposed as possible for best registry of the three colors. Even so, the three rasters will be slightly different in size, owing to the different velocities of the beams when passing through the deflection coil. For this reason the screen should be designed to shift colors with as little change in beam voltage as practicable. With the screen assembly described above, and using a magnetic-type scanning yoke, the red and blue rasters differ in size from the green raster by about 0.4 per cent. The resulting displacement, which is of the order of a picture element, occurs only at the edge of the picture and will be unnoticed.

Construction of an Experimental 45-Degree Color Kinescope

Aperture plates for the experimental tubes were made from copper sheets 0.002 inch thick having openings etched by photoengraving techniques. A photographic master of the pattern desired was first obtained by ruling on a heavy lucite block with a stylus mounted on a vertical milling machine. The radii of the arcs were set to an accuracy of a few ten thousandths of an inch, according to the calculations outlined previously. This pattern was transferred to a photographic negative by contact printing using a point-light source. A second ruling of radial lines was then combined with the curved pattern to give a negative of the slot pattern complete with radial cross bars. The cross bars were made as thin as possible, consistent with adequate mechanical strength of the final aperture plate.

The copper sheet was coated with a "cold top" photosensitive enamel and exposed with ultraviolet light through the slot pattern negative. The action of the light makes possible the formation of an acid-resistant coating over all parts of the copper, except where the slots are to be. Immersion in an etching solution forms the holes in an accurate copy of the original pattern.

The aperture plate was then coated with the three phosphor materials emitting the primary colors. Each material was deposited in turn by settling through a mask similar, but not identical to, the aperture plate itself. Other methods of laying down the phosphors could have been used equally well. For a small target, a copy of the aperture plate itself could be used as a settling mask for all three colors, without appreciable error, by simply displacing the mask in turn for each color. For a large target with a wide angle of scan, each color should have its own settling mask ruled so that the center of its arcs coincide with the center of curvature of the aperture plate. In the experimental tubes with the 7-inch screens, a satisfactory compromise was made in which a settling mask was computed and ruled for the phosphor row falling midway between the slots. The error, resulting from displacing the mask ± 0.007 inch for the adjacent colors, was not objectionable for the 7-inch picture. Fig. 8 shows a photomicrograph of the three phosphors deposited on the aperture plate. The thicknesses of the coatings were adjusted for color balance to give an acceptable white.

When the tube was assembled, the copper aperture plate was mounted on a rigid frame which permitted it to be stretched tight and flat. The frame also supported the glass reflector plate spaced parallel to the mask. The tolerances on parallelism and flatness of each plate were quite close. The inner surface of the glass plate was coated with a transparent conducting coating, called "Nesa," supplied by the Pittsburgh Plate Glass Company. The "Nesa" coating is highly transparent and could be formed on the glass with a surface resistance of several hundred ohms per square. The resistance was sufficiently low to give no objectionable voltage drop or power loss, even when switched at megacycle frequencies. Lavite spacers were used to support the glass 0.4427 inch from the aperture plate.

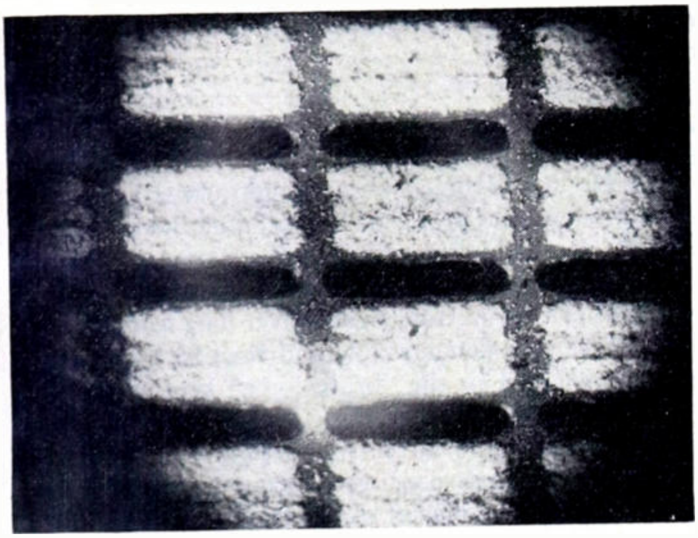

Fig. 8—Photomicrograph of the 3 sets of phosphor strips deposited by settling onto the copper aperture plate.

Early tests of the screen assemblies were made by placing the structure in a demountable vacuum system shown in Fig. 9. Color uniformity, color stability, brightness, contrast, resolution and moiré could all be readily examined without requiring a complete color signal.

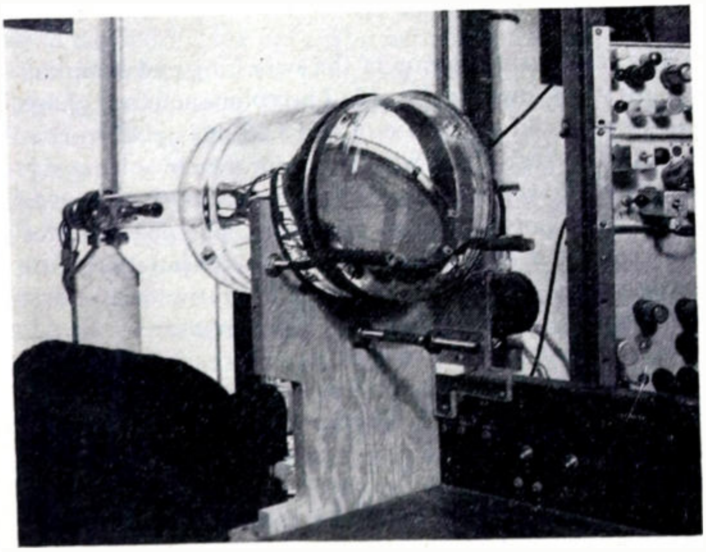

Fig. 9—Demountable vacuum system used for testing color-kinescope screens. A 7-inch diameter 45-degree reflection-type screen is shown in position for test prior to being sealed in a bulb.

In parallel with the development of the screen, the associated circuits were developed for operating the tubes with an RCA color-television signal. Sealed-off experimental tubes with 7-inch diameter screens were built and tested successfully with a full color picture.

Operation of the 45-Degree Kinescope with the RCA Color Television Signal

The 45-degree reflection-type color kinescope belongs to that class of color tubes in which the primary color emitted is determined by a control voltage applied to the screen structure. The phosphor strips were laid down on the aperture plate in groups of three, having the order red, green, blue (Fig. 2). In the absence of the color switching signal, the proper dc bias was applied to the reflector plate to give a uniform green color. For sequential three-color reproduction, a repetitive wave form of proper magnitude was applied to the reflector plate to cause the reflected beam to

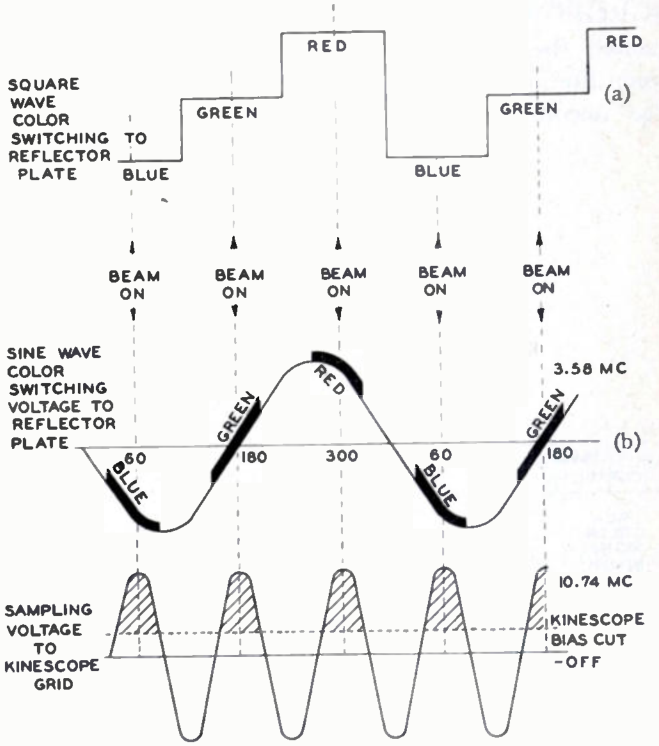

Fig. 10—Waveforms of the color-switching voltage which may be applied to the reflector plate. For low speed switching the step wave shown in A would be preferable. For high speed switching at mc frequencies the sine wave shown in B was entirely suitable. Beam blanking at three times the switching frequency was used to give the required color sequence.

oscillate from the central green phosphor to the adjacent red and blue phosphors. At the same time, the beam current was modulated in turn with each primary signal so that the total light emitted by each tri-color element carried the proper intensity, hue, and saturation.

Fig. 10 shows two forms of switching voltage which may be applied to the reflector plate for a sequential color presentation. In 10(a), a step wave is shown. This wave shape would give the maximum light output, each color being on one-third of the time. Generating this wave form at high sequence rates presents an unusual circuit problem and an attempt was made, with some encouraging results, to do it by means of a multiresonant circuit, as a plate load of a class-C amplifier. For the work with the RCA color television system, however, using a 3.58 (mc) color subcarrier, it was found more convenient and, for all practical purposes, just as effective, to use the sine-wave form shown in Fig. 10(b). Sequential color presentation with the RCA system requires color switching at the subcarrier frequency.[6]

A 3.58 mc sine wave of approximately 75 volts rms was applied to the reflector plate. By switching the beam on at 120-degree intervals with proper timing (say at 60 degrees, 180 degrees, 300 degrees, 60 degrees, etc.) the BGRBGR (blue, green, red, etc.) sequence of the dot sequential presentation was preserved. If the beam was not switched on and off, whichever color was the center color—in this case green—was repeated twice for every one of the other two to give a BGRGBGR sequence. Thus, the beam blanking performed the double function of eliminating the extra green line and of effecting "sampling." Beam blanking was accomplished conveniently by modulating the

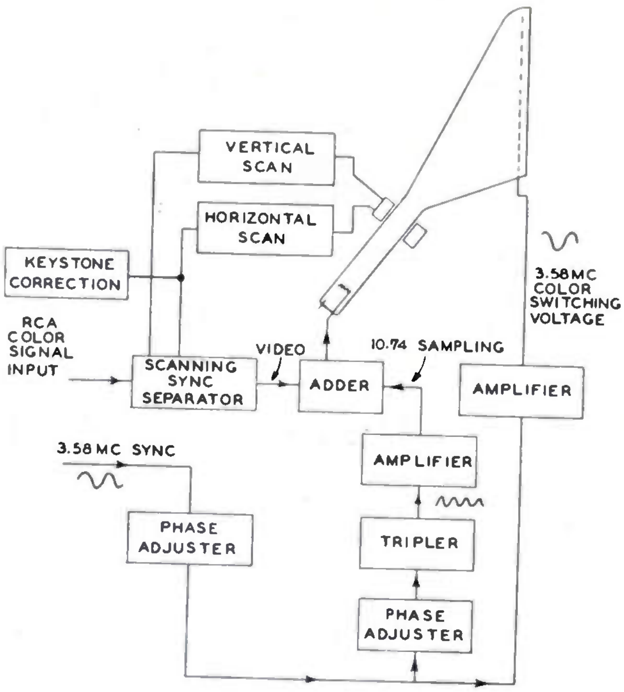

Fig. 11—Block diagram of associated circuits for operating the 45-degree reflection kinescope with the RCA color signal. A 3.58 mc sine wave is applied to the reflection plate and a 10.74 mc sine wave used for sampling the signal at the gun.

video on the grid of the kinescope with a sine wave of three times the switching frequency, or 10.74 mc (as shown in Fig. 10(b)) synchronized with the switching voltage. This was done by linearly adding this sampling frequency to the video and then operating the grid of the kinescope class C, much the same as in grid modulation of an amplitude-modulated radio signal.

[6] RCA Laboratories Division, "A 6-mc, compatible, high definition color television system," *RCA Rev.*, vol. 10, pp. 504–524; December, 1949.

The use of sine wave switching has the advantage of reducing the power requirements of, and of simplifying the circuitry. Resonant circuit techniques were employed throughout.

Fig. 11 is a block diagram showing this use of sine-wave switching and the associated video and deflection circuits.

Switching and Sampling Circuits

The circuits involved were straightforward and presented no unusual problems beyond a mechanization of Fig. 11. A possible exception was keystoning, of which more will be said later. The major difficulty encountered was that of transmitting signals over long leads and/or cables first to a demountable and then to a test rack. This is reflected in the "brute force" type of circuits which were used, rather than the compact circuitry usually encountered in receiver design.

The input signals used were received via two cables connected to the master color television signal generators set up in the television studio at RCA Laboratories. One signal consisted of the 3.58 mc color synchronizing signal and the other was the RCA color signal, i.e., standard black-and-white sync and blanking, a video signal with a 3.58 mc color subcarrier, and a 3.58 mc burst on the back porch of the horizontal sync pulse. The burst was not used because of the availability of the separate color synchronizing signal. The circuits were divided into two parts: the color switching and sampling circuits driven by the 3.58 mc sine wave, and the more or less standard video and deflection circuits.

The schematic diagram of the switching and sampling circuitry is shown in Fig. 12. The color-sequence phase shifter adjusted the phase of the 3.58 mc signal so that it was in correct phase with the color synchronizing signal. This allowed a green portion of picture to appear as green, a red portion as red, and so on. The phase shifter used consisted of a phase inverter in conjunction with a variable rc network to produce a continuously variable phase shift of 0 degrees to 140 degrees.

The output of the phase shifter was put through an isolating stage and then into a switched delay cable. The cable consisted of two lengths of 1,000-ohm coaxial transmission line cut to give a fixed delay equivalent to 120 degrees at 3.58 mc for each section. This arrangement, in conjunction with the continuously variable unit, gave complete control over a full 360 degrees of phase shift. The output was then amplified and applied to the reflector plate of the kinescope by resonating the capacitance formed by the reflector plate and the aperture mask with a coil.

Although the "Nesa" coating of the reflector plate has resistivity, no difficulty was encountered that could be attributed to it. The output of the color-sequence phase shifter was also put through a sampling phase shifter of the continuously variable type just described.

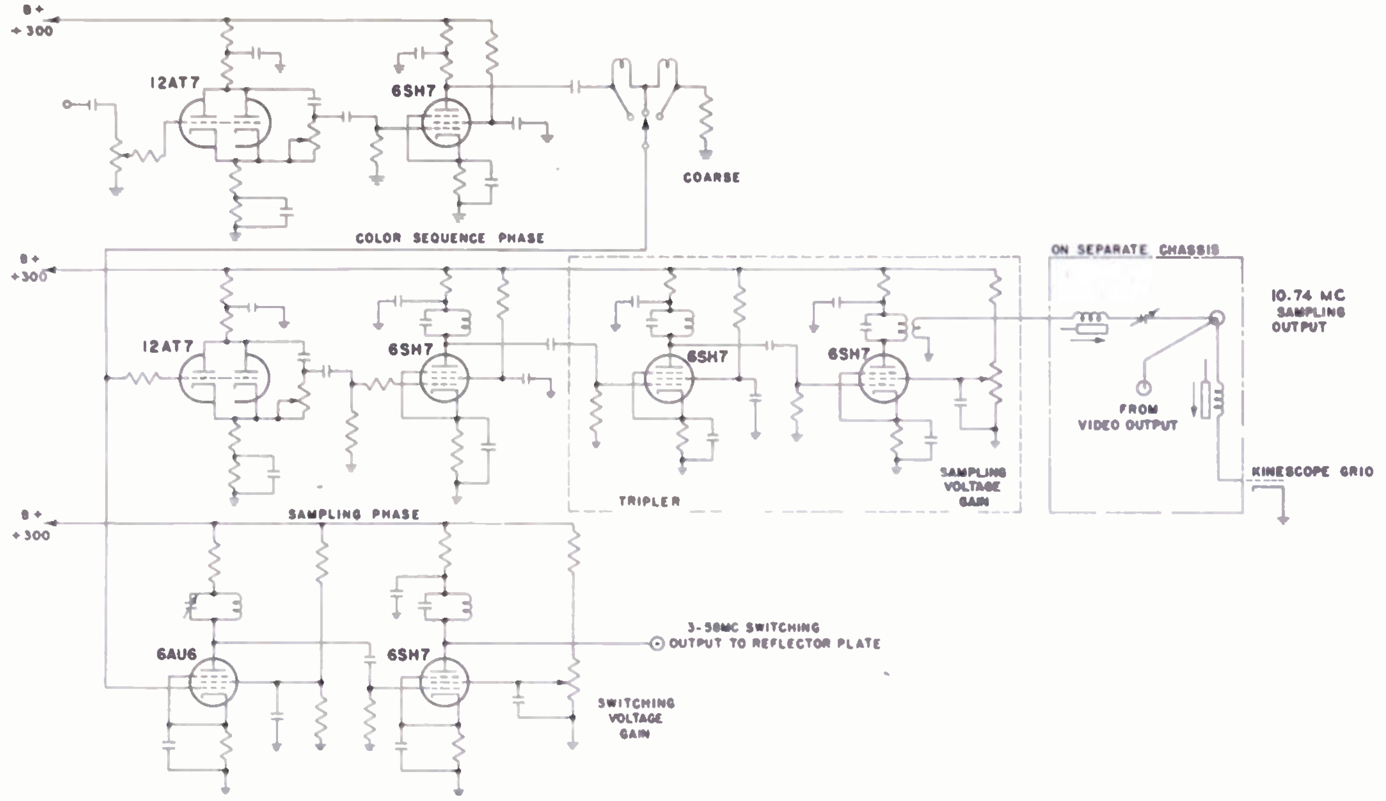

Fig. 12—Schematic diagram of the switching and sampling circuits.

The output of this unit was amplified, tripled, amplified again, and then added to the video. The adding circuit consisted of a step-down rf transformer, the secondary being a link coupling into the resonant circuit shown. The 10.74 mc was then series resonated with a very small capacitor (2–5 $\mu\mu$f). The net effect was to present a low impedance to the sampling frequency and a high impedance to video. The video was injected at the point shown in Fig. 12 and then put through a parallel LC arrangement which presented a low impedance to the video. The LC combination was then resonated with the kinescope grid-to-ground capacitance to form another series resonant circuit for the sampling frequency. In this manner an adequate sampling voltage was developed on the kinescope grid without adversely affecting the video.

The video amplifier was conventional and had a 4 mc response. The final output stage provided a low output impedance to drive a long lead.

Keystoning Correction to the Deflection

The 45-degree angle of incidence of the beam in a tube of the type shown in Fig. 1 causes one side of the screen to be much closer to the gun than the other, resulting in a distortion of the scanning raster. A similar problem has been faced in television pickup tubes such as the iconoscope, although the difficulty is now accentuated because of the wider angle of scan and the higher voltages. The resulting distortion appeared to be somewhat easier to correct when the screen was oriented so that part of it closest to the gun was either at the top or the bottom of the picture. The correction to be applied to the scanning then consisted of modulating the horizontal sweep with a sawtooth component, at vertical frequency.

Relatively small attention was given to the design of the keystoning correction circuit, but the circuit shown in Fig. 13 was found to be adequate. It was necessary to decrease the size of the power feedback capacitor in the horizontal deflection system to allow the deflection unit to follow the modulation and to minimize the effect of rectification by the damper.[6]

Results

Color Uniformity

An exacting requirement of a color kinescope is that it give a uniform color field in each of the three primary colors. The 45-degree kinescope having a screen diameter of 7 inches gave substantially uniform colors, in some cases without the benefit of any correcting coils or magnets. In other cases, one small magnet was mounted near the deflection yoke on the target side. The purpose of such a correcting magnet was to change slightly the angle of incidence of the beam, thus correcting for target misalignment or possible effects of the earth's field. In general, the tests proved the feasibility of using plane electrodes with the aperture pattern computed to compensate for varying angles of incidence.

[6] This rectification amounts to a detection of the vertical sawtooth modulation, and would cause a circulating current of this wave form in the yoke, thus skewing the picture.

Color Purity

Color purity was not measured quantitatively, but in general it appeared to be good. For best color purity it is desirable that the collimated fraction of the reflected beam be slightly narrower than the color strips, or that an insensitive guard band be used between strips. In most of the tubes no guard band was used, but the effective slot width ordinarily gave a reflected beam which was slightly narrower than the phosphor strips.

Brightness

The 7-inch color kinescope of the 45-degree reflection type produced pictures of brightness comparable to that of other single-gun color kinescopes. The target structure itself permits bombarding voltages of at least 15 kv. However, expansion of the aperture plate owing to heat dissipated by the bombarding beam gave some trouble in experimental tubes having a two-mil-thick aperture plate. A four-mil-thick plate was found to be preferable.

An ideal color kinescope of the color-switching type should allow the full beam current I_B to fall in turn on each of the three color phosphors. In the 45-degree reflection tube the maximum transmission of a plane aperture plate is 25 per cent, since the phosphor strips must be laid on the aperture plate itself.[7] The vertical cross bars used in the pattern shown in Fig. 5 reduce the maximum transmission to about 20 per cent, and the oblique angle of incidence further reduced the effective opening to about 15 per cent. This efficiency is comparable to the aperture-mask type of screen used in the developmental tri-color kinescopes described in an accompanying paper.[8]

[7] A 45-degree reflection kinescope for two colors would permit a maximum efficiency of 33 per cent.

[8] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

Resolution

The automatic registry of the three colors over all parts of the screen is a very significant advantage of the 45-degree tube. This characteristic showed up in improved detail when compared with other types of color kinescopes which did not have the automatic registry feature.

In addition to the registry of the three colors, the resolution is, of course, a function of the fineness of the color strips. The 7-inch experimental tube here described had color strips approximately 0.007 inch wide in the center of the target and 0.0065 inch wide at the top and bottom of the picture. Allowing for the aperture itself which is 0.007 inch wide, the total height of a white picture element was 0.028 inch or less. This allowed a vertical resolution of about 360 black-and-white lines in a picture 10 inches high, but allowed only about 180 lines in the 7-inch diameter screens tested.

The limitation on resolution in the tests made appeared to be set by the structure itself and not by electron optical limitations. This suggests the desirability of a finer pattern. In the experimental tubes, the curved slots were also broken up by vertical supporting cross-bars, approximately 0.006 inch wide and 0.040 inch apart in the center of the picture. These vertical black bars were visible upon close viewing of the picture and did limit resolution of a stationary picture slightly. If the test pattern were moved to minimize the effect of the stationary bars, the observed resolution in a picture 5 inches wide was approximately 300 lines.

It should be noted that the focusing action of the reflecting field occurs only in the vertical direction. This means that to obtain maximum horizontal resolution, the beam focus should be set for sharp focus of the reflected beam on the phosphor screen. The focusing action of the reflecting field will, however, make the vertical height of the reflected beam spot the same as

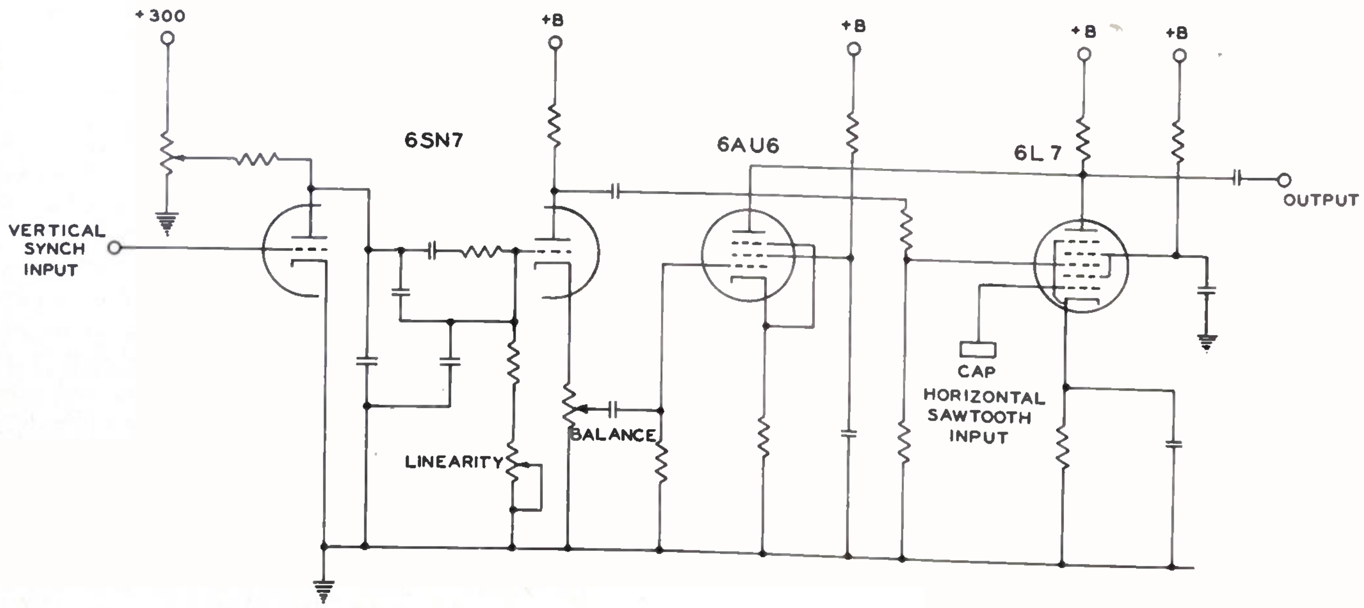

Fig. 13—"Keystoning" circuit used in test of the 45-degree color kinescope.

the height of the defocused beam initially passing through the aperture. The vertical resolution can, of course, never be better than the distance between the slots, and moiré is minimized if the width of the beam covers at least two slots.

The difference in the throw of the beam from top to bottom of the picture will also give some difference in focus, unless a beam of very narrow angle of convergence is used. This effect was not objectionable in the 7-inch experimental tube, but a larger tube may require a slight vertical sawtooth fed into the focusing electrode for best resolution.

Moiré

A moiré pattern resulting from the "beating" between the straight scanning lines and the curved slots was observed. The moiré pattern was most intense when the distance between the scanning lines was about equal to the distance between the slots, and the spot size was less than this distance. Loss of vertical interlace was also noted to intensify the moiré.

In general, the moiré as observed with the 7-inch tube was noticeable but not particularly objectionable. The visibility of the moiré would be expected to decrease with one of the following modifications:

(a) Closer spacing between slots so that the beam alalways covers two or more apertures.
(b) An elliptical spot with the largest dimension perpendicular to the slots to achieve condition (a) with the existing pattern. The 45-degree angle of approach of the beam does give a slight ellipticity to the defocused spot.
(c) Orientation of the scanning raster so that the lines make an angle of 45 degrees to 90 degrees with curved slots. Such a change in angle of approach affects the type of keystoning correction required.
(d) Forming the slots in a curved dot pattern rather than along continuous arcs.

Contrast

Qualitative observation of the color pictures obtained with the 45-degree reflection tube indicated good contrast. This result was due partly to the use of a flat screen, and partly to the complete absence of optical halation caused by multiple reflections sometimes encountered when the phosphor is deposited on a glass plate. However, there is an electron optical effect in a reflection-type tube which partially reduces the contrast. A small fraction of the beam impinging on the phosphor is always reflected at high velocity. If the electric field is such as to return these electrons to the phosphor, the contrast is reduced.

In the 45-degree kinescope an intense stationary beam was observed to have a white halo around the bright spot on the phosphor. The halo was white because the scattered electrons fall uniformly on all three color strips. The radius of the halo was approximately the same as the range S of the reflected beam (see Fig. 14). A still fainter disk of white light was observed around the point on the aperture plate where the incident beam passed through. This disk resulted from scattering of

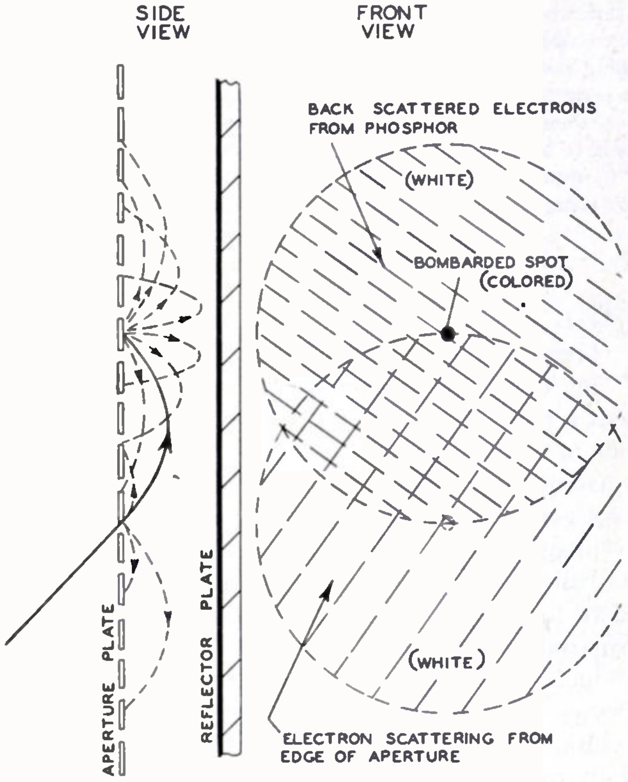

Fig. 14—Electron paths of high-velocity scattered electrons which may contribute to reduction of contrast in a reflection-type kinescope.

the primary beam on the edges of the aperture. The loss of contrast in an actual picture due to the scattering effect was barely perceptible and no effort was made to minimize it.

Color Stability

It is well known that an electron beam striking an insulator will drive the bombarded surface to some equilibrium potential whose value depends upon the secondary emission ratio of the material, the potential of surrounding electrodes, etc. Some concern was felt that the phosphor might assume a potential sufficiently different from the aperture plate to deflect the beam to the wrong color. Experimental tests showed no evidence of charging of the phosphors. The colors remained stable for all anode voltages tested ranging up to 15 kv.

Acknowledgments

The writers wish to express their appreciation for the advice and encouragement of E. W. Herold, H. B. Law, and A. Rose. The co-operation of S. W. Dodge and L. Hart has contributed to the construction of experimental tubes.

A Grid-Controlled Color Kinescope*

STANLEY V. FORGUE†, MEMBER, IRE

***Summary*—A new color kinescope makes use of a series of closely spaced screens, each covered with a different primary color phosphor and separated from each other by fine mesh control grids. Small voltage changes of these grids control the depth of penetration of the scanning beam or beams into this assembly of screens. This arrangement permits individual excitation of any one or combination of the primary colors which go to make up the colored image. Experimental tubes have been built, first in two-color form to test principles, and then in three-color form. They have been operated with a color picture using the RCA color television system signal.**

I. Introduction

THE NAME "grid-controlled color kinescope" has been given to a single multicolor television viewing tube having a number of closely-spaced fluorescent screens, separated by control grids and scanned by one or more electron beams. The beam(s) penetrates this assembly to different depths determined by the control grid voltages and produces a different primary color image on each of the fluorescent screens. When viewed directly, the individual color images are superimposed to form a single polychromatic image.

Proposals have been made for a different color-reproducer tube having a series of fluorescent screens.[1] Colors are changed by keying the screens with a switching voltage of several kilovolts. Such a tube would be difficult to operate, particularly in a television system employing high color switching rates. In the tube here discussed, color-control grids reduce the required switching voltage to small practical values.

An experimental grid-controlled kinescope using a 9-inch envelope is shown in Fig. 1.

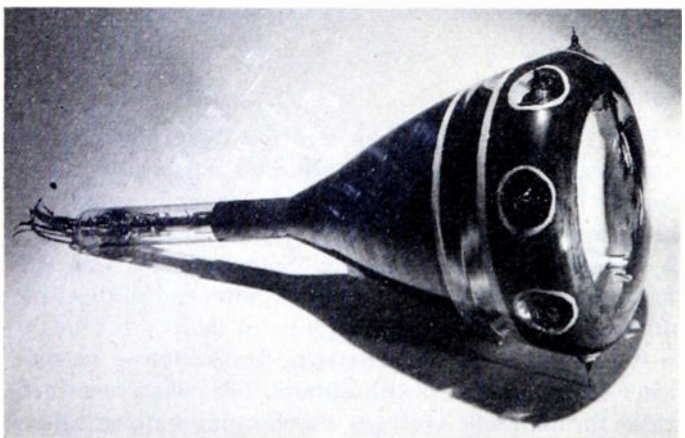

Fig. 1—Experimental grid-controlled color kinescope.

* Decimal classification: R583.6×535.6. Original manuscript received by the Institute, August 15, 1951.

† RCA Laboratories Division; Radio Corporation of America, Princeton, N. J.

[1] A. B. Bronwell, "A new viewing tube for color television," *Tele-Tech*, vol. 7, pp. 40–41 and 60–65; March 1948.

II. General Description of the Tube and Its Operation

A. Two-Color Tube

As an aid in understanding the three-color tube operation, the simpler two-color version will first be described.

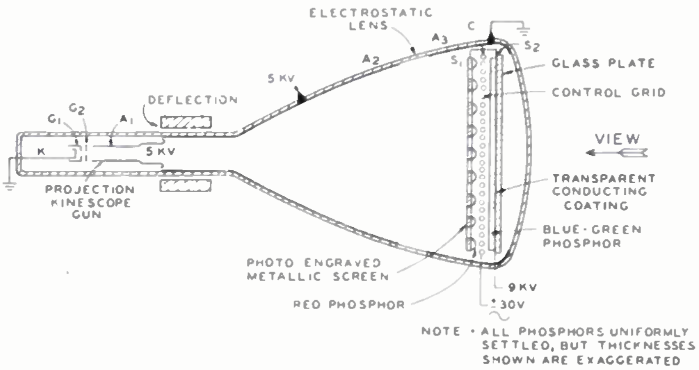

Fig. 2—Two-color, single-gun, grid-controlled color kinescope.

Fig. 2 is a diagrammatic representation of a typical two-color single-gun grid-controlled kinescope. Characteristic operating voltages are shown. Here a conventional kinescope gun scans in normal fashion an array of screens shown as S_1, C, S_2. Screen S_1 consists of a metallic grid structure perforated by photoengraving. On the viewed side of this screen a red phosphor is uniformly settled. A high-transmission mesh of finely woven wire is used as the color-control grid C. Screen S_2 consists of a clear sheet of glass upon the scanned side of which is formed a transparent conducting layer. The thickness of the glass is determined by mechanical strength only. An electrical connection inside of the tube is made to the conducting layer in parallel with the screen S_1, unless it is desired to bring these elements out separately. A blue-green phosphor, complementary in color to the red, is uniformly settled upon the conducting coating in a thickness which is a compromise between phosphor efficiency, light transmission, and secondary electron collection.

In operation, the voltage of the control grid C determines whether or not the scanning beam will penetrate it, and thus, whether the red or blue-green screen will be activated at a given time. If C is about $+30$ volts, the beam passes through it and is then accelerated again up to several kilovolts to strike the blue-green phosphor. If C is negative, the beam, energetically unable to reach it, is reflected, and returns to scan the red phosphor. The graphite wall coating is divided to form an electrostatic lens which insures normal approach of the scanning beam to the screen over all parts of the raster. The three screens are spaced as closely together as possible to avoid parallax. Voltage breakdown sets a lower limit to the spacing.

When the color changes are to be made at a rapid rate, it is necessary to consider the capacitance of the circuit. The high capacitance between the control grid C, and screens S_1 and S_2 is biased through a high impedance bleeder. In this way the capacitance, which is driven by the color changing voltage, is reduced to the free space capacitance of the combination S_1, C, and S_2; this varies about linearly with screen diameter in distinction to the parallel plate capacitance which varies as the square of the diameter. Instead of applying the color-control voltage to this grid combination, it can alternatively be applied to the electron gun which has even lower capacitance. In this case, the voltage of C is held fixed, and the cathode, control grid, and screen grid of the electron gun are varied together. The color control voltage used is too small with respect to the accelerating voltage to affect appreciably either focus or scan size.

In the arrangement shown in Fig. 3, two separate electron guns are used. The color control grid C is biased at a fixed voltage, shown here as ground. The gun cathodes are biased at potentials such that the beam from one gun (biased negatively) can penetrate the screen C and scan the blue-green phosphor at all times that the current from this gun is on. The other gun, biased positively with respect to the control screen, gives an electron beam which is unable to penetrate screen C, is reflected, and always scans the red phosphor. The guns differ in potential so slightly that their scanning patterns are substantially alike. The two-gun tube is suited for either simultaneous or sequential operation with each beam automatically scanning only its own color screen. A double unit gun with separate cathodes and common control-grid and anode elements can also be employed.

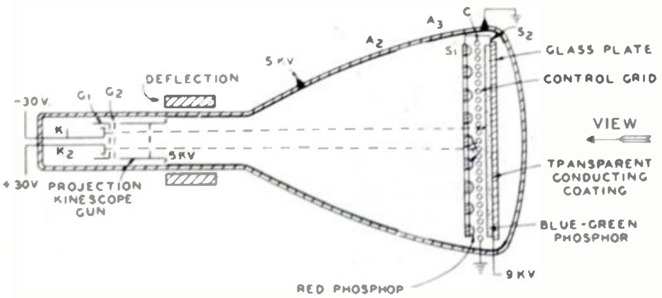

Fig. 3—Two-color, two-gun, grid-controlled color kinescope.

B. Three-Color Tube

Fig. 4 shows the three-color, single-gun arrangement, in which an added color control grid and phosphor screen are present beyond the screens shown in the corresponding two-color arrangement of Fig. 2. Green, red, and blue phosphors are used here. The higher resolution desired in the green has suggested its location on the glass plate, while the red phosphor is uniformly settled on the next phosphor screen. The blue phosphor, least critical in resolution, is uniformly settled on the screen farthest from the viewer. Other factors, such as relative efficiency of the three phosphors, may in some cases suggest a rearrangement of the phosphor locations. For better efficiency for the blue light, which reaches the observer through the red screen, the transmission of the latter is chosen higher than that of the blue screen. Transmissions of 55 per cent to 60 per cent for the red and 35 per cent to 40 per cent for the blue give very nearly equal brightness to the observer; this will be discussed later. The color control grids C_1 and C_2 are again made of high-transmission stainless steel woven mesh.

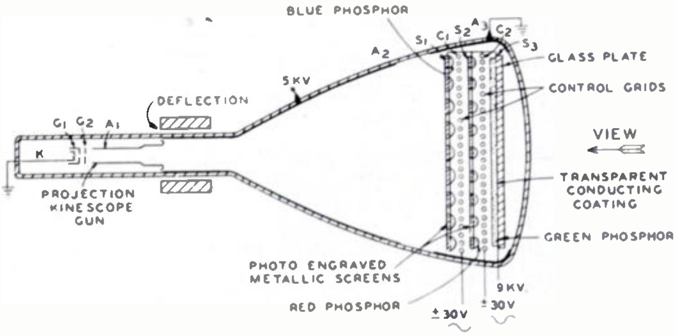

Fig. 4—Three-color, single-gun, grid-controlled color kinescope.

In operation, when both C_1 and C_2 are made positive by say 30 volts, the beam penetrates both control screens and scans the green phosphor. If C_1 is positive and C_2 negative, the electrons are reflected before they reach C_2 and return mainly to scan the red phosphor. If C_1 is negative, the beam is reflected before it reaches it, and scans the blue phosphor. The screens are again all spaced as close together as possible, consistent with adequate voltage breakdown characteristics, to minimize the parallax seen by an observer appreciably off the axis of the tube.

For a sequential color presentation, the colors are keyed by sine-wave voltages on each of the two color control grids with suitable phasing between the two waves. Alternatively, the color change may be effected by varying the gun potential while the two color control grid voltages remain fixed. This has more advantage here than in the two-color case because of the greater reduction in capacitance, for it is not possible with two color control grids to swing only their free space capacitance. A simultaneous presentation with the single-gun tube is achieved by correct application of the color control voltages to the two control grids.

Fig. 5 shows a three-color tube using three separate electron guns for either simultaneous or sequential presentation. With the voltages shown, the beam from the cathode K_1, biased -30 volts, can penetrate both C_1 and C_2 to scan the green phosphor. That from the cathode K_2, biased $+30$ volts, can penetrate C_1, but not C_2, and will turn around just before reaching C_2 and scan the red phosphor. The beam from the cathode K_3, biased $+90$ volts, will be unable to penetrate either C_1 or C_2, will be reflected at C_1 and scan the blue phosphor. Thus, as in the two-gun, two-color case, each gun scans its own color at all times that its beam is biased on.

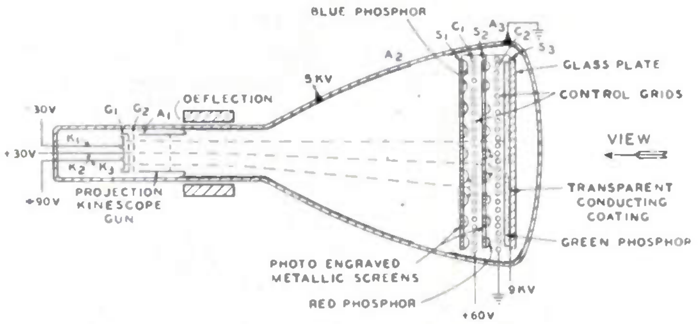

Fig. 5—Three-color, three-gun, grid-controlled color kinescope.

Special guns containing three separate cathodes, a single control grid with three apertures, a single screen grid, and single first anode have been designed[2] and used in sealed-off three-color grid-controlled kinescopes. Each of the cathodes is spaced at a different distance from the common control grid of the gun to allow for the different biases put on the cathodes. Thus, a given voltage change impressed on the gun cathodes produces the same change in current from all three units of the gun.

III. Screen Mounting

Since a high voltage is needed on the phosphor screens to assure bright patterns, the spacing between screens and color control grids should be sufficient to prevent breakdown. Large spacing, however, introduces more parallax. For a given spacing, parallax can be specified as a function of tube size and total viewing angle. While this will be discussed in more detail later, it can be said here that all these considerations make it desirable to have very flat screen surfaces tightly stretched to balance the pull of electrostatic forces between adjacent screens and to insure that no wrinkles are present which would lower the maximum permissible operating voltage.

The electrostatic force between two parallel screens for about ten kilovolts operating potential and a 9-inch diameter picture amounts to about 2 kilograms. The intermediate screens are subject to roughly this same force from each direction, so that the net force tending to pull them to one side is much reduced. The front screen is a rigid, immovable glass plate. The screen nearest the gun, however, must withstand the strong unbalancing force and should be relatively thick to be as rigid as possible. This thickness does not contribute to increased parallax, as it is beyond the last phosphor.

Mechanical tightening rings have been used for stretching both the woven color control grids and the photoengraved phosphor holding screens. In the simplest version the screens were stretched by two concentric rings, with a radial spacing between them slightly greater than the flat stock thickness of the photoengraved screens, or slightly less than the lapped wire thickness of the woven grids. For experimental use more complicated rings sets were designed to clamp the screens, and to permit easy assembly, disassembly, and local tightening around the periphery by means of small screws. In both cases mica spacers were used to separate one screen from another.

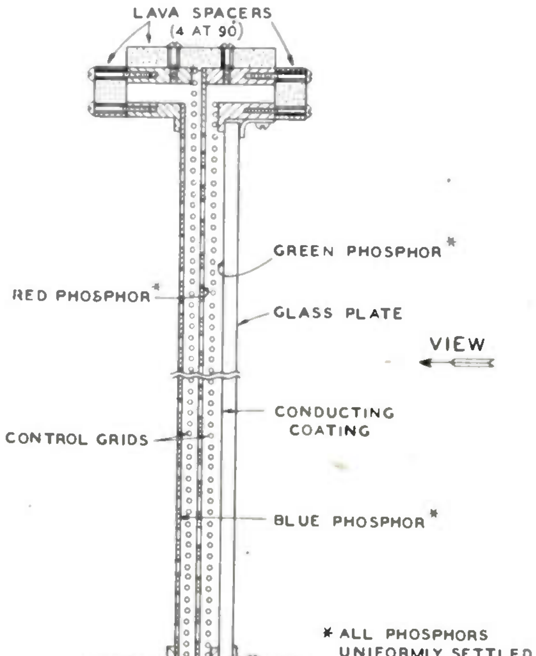

Fig. 6—Screen assembly, three-color, grid-controlled color kinescope.

By making use of the difference in expansion coefficients of the screen material and mounting rings, it is possible to obtain very tightly stretched screens soldered to these rings in a hydrogen furnace. This mounting means is light and uses a minimum of bulb space. Fig. 6 shows a diagrammatic cross section of a three-color screen assembly using screens stretched by this method.

[2] Designed by H. C. Moodey and D. D. Van Ormer, RCA Victor Division, Lancaster, Pa.

IV. Phosphor-Screen Design Considerations

A. Screen Material, Thickness, and Mesh

To avoid a slight moiré pattern between the red and blue phosphor screens in the three-color tubes, these two screens must have identical mesh spacings with no accumulative error. Also, the phosphors should be settled on a flat surface, with no phosphor in the openings to be encountered by the beam approaching from the gun. Since these considerations rule out woven wire screens, it was felt that photoengraved screens offered most promise.

Photoengraved screens of both copper and supernickel proved satisfactory, but preference was given to the latter because of its greater stiffness and brighter reflecting surface. Screen thickness of 0.006 inch proved to be a good compromise between stiffness and satisfactory screen fabrication as to transmission and uniformity of etching. Screens of excellent uniformity, etched from both sides, were commercially available. While the 60 mesh screen used in experimental tubes is capable of giving about 400 lines resolution in a 9-inch picture, one can choose a finer mesh screen when higher resolution is desired.

B. Efficiency versus Phosphor-Screen Transmission

It is of interest to determine the effects of the screens on the efficiency of utilization of the gun beam current to produce light, as compared with a simple monochrome kinescope operating with the same beam and at the same voltage. The assumption will be made that, upon direction reversal, the beam will have a uniform density distribution over the screens on which it falls back. This has been closely verified experimentally. Let us consider the two-color case.

1. Two-Color Case. The current penetrating the red screen is I_0T_R where I_0 = beam current, and T_R = fractional transmission of the red screen (Fig. 7). To reach the blue-green screen, this current is attenuated by the control grid of transmission T_c, therefore

$$I_{BG} = I_0T_RT_c. \tag{1}$$

On the other hand, for the electrons reflected back, the current actually striking the red screen is given by

$$I_R = I_0T_R(1 - T_R). \tag{2}$$

Furthermore, the light from the red screen is reduced by the control grid before it reaches the observer. If P is a performance factor to which the light reaching the front screen of the tube per unit beam current is proportional, one can write:

$$P_{BG} = \frac{I_{BG}}{I_0} = T_RT_c \tag{3}$$

$$P_R = \frac{I_R}{I_0} T_c = T_RT_c(1 - T_R).$$

The performance factor I_{BG} is linear with the red screen transmission, while that of the red screen, P_R, will be a maximum when $dP_R/dT_R = T_c(1 - 2T_R) = 0$. This gives

$$T_R = 0.5 \text{ or 50 per cent (a broad maximum).} \tag{4}$$

A common practical value for T_c is 60 per cent, for which

$P_{BG} = 30\%$
$P_{RED} = 15\%$ Performance factors for 2 colors, one gun, (5)

or

$P_{BG} = 60\%$
$P_{RED} = 30\%$ 2 color, 2 gun case. (6)

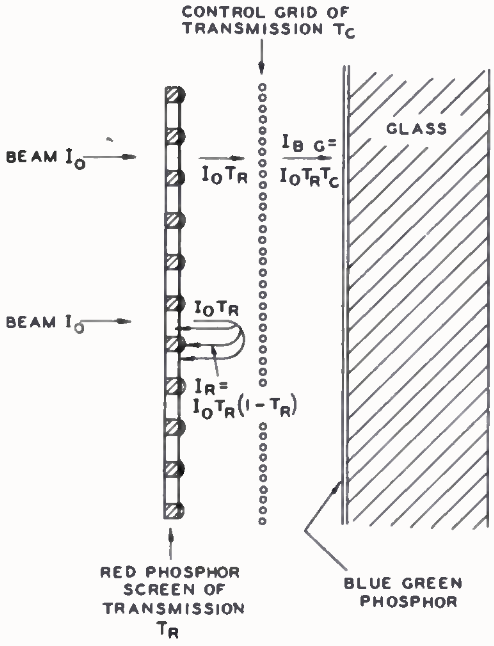

Fig. 7—Currents in two-color kinescope.

Although the red efficiency indicated here on a basis of screen transmission alone is only half of that of the blue-green, several other factors enter into the relative output brightnesses of the two screens. The blue-green phosphor is intrinsically somewhat more sensitive than the red and its thickness cuts down the red light passing through it slightly more than its own light. However, the blue-green phosphor can be settled in a thinner layer than usual so as to offer as little effect as possible on the efficiency and resolution of the red image. This reduces its effective efficiency. Also, because the red phosphor is scanned on its viewed side, and of more importance, because it is laid down on a bright reflecting surface, its brightness is enhanced. In summary then, the higher efficiency of the blue-green phosphor over the red, as determined by the screen transmission equations, can be balanced by other factors, the principal one of which is the thickness of the blue-green layer.

2. *Three-Color Case.* In the three-color case, the considerably more involved efficiency equations, as determined by screen transmissions, take two forms, depending on whether the phosphor screen spacing is large or comparable with the screen mesh size. If the spacing is large, the attenuating effect of the red screen on the blue light which must pass through it is proportional to the simple red screen transmission factor T_R. For close spacing, because of the red and blue screen alignment, the webs of the red screen directly cut off some of the light from the phosphor on the webs of the blue screen. This reduction in blue light is by a factor greater than the ratio of web area to total area, and is given by multiplying the light from the blue by the factor $(T_R - T_B)/(1 - T_B)$, which expresses the open area of the red screen directly opposite the blue webs to the fractional area of the blue webs.

The performance factors (based on screen transmission) will always be higher for the green than for the red and blue. But here again, the over-all performance of the green screen can be lowered to that of the other two, if desired, by reducing the amount of green phosphor deposited. The highest set of performance factors is obtained when the equations are solved under the condition that the blue performance factor be a maximum. In the practical case the red screen transmission should be higher than the blue, but is prevented from reaching its optimum value by the maximum obtainable screen transmission. A typical transmission value for both T_R and T_c is 60 per cent. For this transmission, the optimum value of T_B from the equations is 50 per cent for wide spacing and 28 per cent for close spacing. The practical tube has more nearly approached the wide spaced case for which the three performance factors are

$$\begin{aligned} P_B &= 5\% \\ P_R &= 7\% \qquad \text{3 color, single gun} \\ P_G &= 18\% \end{aligned} \tag{7}$$

or

$$\begin{aligned} P_B &= 15\% \\ P_R &= 21\% \qquad \text{3 color, 3 gun.} \\ P_G &= 54\% \end{aligned} \tag{8}$$

These performance factors take account of losses in beam passing forward through the screens, losses in effective beam passing back out of the holes in the red and blue screens after direction reversal, and losses in light passing out from the blue and red screens through the screens in front.

C. General Comments on the Phosphor Screens

In practice, during assembly, the red and blue phosphor screens of like hole patterns are lined up by eye to sufficient approximation by means of a diffuse light passing through these two screens in series. These are the only two screens aligned. When the phosphors are settled on the screens moderate care must be taken to insure that no phosphor lodges in the holes in the screen.

When the electrons are turned around to strike the red screen a fraction of them passes back through the interstices of this screen. About half of these electrons pass back out through the holes in the blue screen towards the gun and cause no ill effect. Others, striking the blue phosphor, give rise to light reaching the observer when he should see only red. However, this spurious blue light is only about 10 per cent of the red, because it is excited by many fewer electrons and, after being produced, is attenuated further by having to pass through two more screens on the way out than does the red light. While this blue light is small, it can still be noticed with the present phosphors in the form of a slight dilution of the red.

V. Color Control-Grid Design

It is desirable to have the color control-grid transmission as high as possible from the standpoint of beam utilization efficiency and light transmission. On the other hand, a large number of mesh is advantageous for giving a low numerical cut-off (reflection) voltage. Since however, as one goes to a higher mesh number, screen transmission usually drops, a compromise between these factors must be effected. Color control grids of 230 mesh, stainless steel woven screen etched to 60 per cent transmission have proved quite satisfactory.

A uniformly perpendicular approach of the scanning beam to the control grids will permit the use of minimum positive swing of the switching voltages on these grids. In addition to making the switching easier, this lowered voltage swing lessens the chances of primary electrons hitting these grids and giving rise to secondaries which can find their way to the wrong color screens. While a more open mesh minimizes this secondary electron effect, it increases the negative voltage swing required for complete reflection. Uniformly perpendicular approach of the scanning beam was accomplished with the use of an electron lens formed by splitting the graphite wall coating, as shown at $A_2 - A_3$ of Figs. 2–5. The lens action, coupled with the lens effect between A_3 and S_1, reduced the positive swing from over 100 V to about 25 V. An unpublished analysis of this lens effect by E. G. Ramberg predicts the same order of improvement. Because of the greatly reduced secondary electron effects at this voltage, the control-screen mesh could be made finer, which gave better negative control and thus lowered the negative voltage required for reflection. It was now found possible to pass uniformly from one color to another over the whole raster area simultaneously.

VI. Switching Considerations

No switching is required for multiple-gun operation as noted in Section II. For single-gun operation a square wave switching pulse on the control grids is not necessary; sine wave switching has been found satisfactory in both the two-color and three-color cases. The sine-wave subcarrier of the RCA color system was employed for this switching,[3] using a 3.58 megacycle color rate. In operating a two-color switching device from a three-color signal, the driving circuit used for switching the grid-controlled color kinescope permits variation of both amplitude and phase of the sine wave. The most satisfactory operation with a two-color tube having a red and a blue-green screen has been with the tube switched to red to correspond with the red video signal and to blue-green in correspondence with equal parts of blue and green video signals as shown in Fig. 8a. In addition to the sine wave amplitude and phase controls, a variable dc bias source is supplied to set the level of the control screen with respect to cathode potential. This has provided added adjustment to make up for differences between optimum positive and negative swings required for various experimental variations in the tubes. Generally, it has been found that a small positive bias is useful. Too large a bias will give poorer color rendition, however, by changing the time sharing between the colors as shown by the dotted curve of Fig. 8a. A further improvement in color rendition has been observed when blanking is applied to the gun at the double frequency (7.16 mc) to blank during the time the sine wave switching passes near zero.

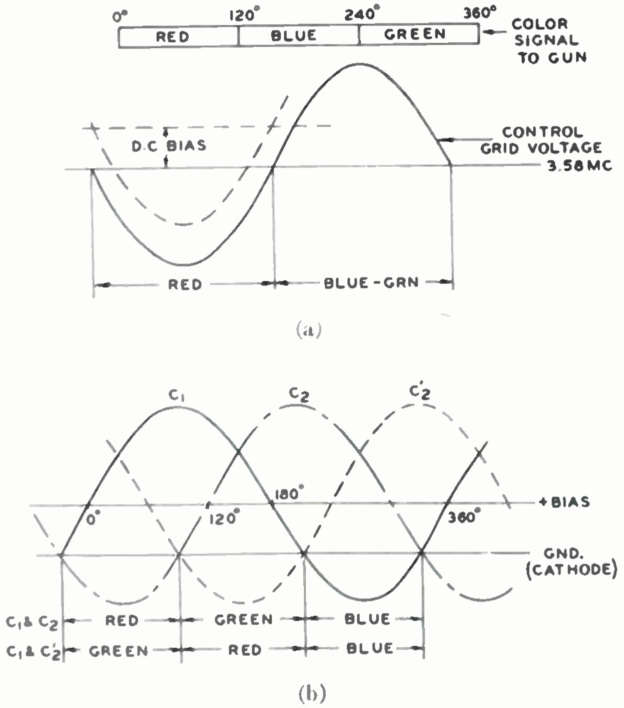

Fig. 8—Sine wave switching of grid-controlled kinescopes. (a) Two-Color. (b) Three-Color.

[3] RCA Laboratories Division, "A six-megacycle compatible high-definition color television system," *RCA Review*, vol. 10, pp. 504–524; Dec. 1949.

The voltage polarity combinations of the two control grids in the three-color tubes for the various colors are:

	C_1	C_2
Green	+	+
Red	+	−
Blue	−	±

If one impresses a sine wave of a given amplitude and adjustable phase on C_1 (solid curve of Fig. 8b) and another sine wave of equal amplitude and 120 degrees lag on C_2 (dot-dash curve), and applies a positive dc bias of $\frac{1}{2}$ of the sine wave amplitude on both of these control grids, then the switching combinations given in the above table can be reproduced. This gives the sequence red, green, blue as shown. The opposite sequence is given when the sine wave on C_2 leads that on C_1 by 120° (curve C_2').

A 3.58-megacycle sine wave generator with enough phase shift to allow adjustment of the phase of the color switching at the screens with respect to the color signal phase fed the kinescope gun, applies the signal to C_1. Another sine wave generator, whose phase is adjustable about that of the first generator, applies a sine wave to the second control grid C_2. Thus, after the phase ϕ_2 is adjusted with respect to ϕ_1, the phase difference $\phi_1-\phi_2$ does not vary when ϕ^1 is then changed to give correct color interlock between these switching voltages and the video signal to the gun. Other voltage arrangements are possible, but appear more complicated and/or make use of higher switching frequencies. Blanking at 11.4 mc applied to the gun near the switch-over time from one color to the next improves the color reproduction but with a slight reduction of brightness.

VII. Experimental Results

Many tests of the grid-controlled color kinescope have been made in a demountable vacuum system, and sealed-off tubes have been built and operated with color pictures up to 8 inch diameter. The kinescope resolution was observed to be about 300 lines on the front phosphor screen which the scanning beam strikes without reversal. A 15 per cent drop in resolution was noted when the beam was reversed in direction to strike the other phosphor screens. The use of higher mesh phosphor screens or the same mesh in a larger tube would improve the resolution. A single gun tube had a measured brightness of a few foot lamberts using earlier less efficient phosphors. The three-gun tubes have about three times more brightness than the single-gun versions. Improved phosphors would improve the brightness considerably.

The lowest satisfactory adjacent-screen spacing has been about 25 mils for 9 kv operating voltage. Analysis of a simplified model for determining parallax effects has indicated for this spacing and 300-line green resolution, a 45-degrees total viewing angle on a $12\frac{1}{2}$ inch tube and 50 degrees on a 16 inch tube. However, in the latter case one might prefer to use a wider spacing, say 35 mils in order to use a higher accelerating voltage consistent with a larger size raster. This would reduce the viewing angle to about 40 degrees.

Both two and three-color tubes were operated with the RCA color system signal.

VIII. Conclusions

The grid-controlled kinescope has several desirable properties. First, since the phosphors are uniformly settled, there is no need for accurate settling of phosphor dots or lines. Second, there is no registry problem in the two-color version, and only at most a non-critical registry of two screens in the three-color arrangement. Third, the operation of the tubes is very insensitive to stray magnetic fields.

On the other hand, there exists the fundamental consideration of balancing parallax against brightness in the directly viewed tube. Improved stiffness and stretching of the screens can improve the tube operation in this respect. The parallax is considerably reduced by making use of a projection screen.

Acknowledgements

The writer wishes to express his appreciation for the support and encouragement of A. Rose, under whose direction the work was carried out. In addition, credit is separately due to several groups and individuals for their participation: to R. W. Smith for his aid in the assembly of tubes, and to J. P. Smith, M. Topke, L. E. Flory, W. Pike, J. Dilley, and G. R. Gray for the design and building of the testing circuit equipment.

Development and Operation of a Line-Screen Color Kinescope*

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Summary—A color-television receiver employing a single kinescope of the line-screen type has been developed. The kinescope screen consists of many hundred narrow parallel phosphor strips of the three primary colors, arranged cyclically. In the method investigated in greatest detail, the raster scanning lines are parallel to the phosphor strips. Circuit means are provided to cause the scanning lines to coincide with the phosphor strips of a single color. The beam is then deflected by a "stair-step" wave to the adjacent lines of the two remaining colors to generate color-dot areas in synchronism with the received color signal. The required registration of scanning lines with the screen elements is obtained by means of a servo circuit deriving control information from secondary-emission-signal areas on the kinescope screen. Various alternatives to this arrangement have also been investigated. Kinescopes of 16-inch envelope diameter have been employed to give color pictures of high horizontal definition and adequate color purity.

I. Introduction

Among the numerous means for portraying color images by a single kinescope, one that has long proved attractive to inventors has been the line-screen kinescope.[1,2] Undoubtedly the reason for such interest is the apparent simplicity of the picture tube. The major problem of securing the proper color images is then transferred to the circuit designer. In the experiments that were conducted, kinescopes were built and a number of circuit arrangements were investigated.

A kinescope of the line-screen type employs a luminescent screen consisting of narrow parallel strips or lines of phosphor materials emitting the three primary colors and arranged consecutively on the glass surface. In a typical tube of the experimental type to be described later, a rectangular piece of plate glass located within the kinescope envelope forms the viewing screen. On the appropriate surface of this plate are deposited several hundred strips of phosphor materials parallel to one edge of the glass. The three colors are repeated cyclically: red, green, blue, and so on.

The design of the electron-optical system of the kinescope is such that the effective diameter of the electron beam at the screen is less than the width of each color phosphor strip or line. At any instant, then, the screen emits light of a color dependent upon the position of the beam with respect to the line structure. The problem becomes one of securing registration of the spot with a phosphor area of the correct primary color according to the color information contained in the received video wave.

Several scanning arrangements suggest themselves. One of these requires the orientation of the screen so that the horizontal scanning lines of the television raster are parallel to the phosphor lines on the screen. The size of the raster is chosen so that there is one scanning

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[1] R. Ruedenberg, U. S. Patent 1,934,821; issued November 14, 1933.

[2] M. von Ardenne, British Patent 388,623; complete accepted March 2, 1933.

line for each group of three phosphor lines (i.e., a "triplet" of the three primary-color lines). Then, in principle, the scanning can take place so that the spot of light produced by the electron beam traverses successively all the lines of a single color during each field, making a pure color raster visible. If the centering adjustment is changed to displace the raster vertically by the center-to-center distance between adjacent phosphor lines, the entire screen will emit the second color. Of course, a further displacement by the same amount can then produce the third color.

Means must be provided for establishing this coincidence of scanning path with the phosphor lines and for changing the vertical centering in accordance with the color identification of the video signal. The circuits for accomplishing this constitute a control, or servo, device, about which more will be said in the remainder of this discussion.

Other screen orientations and scanning arrangements have also proved to be useful. Reference is made to this subject in Section V of this paper.

The control information needed by the servo to specify the instantaneous position of the electron beam on the screen may be derived from various sources. Conductive surface paths on the screen represent one possible method. Another utilizes phototube pickup of light from the phosphor screen. A third depends upon contrasting secondary-emission areas on the screen surface. This last-named method is to be discussed in this paper.

The methods for obtaining correct registration of the beam may be of several types, such as (1) precision deflection with no servo control, (2) continuous control during scanning, and (3) intermittent control, occurring only during a portion of the scanning cycle.

Because of the current importance of a single kinescope for color-television reproduction, the major part of the discussion will refer to this use. It should be borne in mind, however, that some of the methods and results will find application in camera tubes, in monochrome receivers in which precision of geometric deflection must be obtained, in facsimile, in Ultrafax, in kinescope recording, in radar displays, and in such specialized uses as closed-circuit television systems where independent scanning standards may be established.

II. Kinescope Design

The idea of using phosphor lines of different colors for the presentation of color information on the face of a cathode-ray tube is old.[1,2] In the early state of the art it was realized that the making of the screen itself constituted one of the main problems. Experimental work on such kinescopes was undertaken at RCA some years ago to study and demonstrate properties of the screens. Early 9-inch kinescopes which were built revealed various shortcomings in the tubes and indicated some of the general problems remaining.

Many of these problems were solved by advances in design: an improved red phosphor[3] came into more general use, an electron gun capable of giving a much smaller spot diameter was developed,[4] and the process of aluminizing screens was brought out.[5] Screen charging was eliminated and increased brightness was obtained by this last-named development.

The kinescope tubes used in the present development have been both of the 9-inch and 16-inch size. These designations refer throughout to the maximum cone diameter. The smaller size tubes have all-glass envelopes and have been built experimentally to test principles to be incorporated into the larger metal-bulb type. The technique of building the 16-inch metal kinescopes has involved the solution of numerous mechanical and production problems described elsewhere.[6] For the tubes considered here, however, the screen is not assembled from several parts that must be properly registered together, as is the case in the shadow-mask color kinescope.[7] The discussion will be concerned mainly with the 16-inch tubes. A drawing of a typical tube is shown in Fig. 1.

A. Design of 16-Inch Kinescope

The metal bulb is similar to that used in the commercial 16AP4 kinescope except that it is divided in a plane near and parallel to the tube face. The screen can then be assembled on its mounting plate and attached inside the rear section of the metal bulb after the conical magnetic shield of high-permeability material has been inserted. The front annular section of the bulb with the clear-glass face plate sealed to it is welded to the conical bulb section after these assembly operations have been completed.

The secondary-emission control signals required for the servo system to be described later are picked up on the collector electrode near the screen, as shown in Fig. 1. The electrode is an insulated metallic strip about $\frac{1}{4}$ inch wide, supported at right angles to the screen and located adjacent to one side of the secondary-emission signal area. A connection is brought out through an insulated lead in the cone.

In accordance with usual practice, a conductive coating is placed on the inside of the flared portion of the glass neck. However, a ring of uncoated glass is left adjacent to the seal to the outer metal cone. A difference of potential can thus be established between cone and neck to provide an electrostatic lens which may be required for some purposes.

The cylindrical portion of the neck is about 1.5 inches

[3] H. W. Leverenz, "An Introduction to Luminescence of Solids," John Wiley and Sons, Inc., New York, N. Y., p. 147; 1950.

[4] D. S. Bond and V. J. Duke, "Ultrafax," *RCA Rev.*, vol. 10, pp. 99–115; March, 1949.

[5] D. W. Epstein and L. Pensak, "Improved cathode-ray tubes with metal-backed luminescent screens," *RCA Rev.*, vol. 7, pp. 5–10; March, 1946.

[6] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask tri-color kinescopes," Proc. I.R.E., pp. 1241–1245; this issue.

[7] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

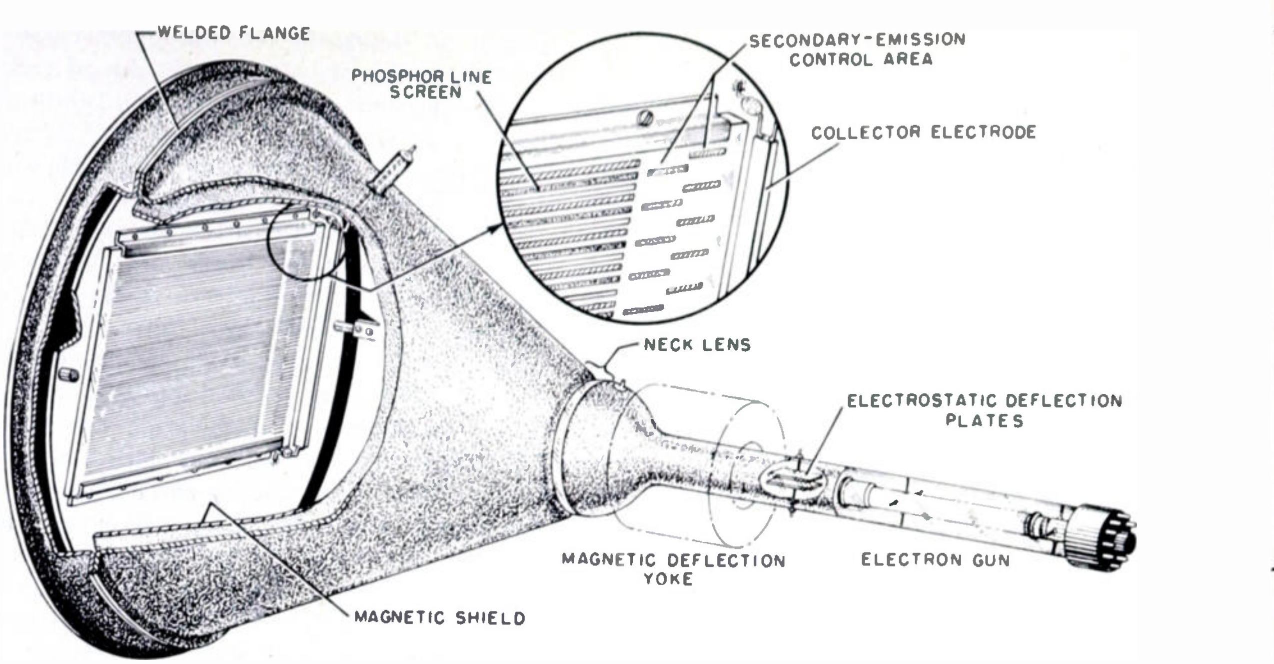


Fig. 1—Sixteen-inch line-screen kinescope.

outside diameter, thus allowing considerable lateral adjustment of the surrounding magnetic deflection yoke, which is 2 inches inside diameter.

Vertical electrostatic deflection is employed in the color-registration circuits tested to supplement the main magnetic deflection in the vertical plane. It is much more practical to include electrostatic deflection because of the very-high-frequency components present in the control signals. The total deflection angle required in the electrostatic portion is less than 0.5 degree. Consequently, the separation of the electrostatic plates is determined mainly by the beam diameter. Rectangular plates are located between the gun and the magnetic-deflection-field region, as shown in Fig. 1. These are accurately centered with respect to the precision-bore tubing constituting the neck. At a second-anode voltage of 18 kv, only a 6-volt potential difference between the deflection plates is required to shift the beam from one color line to the next.

B. Screen Deposition

Accurate deposition of the parallel fine phosphor lines has been achieved through two satisfactory methods. In the first method, the screens are made by settling the phosphors through a metal mask. The latter consists of a grid of parallel wires stretched across a frame. The wires are milled off flat on one side to allow closer contact with the glass plate on which the screen is to be deposited. The spacing between adjacent wires is such as to give an unmasked area the width of the phosphor strip of one color. After one color has been deposited, the mask is moved along the plate and normal to the lines. The lines of the second phosphor are then settled in the proper location, after which the process is repeated for the remaining phosphor. The lines produced by this settling method are particularly even and uniform, and the edges are straight and sharp.

The second method employs a silk-screening technique very similar to that used for other three-color kinescopes.[8] The screens for the 16-inch tubes were all made by this process. A number of advantages were found for this method of screen production, principally the ease of producing the larger size screens in quantity.

Screens for the 9-inch tubes are 4.5 by 6.5 inches in size and contain 450 lines. Each phosphor strip is 0.010 inch wide, and adjacent strips are tangent. Thus, a triplet of three colors occupies 0.030 inch of screen height. The width of a triplet in the 16-inch tubes is also made 0.030 inch. There is a total of 720 lines on the screen of the 16-inch tubes, to conform to the arbitrary scanning standards discussed in Section IV A below. The screen size is 7 by 10.5 inches. It was found desirable to make each phosphor line 0.007 inch wide and leave a dark line 0.003 inch wide between adjacent colors. Slight defocusing or spot displacement is then more tolerable because the beam cannot strike adjacent color lines.

With all the screens used, the phosphor on the useful picture area was coated with a thin film of organic material and then aluminized in the conventional manner.[5] The phosphor materials used for blue and green are silicates. Cadmium borate was chosen for red.[3] More efficient red phosphors have subsequently been developed.

[8] N. S. Freedman and K. M. McLaughlin, "Phosphor-screen application in color kinescopes," Proc. I.R.E., pp. 1230–1236; this issue.

C. Secondary-Emission-Signal Production

Some of the control arrangements for use with line screens require a good secondary-emission signal of special shape. Information on suitable materials for producing contrasty signals at 18 kv is rather scarce since secondary-emission devices usually operate at much lower potentials. At the beginning of this work, it was observed that there was sufficient difference between the emission from the aluminum on the back of the three different phosphors to give a picture showing the line structure of the tube. As a rule, the cadmium borate lines stood out fairly strongly against the others. The reason for this difference was not fully investigated, but it appeared to be largely due to the roughness of the aluminum produced by the granular nature of the phosphor material. In other words, the signal was largely derived from the difference in secondary emission of rough and smooth aluminum. The available signal was further enhanced by using smooth aluminum as the surrounding area and rough aluminum on phosphor as the signal area. The required surfaces were obtained by silk screening the desired signal area with cadmium borate and then aluminizing this area directly without the application of an organic film. Each of the first tubes built in this manner produced a signal that was judged to be reasonably satisfactory at the time.

While the signals from rough and smooth aluminum were fairly good, they were not as large as could be desired. A number of experimental tubes were made in which the signals from various other contrasting surfaces were observed under actual operating conditions.

One type of surface was particularly attractive. It was chosen because it gave a good signal and, at the same time, could be readily produced and registered with the phosphor lines. This pattern consisted of dashed lines of bare glass surrounded by smooth aluminum on glass. These bare-glass portions were obtained by a rather simple technique. The silk-screen process was used to deposit phosphor lines and short dashed lines in the required location. The whole screen, including the dashed lines, was then filmed, aluminized, and air-baked to remove the organic film. In order to obtain the bare-glass area, the phosphor in the dashed-line portion was brushed off. This operation also removed the aluminum on this portion, but did not affect the aluminum on the bare glass.

D. Electron Gun

The earlier work on line-screen kinescopes had indicated the necessity for an electron gun of exceptionally fine focus. This is evident from the figures given for line width. It was actually found that the effective beam-spot size at any point on the screen must be less than about 0.008 inch. An improved gun structure to meet these requirements had meanwhile been developed for Ultrafax.[4]

The improved electron gun is of the electrostatic-focus type. The magnification of the electron-optical system is reduced by employing a gun structure of almost twice the length of that of the RCA 5TP4 projection kinescope. The spherical aberration of the final electrostatic lens is minimized by a reduction in beam diameter in this lens. This stopping down reduces the usable beam current, but the maximum current remains adequate. Care was taken to insure symmetry of the electron-lens system: the metal tubing for the anode lens was held to close tolerances on roundness, and precision-bore glass tubing was used for the neck to permit accurate centering of the gun with spacing legs.

E. Focus and Geometric Distortion

The required spot diameter of 0.008 inch for the 720-line, 16-inch kinescopes could be readily achieved over the major part of the screen area. At the corners, particularly in the marginal area of the control pattern, focus was not entirely adequate with the conventional arrangement of focusing potentials. Part of the difficulty was due to changes in required ratio of first- to second-anode potentials at the extremes of deflection. This was corrected by electrical focus modulation produced by varying the first-anode potential. Further improvement was made by including a weak cylindrical lens in the electron-optical system to correct spot ellipticity or to produce deliberately an elliptical spot with its major axis horizontal. For the usual video bandwidth, this latter condition did not impair the horizontal resolution. The lens was produed by operating the *pair* of electrostatic deflection plates some 500 to 600 volts above second-anode potential.

As shown in the diagram of the metal-cone tube in Fig. 1, provision was made for producing an electrostatic lens (the "neck lens") between the flared portion of the glass neck and the metal cone. It had been determined previously that most of the pin-cushion shape of the raster could be removed by modifying the field distribution of the deflection yoke in the correct manner. However, it is desirable to have some electrical control over the amount of field modification to compensate for variations from yoke to yoke. With the deflection yoke as finally designed for this arrangement,[9] there still remained a slight amount of pin-cushion distortion. This could be completely eliminated by a ratio of cone voltage to neck voltage of about 1.2. When this voltage ratio was changed to 1.5, the horizontal edges of the raster could be made very slightly barrel shaped. In any case, the total bending produced was not large enough to affect picture geometry perceptibly, but the effect was nevertheless of importance in obtaining proper colors.

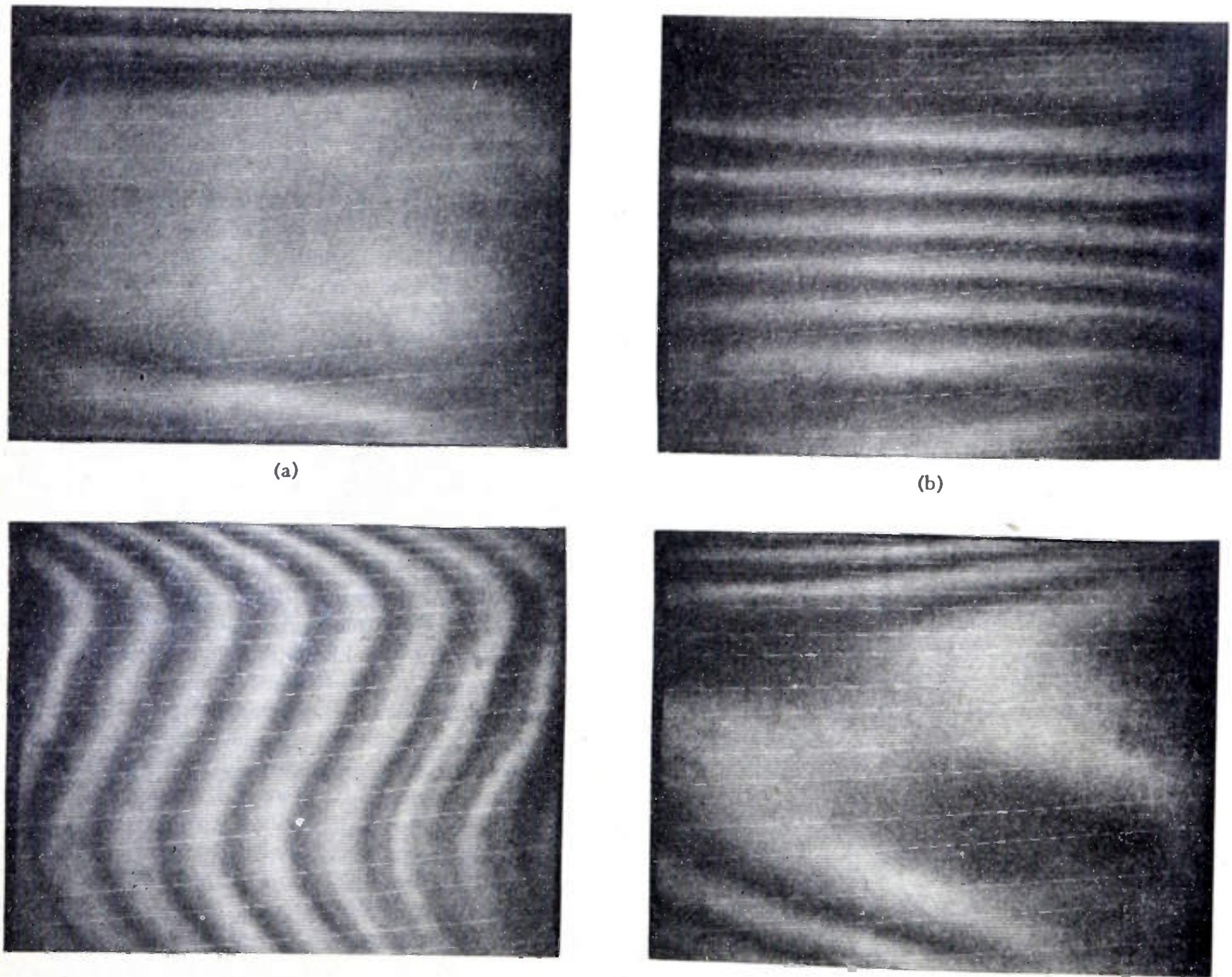
[9] A. W. Friend, "Deflection and convergence in color kinescopes," Proc. I.R.E., pp. 1249–1263; this issue.

III. Precision Deflection Method of Registration

The possibilities of achieving a satisfactory result with a three-color line-screen kinescope by accurate registration of the lines of the scanning raster with the corresponding screen lines were investigated in some detail. The purpose was threefold: to discover the lengths to which this method can be carried in the present state of the art, to develop elements needed in the circuits to be described in Sections IV and V, and to demonstrate how picture quality for other television applications can be bettered.

Kinescopes having 450 phosphor lines, i.e., 150 in each of the primary colors, served as the starting point. With the lines horizontal and parallel to the scanning lines, the requirements of precision deflection are almost entirely confined to the vertical-deflection channel and the magnetic-deflection yoke. The raster height must remain constant, and the scanning lines must be equidistant. A departure from either of these conditions by an amount sufficient to misplace the scanning beam vertically by one-half the separation of two adjacent phosphor lines causes a very prominent color change. Geometric precision to better than one part in 1,000 is thus needed even for these relatively coarse line screens.

It is instructive to note the analogy between the measurement of such departures from geometric exactness of scanning and the measurement of departures from perfect flatness in optical surfaces by means of light interference fringes. The well-known test for flatness of a glass surface involves bringing it into contact with a similar optically flat surface and observing the uniformity of the interference fringes in monochromatic light. Departures from a plane by a fraction of a wavelength of the light produce readily observed distortion of the fringe pattern.



(a) (b) (c) (d)

Fig. 2—Typical color fringe patterns of misregistered rasters on line-screen kinescope. (The bright narrow retrace lines should be ignored.) (a) Slight nonlinearity of vertical deflection. Maximum displacement error 0.8 per cent. (b) Vertical size incorrect by 3 per cent. (c) Deflection yoke rotated 1.5 degrees. Sweep linearity same as in (a). (d) Deflection-yoke axis not coincident with electron-gun axis.

In the case of the kinescope, a screen pattern of color fringes can be deliberately produced due to non-linearity of vertical scan, incorrect size, or geometric pattern distortion. This pattern is extremely sensitive to small defects. A typical situation that can be set up experimentally might be one in which vertical-deflection velocity is correct over the major part of the scan, but where considerable pin-cushion effect is present. Then at the corners of the screen there is a series of color fringes while the central zone across the screen is of a single color. A vertical displacement of the raster of 0.010 inch causes the single-color area to change from one primary color to a second. A vertical displacement might be due to change in centering adjustment, hum signals, motorboating in the vertical-deflection circuit, interlace, and the like. The picture is quite sensitive to any of these effects. The color pattern of fringes then gives quantitatively the displacement of the scanning path from a straight line. Photographs of the face of a line-screen kinescope showing the effects of incorrect adjustments are given in Fig. 2.

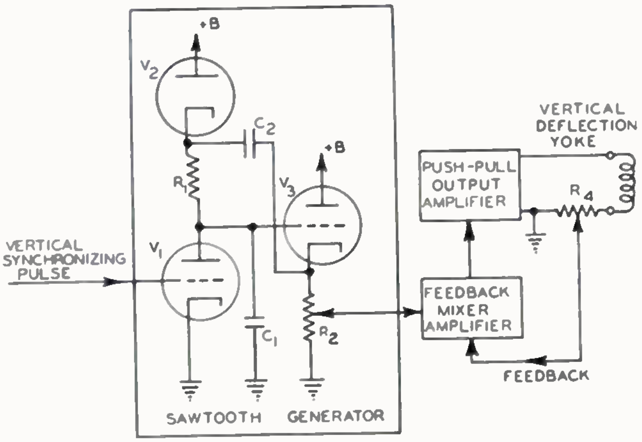


Fig. 3—Vertical-deflection circuit.

Tests were conducted on a television video system of arbitrary scanning standards with the 450-line kinescopes. The receiver vertical-deflection system, shown in Fig. 3, was designed to be as linear and as stable as was practicable. A sawtooth wave of good linearity is generated across capacitor C_1, which in turn is charged from a constant-current source through resistor R_1. This source includes diode V_2 and cathode-follower stage V_3. The sawtooth voltage across resistor R_2 is fed back through capacitor C_2 to the high-potential end of R_1. The potential of this latter point thus rises at approximately the same rate as the plate of V_1 to maintain constant current through R_1. Diode V_2 isolates R_1 from the B-supply during this part of the cycle. This "bootstrap" circuit has been utilized rather extensively in the past.[10]

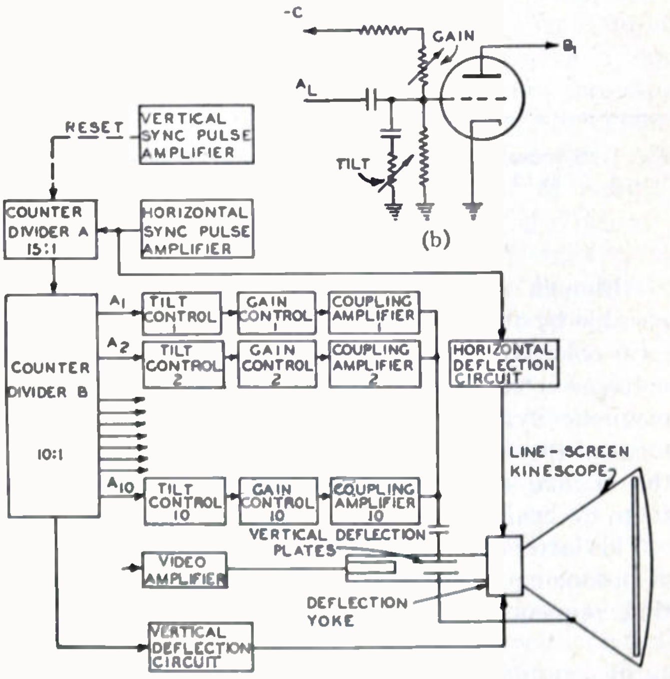
[10] T. Soller, M. A. Starr, and G. E. Valley, "Cathode-Ray Tube Displays," McGraw-Hill Book Co., New York, N. Y.; 1st ed., pp. 135–138; 1948.

A three-stage amplifier follows the sawtooth generator. This may be regarded as a wide-band audio-frequency amplifier passing a fundamental of from 40 to 60 cycles and the large number of harmonics necessary to reproduce the sawtooth wave. Since the current wave through the vertical-deflection yoke should be a reproduction of the generator sawtooth, the current through a low resistance R_4 is sampled, and the signal is fed back to the first amplifier stage. The signal is phased to give negative feedback around the entire amplifier loop.

The output stage is push-pull to reduce dc core saturation in the output transformer. A balancing control in the cathode circuits of the amplifier tubes in this stage is needed to reduce residual dissymmetry in the two plate currents. The apparatus is operated with a carefully regulated B-supply, and the heaters of the tubes are fed from a dc source. It has been found feasible to obtain linearity within 0.3 to 0.5 per cent with stable operation. After careful adjustment, the linearity can be maintained somewhat better than this for brief periods of time.

Scanning standards were established with the horizontal-scanning frequency 150 times the vertical rate. Thus, a few lines on the screen are not scanned because of the time lost in vertical retrace.

This discussion makes it obvious that it is necessary to correct vertical linearity further for 450-line tubes. Accordingly, a deflection wave of the desired shape was synthesized. This was done by correcting the deflection produced by the circuit of Fig. 3 by a series of adjustable voltage waves generated successively during each vertical scan cycle. The diagram of Fig. 4(a) illustrates the manner of accomplishing this result.



(a)

Fig. 4—Deflection circuit for synthesizing vertical-deflection wave. (a) Block diagram. (b) Typical pedestal channel.

A counter chain, dividing down from horizontal- to vertical-repetition frequency, controls the receiver vertical-deflection unit previously described. The final divider provides at the same time 10 pedestal waves occurring as shown in Fig. 5(a). The amplitude and the tilt of the top of each can be controlled independently. The 10 waves are combined to give a synthesized wave like that of Fig. 5(b), and this is applied to the electrostatic vertical-deflection plates. One will note that the main vertical deflection is magnetic and that only the correction is accomplished by electrostatic deflection. A method of obtaining the pedestals from the counter chain at points $A_1, A_2, \cdots A_{10}$ has been described by Grosdoff.[11] Gain and tilt controls and the coupling amplifier for each pedestal channel are shown in Fig. 4(b). Each of the 10 channels requires one-half of a double triode tube.

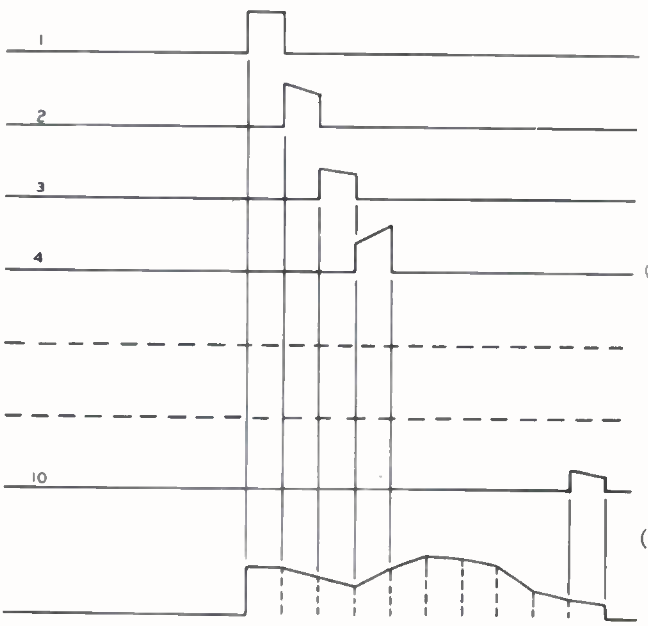


Fig. 5—Synthesized vertical-deflection wave. (a) Typical pedestals in 10 individual channels. (b) Combined wave.

Although adjustments were critical, it was found possible by this arrangement to obtain a raster of uniform color with the 450-line kinescopes. Power-supply voltages were regulated, the kinescope was shielded magnetically, and provision was made to secure uniform focus of the spot over the entire screen. Adjustment of the manual centering control would cause the raster to go cyclically from red, to green, to blue, and so on.

This latter adjustment suggests immediately a means of producing automatically the three color pictures in time sequence. Tests were conducted with the RCA color system[12] in which the color subcarrier frequency was of the order of several megacycles. This system permitted a dot-sequential type of presentation. It is obvious how frame- or line-sequential signals can also be accommodated.

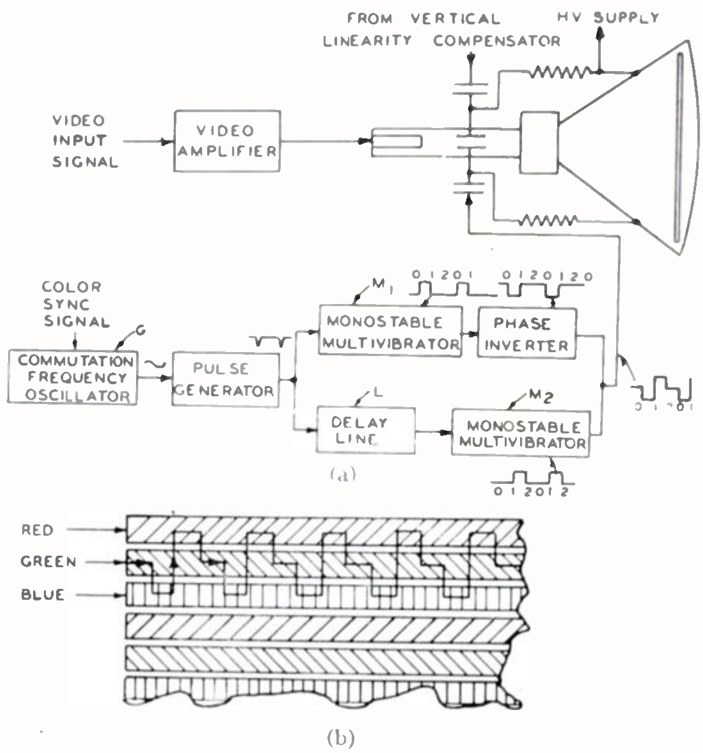


Fig. 6—Color commutation method. (a) Stair-step generator circuit. (b) Deflection path of electron beam on line screen.

In Fig. 6(a) the color-commutation method is shown for a dot-sequential presentation. The commutation-frequency oscillator G operates in synchronism with the color-system subcarrier. In the present case this frequency f_c was chosen to be 2.0 mc so as to be consistent with the arbitrary scanning standards adopted for test purposes during the early phase of this project. It can be synchronized and phased with the color subcarrier either by a "burst" of a signal of frequency f_c during line-blanking time or by direct connection with the transmitting terminal for laboratory purposes. Pulses are generated from the sine-wave output of G and used to trigger two multivibrators M_1 and M_2. Each of the latter produces a single pulse of length adjustable to one-third of a period of f_c for each trigger pulse, returning to its initial condition until another pulse is received. A delay line L retards the pulses fed into M_2 by one-third of a period of f_c. The output of one multi-

[11] I. E. Grosdoff, "Electronic counters," *RCA Rev.*, vol. 7, pp. 438–447; September, 1946.

[12] "A six-megacycle compatible high-definition color television system," *RCA Rev.*, vol. 10, pp. 504–524; December, 1949. Also "An analysis of the sampling principles of the dot-sequential color television system," *RCA Rev.*, vol. 11, pp. 255–286; June, 1950. In these papers the *color subcarrier* frequency is identified as the *sampling* or *commutation* frequency.

vibrator is inverted in phase and combined with the other. The waveforms at the various points in Fig. 6(a) show how the final desired "stair-step" wave is generated. This latter signal is applied to the vertical-deflection plates shown and has the correct amplitude to cause the spot to coincide successively with three adjacent phosphor lines. The deflection action is illustrated in more detail in Fig. 6(b).

The composite video signal is fed to the kinescope grid in the usual fashion. It was possible to obtain a color picture of over 35 foot-lamberts high-light brightness on the 4.5-by-6.5-inch screen at a second-anode potential of 18 kv. Color purity was judged to be satisfactory.

Careful attention to the winding arrangement and current distribution in the vertical coils of the deflection yoke[9] reduced the initial pin-cushion distortion to about one-half of a color fringe at the corners. This very small geometric distortion was then eliminated (or could be overcompensated to give barrel distortion) by the converging electron lens at the apex of the bulb cone described in Section II *E*. Any scanning line was straight to considerably better than 0.005 inch throughout its 6.5-inch length. The precision deflection system and the vertical-linearity compensator gave a vertical deflection that was linear to about one part in 1,000.

IV. Aided-Tracking Registration Method

A. Noncumulative Control Method

It became evident that the method just described has limitations as to the number of scanning and phosphor lines that can be registered with the required precision. Adjustments were somewhat critical for the 450-line kinescopes and the scanning standards chosen. For a noninterlaced picture on the 525-line monochrome standards of broadcast television, 262.5 lines of each color would be needed if no allowance were made for vertical blanking. Actually, about 240 lines of each color (or 720 total) would be required in such a system where odd and even fields are superimposed. For a full interlaced color picture with 525-line standards, 480 groups of phosphor lines on the screen would be needed, more than a three-fold increase over the 9-inch experimental tubes discussed. A noninterlaced picture of half the theoretical limiting vertical resolution offered an initial goal to determine the further possibilities of the line-screen-kinescope method. Accordingly, screens having 240 groups of color lines were employed.

A servo circuit was developed to control the vertical deflection of the beam so as to maintain registration with the proper color lines. For the moment, one can limit the problem to that of obtaining a single-color raster (e.g., green) by means of the servo with no color multiplex video signal applied. Then the other two colors can be obtained by the supplementary stair-step deflection illustrated in Fig. 6. Contrasting secondary-emission areas on the kinescope screen provide the information as to the beam position with respect to the chosen green phosphor lines.

Appreciable variations in control information due to the range of beam currents encountered during picture modulation must be avoided. A control circuit must operate down to black level and provide correct color registration in low brightness portions of the picture as well as in high lights. No restrictions on contrast range should be imposed by the color control means.

To meet these requirements a "control area" having a characteristic secondary-emission pattern is placed on the left-hand margin of the phosphor screen and covered with an opaque mask on the viewer's side. The beam current is brought up to a value corresponding to full brightness level during the latter part of horizontal-blanking time as the beam scans this marginal area. The characteristic pulse signals picked up by the secondary-emission collector indicate whether the beam is correctly registered with the beginning of the green phosphor lines or, if not, the sense and the magnitude of the deviation. Vernier deflection is then supplied by the vertical-deflection plates to start the beam in proper register as it begins to traverse the visible phosphor area. No further control is applied for the duration of that scanning line. Reliance is placed upon the freedom from geometric distortion, from stray fields, or from other sources of disturbance in the vertical-deflection circuit.

Control signals are derived from a screen having secondary-emitting areas, shown diagrammatically in Fig. 7(a). A series of rectangular strips A_B is arranged in a vertical column, each strip being in the same horizontal plane as a light-emitting blue phosphor line or strip L_B. Similarly, there are strips A_R placed on the axes of the corresponding red phosphor strips L_R. The vertical column of A_R areas is displaced to the right of that of A_B areas, as is evident from the figure. There are no control areas to correspond to the green phosphor strips L_G, the green lines being of the arbitrarily chosen color with which the scanned raster is to coincide.

The electron-beam spot S is keyed on to "white" during the interval of pulse 3 shown in Fig. 7(a), i.e., for the duration of the traverse of the control area at the beginning of each horizontal-scanning line. If the spot starts at position S_1, it encounters neither an A_B nor an A_R control area, but strikes L_G along axis XX'. No control signal is generated to deflect the beam vertically. On the other hand, if the beam starts below this desired position, at S_2 or S_3, for example, it generates a secondary-emission signal of magnitude dependent upon the departure from XX' as the spot crosses an A_B region. Departure from XX' in the opposite direction (S_4 or S_5) causes the generation of a similar pulse as the beam crosses an A_R region. In either case the magnitude of the signal increases with vertical departure from XX' until the beam is centered on an A_B or an A_R area. The *sense* of the departure is deter-

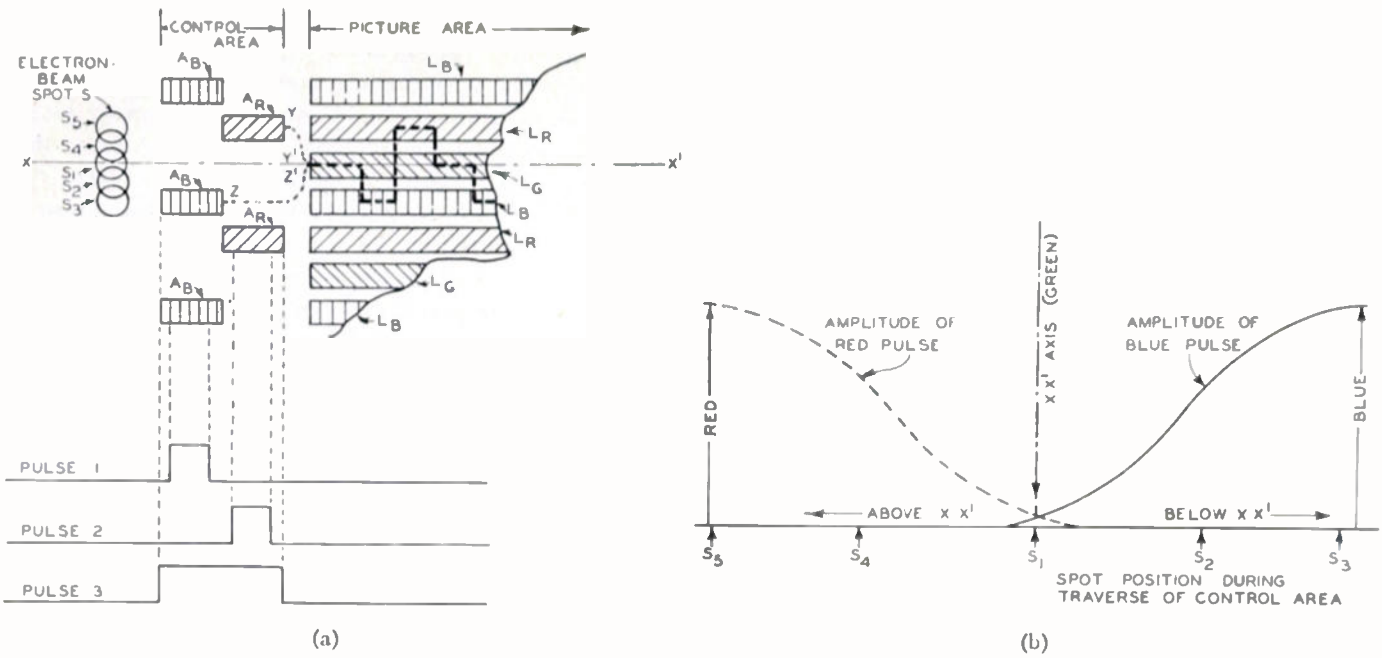


Fig. 7—Control-signal generation process. (a) Beam scanning path in control and picture areas. The times of occurrence of pulses 1, 2, and 3, referred to spot travel, are shown. (b) Amplitude of "red" and "blue" pulses as a function of vertical misregistration of beam in control area. Spot positions $S_1 \cdots S_5$, shown in (a), are indicated along the abscissa axis.

mined from the difference in time of occurrence of the two types of pulses. For convenience, the pulse due to the scanning of an A_B area will be called a "blue" pulse and, similarly, for A_R, a "red" pulse. The servo device will be called upon to sample the amplified secondary-emission signal at two time intervals, corresponding to pulses 1 and 2 in Fig. 7(a), and to compare signal amplitudes so obtained. The continuous nature of the signals obtained is illustrated in Fig. 7(b). In practice, it is found that there is just sufficient overlapping of the spot on adjacent strips to cause a small pulse signal from *each* area when the spot is on the axis XX'.

A diagram of a basic servo employing this type of control information is presented in Fig. 8. The relative order of occurrence of the pulses is shown in Fig. 9. In the former illustration, there are four pulse generators. Each is triggered by one edge of the horizontal synchronizing pulse, and each may contain a delay circuit—a multivibrator to produce a control pulse of adjustable delay in the actual apparatus—and a pulse multivibrator. All pulses occur during the "back-porch" interval of horizontal blanking. One may neglect for the moment pulse 4, the clamp restoration pulse. It will be observed that pulse 3, the white gating pulse, supplies a signal to the video amplifier to turn the kinescope beam on full as the spot traverses the control area. At the same time, this pulse gates off the stair-step generator.

The signal from the secondary-emission collector is amplified and applied to two gate amplifiers. The input wave at the latter has a typical form given by s of Fig. 9. The two relatively flat-topped portions of unequal amplitudes are generated as the beam scans A_B and A_R.

A sample of the secondary signal is passed through gate amplifier 1 at the time of occurrence of pulse 1, while a second sample passes through gate amplifier 2 at the time of pulse 2. These pulses occur at the time of scanning the two control areas. The first signal (the "gated blue signal") is delayed by Δt_1 (see Fig. 9) by means of a delay line and is combined with the second signal (the "gated red signal") inverted in phase. Thus, at the input to the clamp circuit of Fig. 8 the differential signal indicates the magnitude and sense of the vertical error in initial beam position. The signal is retarded by delay line 2 by approximately the pulse width, while pulse 2 itself is delayed and fed into the clamp circuit to establish the dc axis at the time of occurrence of the differential signal. The clamp circuit is of the double-keyed type described by Wendt.[13] Then, for the duration of one horizontal-scan interval, the potential applied to the kinescope deflection plate by the clamp will equal the differential signal. The beam is thus deflected along a typical path YY' or ZZ' to coincide with XX' in Fig. 7(a).

A little consideration will show that in the circuit just described it is necessary to restore the clamp circuit to

[13] K. R. Wendt, "Television dc component," *RCA Rev.*, vol. 9, pp. 85–111; March, 1948.

its initial condition before a second line is scanned. In this manner a false vertical correction on alternate scanning lines can never be established, an effect that would result in color "pairing." Accordingly, in one arrangement a clamp restoration pulse (pulse 4 shown as *v* in Fig. 9) is caused to occur before pulses 1 and 2 at the beginning of each scanning line to establish a fixed potential on the output circuit of the clamp. The beam is then in its uncorrected position as it begins its sweep through the control area, and the operation of the servo is not influenced by the history of the previous scan.

dependence on screen uniformity would be very desirable.

A method of improving servo operation utilizes a cumulative control in which the correction voltage applied to the deflection plates for one scanning line is reapplied at the beginning of the next scanning line

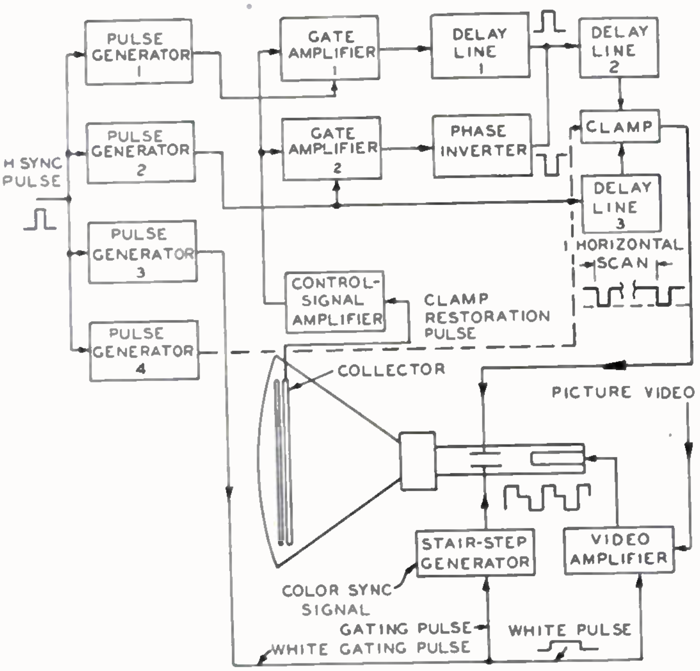


Fig. 8—Aided-tracking circuit employing noncumulative control.

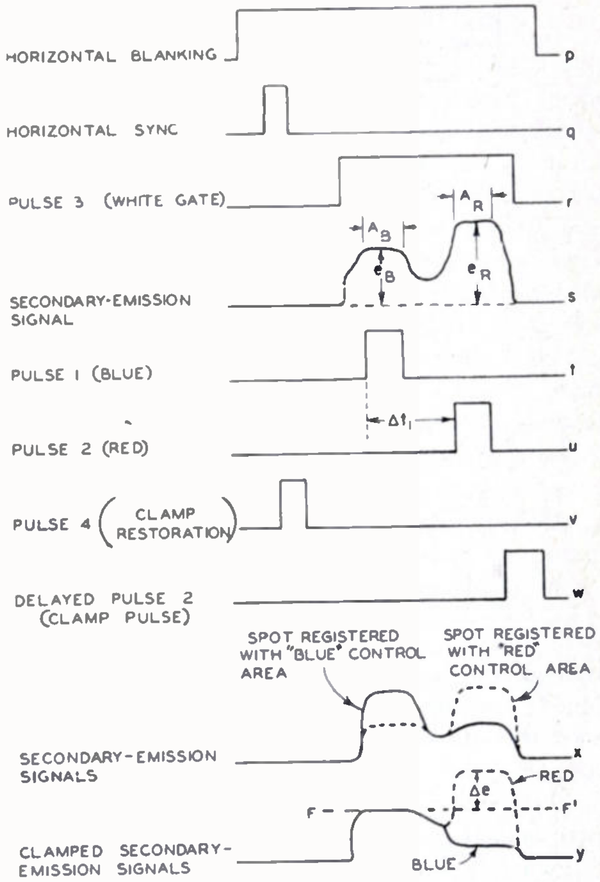


Fig. 9—Diagram of pulses in aided-tracking circuit.

B. *Cumulative-Control Method*

Several improvements over the previous arrangement were next considered for the experimental color receiver. At the beginning of each scan the servo mechanism of the method described in Section IV *A* retained no information as to the previous correction required. Then, when progressively greater corrections were needed on successive scans, a condition would soon be reached in which deflection by more than the width of a color triplet was required. The control circuit did not accomplish this, however, but gave the smallest possible deflection to arrive at the correct color. A gap or an overlap in the scanning pattern then resulted. It was also noticed that the amount of correction provided depended upon the secondary-emission ratio of control areas A_B or A_R. In experimental tubes considerable variations in this ratio were sometimes observed. Less

before the beam sweeps across the control region. The control circuit then determines the *incremental* correction required to provide precise registration of the second scanning line. The servo device may thus be said to have a "memory."

A circuit of this type may be capable of accumulating correction information corresponding to several color cycles on the screen so that no discontinuities in the pattern occur. The second problem, that of screen uniformity, is much diminished since it is only the increment of signal on each scan, after the first, that is dependent upon control-area secondary emission.

A circuit arrangement having this type of "memory" is shown in block diagram form in Fig. 10, with further details of the memory circuit in Fig. 11.

As the beam scans the control area, pulse 3 keys the beam on full and cuts off the stair-step generator as in the earlier system. The secondary-emission signal shown as curve *s* in Fig. 9 is redrawn as curve *x* to show the con-

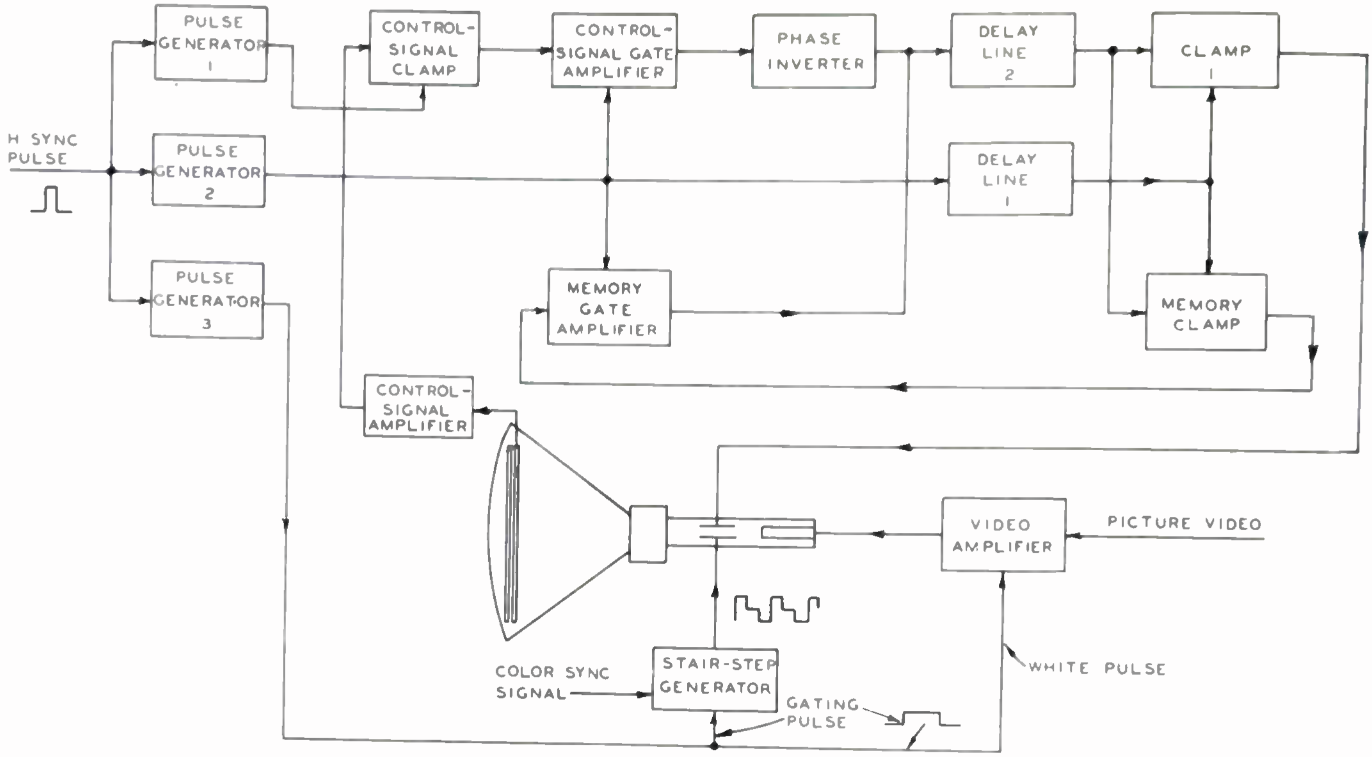


Fig. 10—Aided-tracking circuit employing cumulative control ("memory").

ditions of the spot initially in register with an A_B area ("blue") and an A_R area ("red"), respectively. In this circuit the control-signal clamp is keyed on by pulse 1 at the time the beam crosses the A_B region to establish a fixed dc axis FF' of curve y in Fig. 9. Then, when the control-signal gate amplifier is keyed on by pulse 2 as the beam crosses the A_R region, the voltage Δe is developed with respect to this established dc axis. The quantity Δe may be of either polarity, depending on the relative magnitudes of e_B and e_R. It will be noted that the operation is not influenced by the magnitudes of e_B or e_R but only by the difference Δe.

The difference signal is amplified and delayed as before. Clamp 1 brings the deflection plates to the same potential at the time the control pulse emerges from delay line 2. Then, for the remainder of that horizontal-scan cycle, the deflection plates maintain a voltage equal to that of the amplified difference-signal appearing at clamp 1. During the time of scanning the picture area, the stair-step wave is superimposed on this signal.

The memory clamp (like clamp 1 except with its double-keyed diode near ground potential instead of substantially at second-anode potential) delivers a similar voltage to the memory gate amplifier. Grid G_1 of this latter maintains a bias or pedestal voltage of this pulse amplitude starting at the time of occurrence of the delayed pulse 2 (curve w of Fig. 9) and continuing through the beginning of the next scanning line until the occurrence of the next delayed pulse 2. When a new pulse 2 (not delayed) is applied to G_3 (Fig. 11), this pedestal voltage is amplified and appears in the output of the memory gate amplifier. The output is thus proportional to the deflection-plate signal applied for the previous scanning line. The signal is added to the new signal from the control-signal gate amplifier and fed into delay line 2. The phase inverter of Fig. 10 is required to combine these signals in the proper polarity.

Each gate amplifier used in the experimental apparatus uses a type 6AS6 pentode. This type is particularly suitable because of the high transconductance between the suppressor grid G_3 and the plate. The bias $-C_2$ (in Fig. 11) is sufficient to cut off the tube until pulse 2 (of positive polarity) is applied to the suppressor.

The receiver employing the cumulative-control method proved easier to adjust and maintain in color registration than its predecessors. Mention may be made of a number of refinements that were incorporated to improve picture quality.

When the subcarrier frequency f_c was increased from 2.0 to 3.58 mc, the stair-step generator was changed from the multivibrator system to a combination of clipper stages, a delay line, and a wide-band video amplifier. While this gave a fairly good waveform, each rise time was a substantial portion of the total period. By the introduction of a circuit tuned to $3f_c$ inserted in the kinescope cathode lead and driven from the 3.58-mc color-synchronizing signal through a tripler stage, substantial freedom from color dilution was achieved despite the fact that the shape of the stair-step wave was not ideal.

Focus-modulation voltage was utilized to improve spot sharpness at the corners of the raster. The horizontal-deflection wave generated a parabola of from 200 to 300 volts that, in turn, was applied to the first anode of the kinescope. Focus modulation in the vertical direction was also tried but later omitted because of the minor additional improvement it contributed.

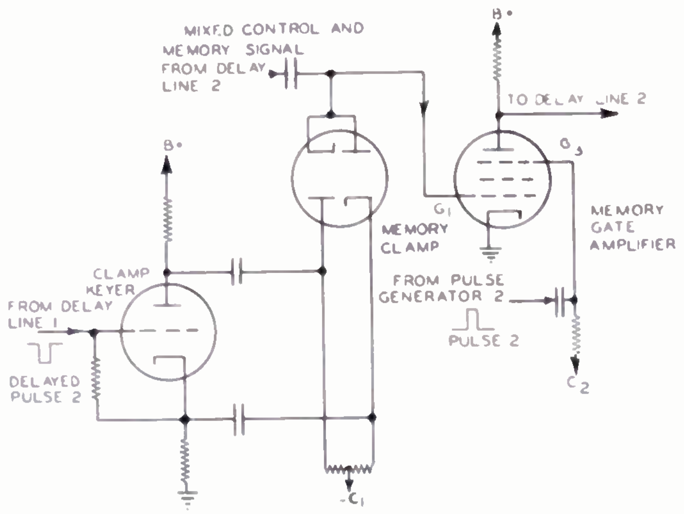


Fig. 11—Memory circuit used in Fig. 10.

The 525-line picture was deliberately converted into one having no interlace, i.e., *odd* and *even* fields were superposed. This process of "de-interlacing" was made necessary because, as was previously mentioned, the screens employed only 240 color-line triplets. A 30-cycle square-wave generator phased with vertical synchronizing signals furnished a voltage to the vertical-deflection circuit to make successive fields coincide.

Brightness of blue and green phosphors was deliberately reduced to maintain color balance with the relatively inefficient cadmium borate red phosphor available at the time. A receiver using a 16-inch line-screen kinescope with these phosphors was found to give a dot-sequential color picture of high-light brightness of 5 to 15 foot-lamberts at 18 kv. Color purity was satisfactory when all the precautions described were taken. While the aided-tracking system required careful adjustment, correct color phase could be maintained over substantially all the picture area. Some difficulty was encountered because of the lack of adequate secondary-emission signals from the extreme top and bottom parts of the screen control areas.

Horizontal resolution through the video portion of the receiver was very substantially higher than in current commercial television equipments because the usual limitations of kinescope spot size, defocusing, and the like, had been much reduced. This condition held true over the entire raster area.

The three color images were precisely registered horizontally. The red and blue pictures were displaced up and down, respectively, by just 0.010 inch from the green picture. At normal viewing distances the registration of the three images appeared exact.

The very nature of the color-registration process required that the vertical linearity appear perfect as far as the observer could tell from picture geometry.

V. Picket-Fence Registration Method

Brief mention may be made of another method of securing color registration. It was considered to be rather attractive because of its potential simplicity, particularly with the RCA color system.[12]

The name *picket-fence method* indicates clearly the orientation of the phosphor strips on the screen. The lines are vertical and spaced apart by the mean horizontal distance scanned by the electron spot during the time of one color element. (This applied to a presentation not incorporating dot interlace. In case dot interlace is employed there are *two* color triplets in such a scanning distance.) Then if the beam scans the screen with perfect horizontal linearity and size and if the starting phase is correct, the beam will coincide with a phosphor line of the correct color at the time the video modulation of the beam corresponds to that same color. The screen thus inherently performs the function of the color demodulator. The distance between centers of a triplet of color lines can be very nearly the same as for the 720-line screens previously described. The relation of strip width to scanning-spot diameter involves the duty cycle of the multiplexing process.

In the picket-fence arrangement, the stringent requirements on vertical deflection and yoke geometric distortion are removed, and the stair-step generator is omitted. The full vertical resolution of a line-interlaced picture is obtainable. On the other hand, additional requirements may be imposed on the precision of *horizontal* scan. Alternatively, a servo operating throughout the scanning time may accomplish the required color registration. When such a servo is used, the information as to instantaneous beam position must be furnished to the control device regardless of beam-current amplitude.

Considerable progress has been made during the course of this project on servo devices of two types: (1) circuits in which the *color information* is *independent* of the receiver operation and in which the horizontal deflection is controlled by the servo; and (2) circuits in which the *deflection* is *independent* of the servo, while the receiver color commutation is governed by the control means.

A discussion of such methods would be too extensive for inclusion in the present paper.

VI. Conclusion

Line-screen three-color kinescopes have been built in sizes up to 16 inches diameter. The phosphors can be deposited either by settling or by silk-screening. Tubes of 720 lines were produced by the latter method. Precautions in the electron-optical system are required to insure uniform sharp focus. The kinescopes are comparatively simple and appear to be well-adapted to factory production.

Among the various methods employing line-screen kinescopes described here, the aided-tracking system of color registration offered about the most satisfactory system studied in detail. The improvement of cumulative control in the servo system was found very desirable. The circuits are somewhat elaborate, but a picture of high horizontal definition and of adequate color quality results. Improvements in the production of secondary-emission surfaces to give greater and more uniform contrast may be expected to improve color purity and simplify the adjustment of the servo-circuit controls.

The methods of securing color registration are potentially useful in other applications where geometric exactness of the picture is required. Circuits suitable for the smaller earlier tubes, described in Section III, should be valuable for many of these uses.

Phosphor-Screen Application in Color Kinescopes*

N. S. FREEDMAN†, AND K. M. McLAUGHLIN†, SENIOR MEMBER, IRE

***Summary*—A technique has been developed whereby fine-detail printed patterns of color phosphors are deposited onto a glass surface suitable for use as the viewing screen in a color reproducer of the cathode-ray type. The phosphors, suspended in a lacquer, are squeegeed in turn through a stainless-steel-mesh-supported gelatin stencil. The lacquer is subsequently entirely removed by simple bakeout in air at elevated temperature. The glass plate is rigidly fixed by vacuum onto a table which can be accurately adjusted in two horizontal perpendicular directions. Exact position of the glass on the table is indicated by two dial gauges; the accuracy attained is such as to intermesh the three color phosphor patterns to better than 0.001 inch over the entire area. Phosphor screens have been made in substantial quantities for several types of color kinescopes, and have given very satisfactory performance.**

Introduction

TELEVISION-reproducing tubes of the cathode-ray type make use of luminescent materials or phosphors which are deposited on the glass viewing screen. In the past, such phosphors have been dusted, sprayed, or settled in a uniform layer on the electron-beam side of the faceplate. Of these methods, the most popular is the settling process which, although relatively slow, has led to the highest degree of screen uniformity and minimum optical contact. The latter is desirable because it reduces halation. The phosphors used in black-and-white kinescopes are mixtures of color phosphors which produce white light when they are simultaneously excited. In a kinescope for reproducing color pictures, it is necessary to use separate color component phosphors; normally, three such phosphors, red, green, and blue, are used. Most of the methods employed in color kinescopes require an accurately intermeshed pattern of these color phosphors; the patterns take the form of thin lines, dots, or other arrangements. Although it has been found possible to produce appropriate phosphor screens for color kinescopes by settling the phosphors through special masks, the length of time involved in a three-step settling process made it very desirable to investigate other methods.

This paper describes the successful application of printing techniques to the deposition of phosphor patterns on flat surfaces such as glass or metal. The work was initiated because it appeared to be essential to quantity production of a color kinescope. For simplicity, the discussion will be confined to deposition on glass of patterns of the dot type and of the line type which are described in other papers.[1,2] The method which was successfully developed for these purposes is based on the technique known as "silk-screen printing."[3] This process involves the use of a stencil through which the phosphors are forced.

In the printing of a line screen (i.e., one having adjacent narrow lines of different color phosphors) with a set of three different color phosphors, a stencil having only one set of lines may be used. By accurately moving the glass plate a predetermined distance underneath the stencil in a direction perpendicular to the lines, it is possible to print a second and third set of color lines. For the dot pattern, a single stencil is also used but, depending on the geometry of the array, it may be necessary to move the glass plate in two directions for the other two colors. Accurate intermeshing of the three colors, of course, requires careful relocation of the stencil for each printing step and a means whereby the glass can be moved in two directions beneath the stencil. Because commercial equipment of sufficient accuracy and

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[1] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

[2] D. S. Bond, F. H. Nicoll, and D. G. Moore, "Development and operation of a line-screen color kinescope," Proc. I.R.E., pp. 1218–1230; this issue.

[3] J. I. Biegeleisen and E. J. Busenbark, "Silk-Screen Printing Process," McGraw Hill Book Co., New York, N. Y.; 1941.

versatility was not available, the necessary equipment for this printing operation was designed and built.

A printing medium containing the suspended phosphor particles, which would permit printing on a nonabsorbent surface, such as glass or metal without affecting the operation of the tube, was also developed. Before the phosphor plate could be used, however, all constituents of this medium which would affect tube operation were completely removed from the glass plate after printing. During experimentation with various printing media, the only compromises made were those which affected printing qualities; no compromises were made which affected tube operation.

As for the printing itself, the geometry of the color kinescopes under consideration required a precision of an order of magnitude greater than that required for four-color commercial printing, and such precision was, in fact, obtained.

Typical pattern dimensions for the line screen are a line width of 0.007 inch with a 0.030-inch spacing between line centers. For the dot pattern, dot diameters ranging from 0.017 inch with dot centers spaced at 0.030 inch, down to dot size of 0.010 inch with dot centers spaced at 0.018 inch are used. The figures given are for the pattern of a single color.[4] The pattern is printed to conform to the original photograph over the entire array to better than 0.001 inch.

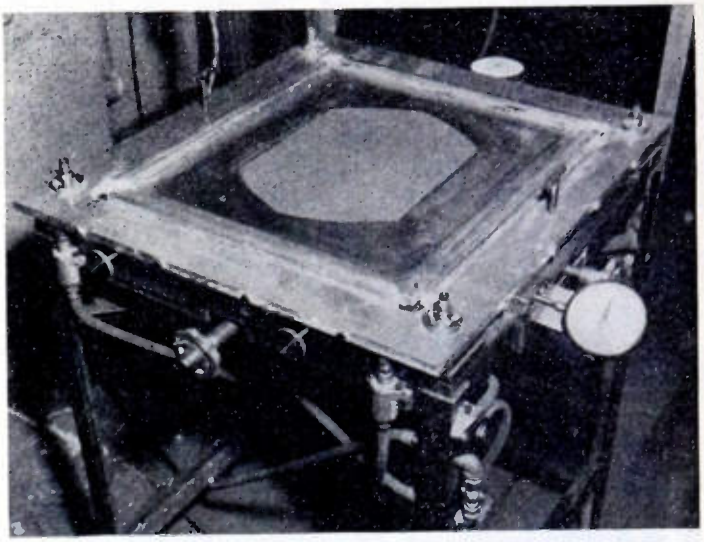
Technique Considerations

For the printing of either the line or the dot patterns, the development of a suitable process was simplified because a single stencil could be used for all three colors. After preliminary work, but before the design and development of printing equipment, it was found necessary to solve two fundamental problems: (1) whether the stencil or the glass plate should be moved with respect to the other, and (2) whether consecutive plates should be printed with one color at a time by removing the glass plate from the table after each color, or whether each plate should be printed with all three colors without removing the plate from the table.

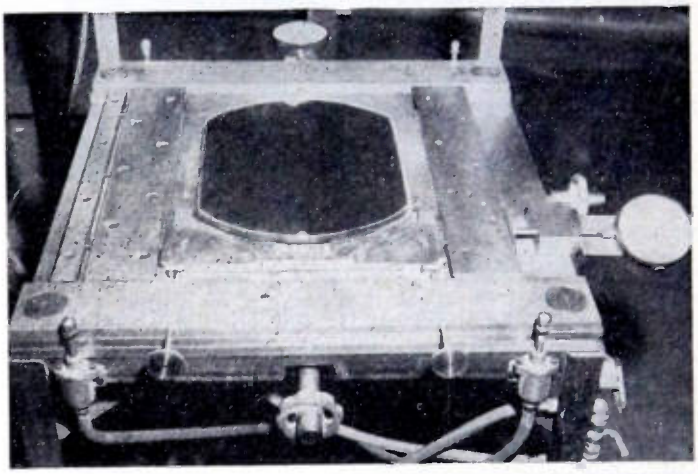
Since the stencil frame would always be large compared to the glass plate, it seemed reasonable that greater precision could be obtained by movement of the smaller glass plate, rather than the larger, bulkier stencil frame. This principle was followed throughout.

As for printing the glass plates completely or consecutively, the decision was dictated by circumstances. Only small quantities of tubes were needed at the start of the developmental program. In addition, only a few printed plates were to be made from each stencil. It was obvious, therefore, that complete printing of each plate would be satisfactory, at least during the development stages. It was advantageous, too, because having the glass clamped to the printing table for the entire printing of the three colors eliminated the need for registration which would occur if the glass plate had to be replaced on the table before each color pattern could be printed.

[4] When all three colors are printed, lines of different colors are separated by 0.003 inch. In the dot patterns, the dots become tangent.



(a)



(b)

Fig. 1—(a) Printing table with stencil frame in position. (b) Printing table with stencil frame removed. Two air pistons are visible in front.

Printing Equipment

The first printing table was of wood and had a hinged stencil frame such as is used in conventional silk-screen printing. A micrometer-head screw feed was used for adjusting the glass plate, but accuracy required ground-glass edges or the cementing of the glass to a machined plate. The hinged stencil proved too inaccurate until locating pins were used. A further difficulty was that even the finest silk used by silk-screeners had too little open area for rapid printing. An all-metal table having a lathe-type cross feed and a vacuum suction system for holding the glass plate was then built. Dial gauges were used to indicate the position of the glass plate to better than 0.001 inch. Stainless-steel mesh, 165 by 165 strands to the inch, woven with wire 0.0019 inch in diameter and having an open area of 47 per cent, was then adopted, supplanting silk for all future work.

A third table (Fig. 1) is a prototype of several later tables. In this table, clearances and movements in the cross-feed unit are eliminated. The platform on which the glass plate is supported is roughly 20 per cent larger than the maximum dimensions of the glass plate. Both edges of the platform along the length have V-shaped grooves machined in the thickness. Along each side of the V groove a machined-steel block with a similar V groove is placed. Hardened and ground steel balls are interposed between the two grooves so that the platform is, in effect, supported by large steel balls. One of

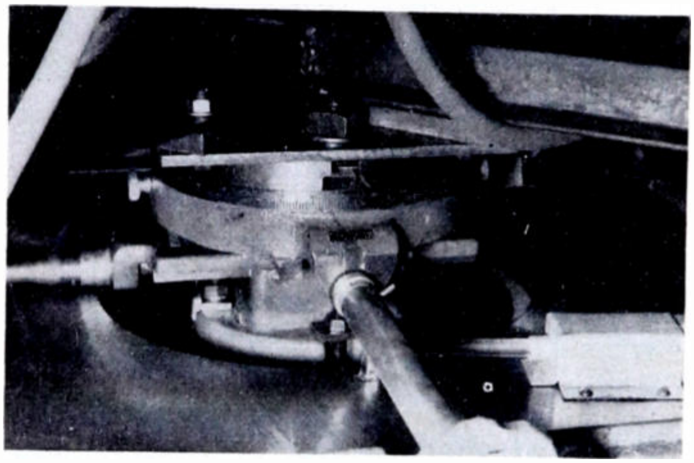


Fig. 2—Closeup of cross-fed mechanism for positioning phosphor-dot plate on printing table.

the two V blocks alongside the platform is adjustable so that clearances can be made practically zero while the platform remains free to move along one axis. To permit movement in the horizontal plane in a perpendicular direction, the two V blocks and platform assembly are mounted on a larger steel plate with similar V grooves and V blocks oriented at an angle of 90 degrees to the V grooves of the platform. To control the movement of the lower steel plate and platform, a lathe-type cross feed is inverted and fastened to it. The actuating device for the platform permitting movements in both directions is supported by the frame of the table (Fig. 2). In this table also, the position of the platform (and of the glass plate) is determined by calibrated dial gauges rigidly mounted to the frame of the table. With this type of table, accuracy of the order of 0.0005 inch has consistently been attained over a considerable period of time.

An all-metal stencil frame was designed which clamps the stainless steel mesh on four sides between two aluminum-bar clamps. The clamping bars are tightened and adjusted by a bolt arrangement. With this metal frame it is possible to get the mesh relatively uniform and sufficiently taut and also to tighten or adjust the mesh tautness periodically. A set of locating holes is used to position the metal stencil frame on the printing table. Four threaded and hardened bushing-type inserts are bolted to the stencil frame. These inserts are accurately aligned with four hardened and ground bushing inserts in the table. An adjustable pin having a fine thread for easy height adjustment is precision fitted to each stencil-frame insert. This pin also has a conical-shaped end which fits concentrically into the inside top edge of the hole in the printing-table insert. The height of the stencil frame is adjusted by rotating these pins in the stencil frame. The conical ends of the pins, fitting into the table inserts, maintain the desired stencil frame location. Everything, except the hardened steel inserts and pins, is made of aluminum to keep weight to a minimum. With this arrangement it is possible to relocate the stencil frame exactly at all times and to print as many as seven coats of the same pattern in registry, with removal of the frame after each coat. A 30-power magnifying device is used to determine registry; the accuracy of registration is considerably better than 0.001 inch.

Preparation of Gelatin Stencil

The exact reproduction of a pattern requires a suitable stencil as well as satisfactory printing equipment. At the start, gelatin stencils were made by means of the conventional "temporary" transfer technique. In this process, a pigmented gelatin coated onto a paper backing is first sensitized in dichromate solution and then placed wet on a temporary transfer sheet to which it adheres. With a pigmented gelatin, the final thickness of dry gelatin stencil is wholly dependent upon the amount of light during exposure. Because of the light-scattering characteristics of the pigment, fineness of detail can be lost by overexposure. Thus, proper exposure depends primarily upon the type of pattern; the thickness of the gelatin stencil which controls, to some extent, the thickness of phosphor deposit, becomes of secondary importance. Materials made by several manufacturers were tried, and a suitable, reliably consistent material was found.

At first, clear cellulose nitrate, 0.005 inch thick, was used for the temporary transfer sheet. Because the final printed plate must be accurate, the choice of the transfer sheet material is important. Since the coefficient of thermal expansion of cellulose nitrate[5] is high ($12-15\times10^{-5}/°C$), it became apparent at this stage that the use of this material greatly increased the problems of temperature control. To minimize these problems, it was decided to substitute Vinylite since it has a lower thermal expansion coefficient of $7\times10^{-5}/°C$. The use of this material resulted in the printing of many successful plates.

Distortions were still troublesome, however, even with the Vinylite support, and eventually led to

[5] Cellulose acetate is equally unsatisfactory; its thermal coefficient of expansion is approximately $15\times10^{-5}/°C$.

abandonment of the temporary-transfer process. The direct transfer was in moderate use in the silk-screen industry at that time. In this process, the gelatin is placed directly on the glass photographic positive plate, and the glass plate supports the gelatin. The glass photographic plate is first coated with a thin layer of clear lacquer to protect the water-swelling emulsion. When the lacquer is completely dry, the lacquer coating on the emulsion side of the glass photographic plate is waxed to permit easy separation of the gelatin from the glass plate after the gelatin has dried. The wet, sensitized gelatin and paper backing is squeegeed on to the emulsion side of the photographic plate. The photographic plate is in direct contact with the gelatin except for the intermediate lacquer coating.

A Kodalith glass photographic plate, exposed to produce black dots in the emulsion at locations corresponding to the dots of phosphor to be printed, is used for exposure of the gelatin. Kodalith glass plates are highly satisfactory because of the extremely high contrast characteristics of the Kodalith emulsion. Glass plates, rather than film, are used for accuracy. The preparation of patterns on the photographic glass plates is part of the technique for each particular type of color kinescope. Procedures for making the dot pattern for the tri-color aperture-mask tube are discussed in an accompanying paper.[1] The configuration of patterns for the line-screen tubes, which are made on photographic glass plates by use of a special ruled-glass master, are discussed in another accompanying paper.[2]

For exposure, a carbon arc lamp is placed 80 inches from the sensitized gelatin for approximately 3 to 4 minutes. The gelatin in contact with the photographic plate is then developed in tap water at approximately 45°C. The water dissolves the unexposed gelatin beneath the paper and permits the paper backing to be lifted off. Continued washing of the gelatin dissolves all the unexposed gelatin, leaving behind only the light-exposed, insoluble chromated gelatin. At this stage, the gelatin stencil is ready to be transferred to the metal mesh. Before actual transfer, however, it is first necessary to bring the photographic plate support and the gelatin to the proper dimension by soaking them in a controlled-temperature water bath. Since the thermal expansion coefficient of glass ($0.9 \times 10^{-5}/°C$) is so much less than that of Vinylite, controlled dimensions are more easily achieved and maintained when the direct transfer techniques are used. The conventional method of placing the metal frame on top of the wet gelatin often causes up to an 0.002-inch error in a 10-inch length. To eliminate this, the metal frame is positioned upside down and the gelatin is carefully placed on top of the mesh, with only the weight of the glass plate bearing down on the gelatin. The gelatin is then dried in air with the help of a fan. This improved technique of placing the gelatin on the stencil eliminates any consistent, measurable distortion.

The mesh on the stencil frame can be used repeatedly with only minor adjustments of the tension of the mesh from time to time. To clean the stencil gelatin from the mesh, glacial acetic acid is used, followed by hot-water rinsing. An alternative technique for washing off the gelatin uses a solution containing 5-per cent sodium carbonate, 1-per cent potassium silicate, and 2½-per cent hydrogen peroxide.

Printing Considerations

A discussion of some dimensional distortions occurring during conventional printing is necessary before proceeding to the improved mechanics and procedure of the printing technique used for the phosphor application. Initially, the printing technique was almost an exact duplication of the technique used in the silk-screen process. For instance, the gelatin stencil frame was located and adjusted so that the stencil was spaced from 1/32 to 3/16 of an inch above the glass plate on which the pattern was to be printed. During printing, when the squeegee is being drawn across the stencil, the squeegee actually displaces the mesh-supported gelatin downward so that the gelatin stencil just below the edge of the squeegee contacts the glass plate. In the usual silk-screen process, this spacing between the stencil and the work permits sharp printing and causes a spring action which provides for good release of the stencil from the work being printed. This distortion of the mesh and gelatin stencil does not appear to cause noticeable errors in commercial screen-process work. However, with the precision needed for phosphor plates of color kinescopes, this distortion of the mesh screen is serious because it results in an elongated pattern caused by the progressive drawing of the squeegee across the stencil. This elongation is as high as 0.005 inch over the pattern length of approximately 12 inches and is proportional to the spacing between the stencil and the printed plate. In addition to the uniform distortion caused by the uniform spacing between the stencil and the glass plate, errors were found which were caused by nonuniform stencil-to-glass spacing over the area of the pattern. Accordingly, it appeared necessary to keep the spacing between the glass plate and the stencil uniform and at a minimum. At best, with accurate adjustment of position of stencil above the glass plate, a pattern may be printed that has a small uniform elongation.

To eliminate the effect of this pattern elongation caused by stretching of the stencil, a compensating factor was introduced into the stencil. The stencil, before transfer to the mesh, was cooled below room temperature in a temperature-controlled water bath. A uniform contraction of the pattern in both directions resulted. Since the printing caused a distortion only in one direction, this added compensation by uniform contraction of the gelatin was, of course, only an approximation, and was termed "compensated printing." It was difficult, indeed, to reproduce by this printing technique patterns which were accurate to within less than 0.001 inch of the original array.

The difficulties of producing accurate printed reproductions, even with the refined techniques which were developed, prompted an investigation intended to improve fundamentally the printing process rather than merely to refine the compensated-printing technique. The successful method evolved is termed "noncompensated printing." It is obvious that the printing should be done, if at all possible, with no distortion of the stencil during actual squeegeeing. It is then not necessary to shrink the stencil to compensate for pattern elongation. In the noncompensated printing technique, the stencil is adjusted to be in contact with the glass plate so that pressure of the squeegee during printing causes no distortion in the stencil. Only light pressure of the squeegee during the printing operation is required since it is no longer necessary to distend the mesh-supported stencil. At the four corners of the metal stencil frame, four air pistons are mounted on the printing-table frame in contact with the stencil frame. By actuating the four air pistons simultaneously, it is feasible to raise the entire frame uniformly and quickly above the glass plate. This operation provides a clean break of the gelatin stencil away from the glass plate, and results in a sharply printed pattern. This noncompensated technique has two desirable advantages over the compensated technique: (1) it is not necessary to shrink the gelatin; and (2) nonuniform tensions in the mesh are not a cause of distortions since the mesh is actually never distended either during printing or during transfer of the stencil to the mesh. The accuracy of the pattern printed by this technique has been consistently better than 0.001 inch, which is about the limit of measurement over a large pattern.

Printing Medium

A printing ink or paint, hereinafter referred to as "phosphor-printing medium," has been developed especially for printing phosphor plates for use in color kinescopes. The basic requirements of the phosphor-printing medium are as follows: The phosphor-printing medium must dry rapidly to minimize flow or spread on the glass after the pattern is printed. Rapid drying has a second advantage: Inasmuch as consecutive printings are made on the same glass plate with different colored phosphor-printing media, it is possible to print second and third coats of the same phosphor without long waiting times. A further requirement of the phosphor-printing medium is that it must be capable of being easily and thoroughly cleaned from the stencil between colors to avoid contamination of one phosphor with the next. Most important in the formulation of the phosphor-printing medium is the avoidance of "poisoning" of the phosphors by the addition of foreign materials which reduce their light-emitting efficiencies. For this reason, the use of metallic salts or other inorganic constituents, such as "drying," "tacking," or "shortening" agents, must be completely ruled out since most common materials used for these purposes would seriously impair the light output of the phosphors. Moreover, any materials mixed with the phosphor powder in preparing the phosphor-printing medium preferably are removed after printing and before assembly into a color kinescope; only the phosphor powders are then left on the glass phosphor plate.

Because chromated gelatin is the stencil material, a lacquer is used as the base for the phosphor-printing medium. A viscous solution of ethyl cellulose in amyl alcohol is used for the lacquer base. The phosphor printing medium is prepared by mixing phosphor powder with the lacquer base. During the drying of the printed plate, the amyl alcohol evaporates, leaving behind the phosphor powder suspended in ethyl cellulose. The ethyl cellulose is, subsequently, completely removed by baking in air so that only the pure unaffected phosphor powder remains. Although difficulties were experienced with some special phosphor powders which were contaminated by extremely small traces of metal impurities present in commercial ethyl cellulose, the phosphor materials most widely used are not so affected. While particle size of the pigments used in commercial letterpress printing is generally less than one micron, the phosphor particle size used in the present phosphor-printing medium is generally larger than two microns.

Printing Procedure

A chemically cleaned glass plate and the stencil frame are placed in position on the printing table. The four alignment pins are carefully adjusted so that the gelatin stencil just contacts the glass plate evenly over the surface of the glass. Depending upon the pattern being printed, the glass plate is aligned so that its locating marks are aligned with registry marks in the gelatin stencil. For the dot pattern of the aperture-mask tricolor kinescope, for example, a 50-power microscope is used so that the stencil pattern can be aligned with the glass plate to within ± 0.001 inch. When vacuum is applied, the glass plate is clamped to the table platform. The position of the glass plate is rechecked with the microscope and any further necessary adjustments are then made. The dial gauges, which locate the platform position, are adjusted to zero so that they can give the exact location of the glass during all subsequent printing operations.

The apparatus is now ready for printing the first coat. A stainless-steel spatula is used to apply the phosphor-printing medium across the top of the screen. A neoprene squeegee is used to squeegee the phosphor-printing medium across the stencil which prints the pattern on the glass plate in much the same manner as that of silk-screen printing. As the stroke is completed, an air valve is depressed which actuates the four air pistons. The pistons quickly and uniformly raise the stencil above the glass plate. The stencil frame is removed from the table and placed in a screen-cleaning hood. At the cleaning position, the stencil is carefully cleaned with industrial cleaning tissues saturated with amyl acetate to insure freedom from color contamination. Absorbent paper-toweling sheets are placed underneath the stencil to absorb both the solvent and the phosphor powder. The screen is washed a minimum of three times; fresh tissues and absorbent paper sheets are used each time. During the cleaning operation, a bank of infrared lamps is pivoted into position on the printing table to dry the phosphor pattern printed on the glass plate. For the second color position, the table movements are adjusted so that the proper dial gauge readings are obtained. The cleaned stencil frame is replaced on the printing table so that the alignment pins are in correct position. Squeegeeing, printing, and cleaning are then repeated for the second color, and finally for the third color.

Several coats of phosphor may be applied to each set of color dots in order to build up the amount of actual phosphor powder in each dot, although present practice permits good results with one coat. To print sharp dots, the gelatin stencil openings should be in contact with the actual surface being printed. The first patterns printed, therefore, must not interfere excessively with making good contact. To prevent interference, it is desirable to print one coat of each of the three colors before the second-coat printings are made. Under white light, the three different color phosphors appear white, and it is impossible to distinguish the three different phosphors from each other. Under ultraviolet radiation of the proper wavelength, however, the phosphors will fluoresce in their respective colors. Ultraviolet radiation, therefore, is used as a check for contamination of the printed phosphor plates and for over-all uniformity of appearance of the printed pattern.

Early in the printing sequence, the first printed dot pattern is checked to uncover any inaccuracies due to errors in either the gelatin stencil or the printing-frame adjustments. After the first single pattern array is printed on the glass plate, the plate is removed from the printing table and checked for accuracy and freedom from distortion on a lightbox against a glass-plate photographic negative of the original pattern. The emulsion side of the negative is placed in contact with the printed phosphor pattern. The entire pattern is carefully scrutinized with a 30-power microscope; if any misregistration is observed, the stencil is considered unsuitable. It is conservatively estimated that any errors in excess of 0.001 inch are thus detected.

The possibility of pattern moiré arose early in the program. It may be recalled that the width of the printed line in the line pattern was approximately 0.007 inch. This narrow line width is not far different from the spacing of the supporting mesh strands which are spaced on 0.0061-inch centers; the wire strands of the mesh are 0.0019 inch in diameter. If the lines of openings in the stencil are not exactly parallel to the strands of mesh, a "beat" pattern could be set up between the phosphor lines and the strands of mesh, and an over-all moiré pattern on the printed phosphor plate would result. To eliminate such moiré, it is important that the lines of openings in the stencil be placed at an angle of 45 degrees to the direction of the mesh strands.

A similar moiré possibility could exist in some dot patterns in which the phosphor dots are in straight parallel rows. In the preferred dot pattern for the shadow-mask color kinescopes, there are rows of dots at angles of 60 degrees to other rows of phosphor dots. For this dot pattern, several preventive means can be employed. First, moiré can be radically reduced by mounting the stencil so that one set of parallel rows of dots is at an angle of approximately 7 degrees to the strands of mesh. For practical reasons, the mesh is mounted at an angle of 7 degrees to the stencil frame, and the gelatin stencil is placed so that its long axis is parallel and perpendicular to the directions of table movements. The very small residual moiré effect is then eliminated by printing the second coat of phosphor dots in a dot location adjacent to the first printed-dot location. Thus, when the second coats of the three color patterns are printed, the table movements cause the second coat to be deposited on the same color phosphor, but on adjacent dots. Because the geometry of the pattern array is regular and even, adjacent dot printing does not result in any inaccuracies in the pattern.

Processing of Printed Phosphor Plates

The following processing steps take place after printing. In order that the ethyl cellulose be removed completely from the printed plate so that only phosphor powder remains, the printed phosphor plate is baked (oxidized) in air at 425°C for approximately a half hour. After bakeout, a pattern of phosphor powder, not bonded in any way to the glass, remains on the glass plate. At this stage, the glass plate must be handled carefully and kept free of drafts because the powder can be easily disturbed. A bond is provided by gently spraying a fine mist consisting of an aqueous solution of potassium silicate onto the phosphor pattern and the glass plate. When dry, the silicate acts as a bonding agent, bonding the phosphor particles to each other and to the glass. When bonded, the powder is not easily wiped or blown off the glass plate.

The next operations are concerned with providing a metal backing for the viewing screen (a thin, reflective aluminum film deposited on the glass plate over the phosphors). The plate is first "filmed" by means of a special technique.[6] In the "filming" process, the plate is completely immersed in water, phosphor side up, and a specially prepared nitrocellulose solution is then floated on the surface of the water. While the film is drying, the water level is lowered until the film, floating on the surface of the water, is deposited on to the glass plate over the phosphor powder. After the "filmed" plate is dried, it is trimmed and placed in a vacuum jar. Under high vacuum, a reflective aluminum film is then evaporated

[6] D. W. Epstein and L. Pensak, "Improved cathode-ray tubes with metal-backed luminescent screens," *RCA Rev.*, vol. 7, pp. 5–10; March, 1946.

on top of the nitrocellulose film. The phosphor plate is rebaked in air at 425°C for a short time to remove the nitrocellulose film. The phosphor plate is then ready for operation in a color kinescope.

Accuracy Considerations

The accuracy necessary for the printing of the color phosphor has been achieved without unduly complicated equipment. On the printing table, the ways of the cross feed are machined to a high precision. Four adjustable hardened and ground steel dowel pins and four hardened and ground steel bushing inserts, handlapped together in sets, maintain accurate positioning of the stencil frame. Dial gauges are used to position the table and the glass plate to an accuracy of better than 0.001 inch. Accurate temperature control and constant humidity in an air-conditioned area provide for constant conditions of gelatin exposure and gelatin drying. Likewise, temperature control keeps the dimensions of glass photographic plates and the parts of the printing equipment constant and reproducible. Careful comparison of the printed pattern with a glass-plate photographic negative in contact with the printed pattern, by means of a conventional 30-power microscope, gives an accurate determination of any errors which may occur in stencil making or printing. It is a conservative estimate that the accuracy maintained for the printing techniques described is better than ±0.001 inch over printed patterns of the order of a foot in size.

Acknowledgment

The successful development of the processes described in this paper has been due to the co-operation and work of many. A sincere acknowledgment is due to G. Wolfe, E. V. Space, A. E. Chettle, W. J. Bachman, D. Pearson, E. J. Smith, S. Kozar, and many other members of the tube development shop at the Harrison, N. J. plant of the RCA Tube Department.

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Mention should also be made of the help given by Mr. Masi of the Francis A. Masi Company, Newark, N. J., during the early experimental stages. It was in his shop that one of the authors received indoctrination in the art of silk screening, and it was there that gelatin stencils for some of the early tubes were made.

Three-Beam Guns for Color Kinescopes*

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Summary—**The three-beam gun assembly for the aperture-mask tri-color kinescope consists of three guns located so that their axes are mutually parallel, equidistant from, and spaced 120 degrees about the axis of the assembly. The No. 4 grids open into a large common cup. The three electron beams are converged to a point on the aperture mask by an electrostatic lens formed between the large cup and the conductive neck coating. The focus of the individual beams is controlled mainly by the voltage applied to grid No. 3. The potentials of grids Nos. 3 and 4 may be varied in synchronism with the scanning frequencies so as to maintain beam focus and convergence over the entire screen area.**

The individual guns, of glass-beaded construction, are held in position by support spacers welded to eyelets around the gun cylinders. Many standard-type gun parts and manufacturing procedures are used. The beam spacing and gun placement are related to the design dimensions of the screen assembly. The guns are positioned with accurately machined, three-fingered fixtures which use the gun apertures as reference positions.

Separate leads for cathodes and grids Nos. 1 and 2 of the three guns permit adjustment of grid drive characteristics so the ratios of three beam currents are constant with grid drive. Thus, correct color is maintained, independent of changes in brightness.

A variation of the parallel-beam type of gun uses a single set of cylinders in which triple-aperture disks are placed in appropriate positions. The final cylinder, which contains no aperture disk, forms an electrostatic converging lens with the neck coating. An arrangement of mechanically converged guns, used with magnetic dynamic convergence, is also described. Another type of gun, designed for a minimum neck diameter, employs electrostatic divergence of the beams before convergence. Still another type of construction is the "coincident-crossover" gun in which the beams may be focused and converged by a common lens system.

Introduction

The design and construction of several types of three-beam gun assemblies for color kinescopes, particularly those for use with the shadow-mask phosphor-dot screen, are discussed in this paper. Other papers in this series[1,2] describe the operation and use of these gun assemblies, as well as single-beam guns, in color kinescopes of the shadow-mask type. The salient feature of the three-beam gun assembly is the availability of a separate and independently controlled beam of electrons for excitation of each of the phosphors in the

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[1] R. R. Law, "A one-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1194–1201; this issue.

[2] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

screen. Thus, the intensity of each of the three primary colors may be varied independently of the other two.

Initial experimental tubes[2] used mechanically converged guns; i.e., the assembly was constructed with the guns tilted at an appropriate angle toward the tube axis. In pilot-plant production, however, it was considered advisable for reasons discussed in this paper to use the parallel-gun type of construction with an electrostatic beam-converging lens.

Design Features

The three-beam gun assembly (Fig. 1), which was used in color kinescopes for the 1950 demonstrations of the RCA color television system,[3,4] consists of three similar guns located so that their axes are mutually parallel, equidistant from the axis of the assembly, and spaced 120 degrees about the latter. This construction permits accurate alignment of the three guns by means of a parallel-membered, three-fingered jig; it is a compact arrangement mechanically, requiring a tube neck diameter of only 2 inches. The design of the guns is a modification of a conventional cathode-ray tube gun design, and consists of an indirectly heated cathode, control grid, cup-shaped grid No. 2, a grid No. 3 containing a beam-masking aperture, and a grid No. 4. Beyond this point, there is somewhat less resemblance to conventional guns. The small-diameter grid-No. 4 cylinders of the three guns open into a common cup of large diameter, and are connected to it electrically. The grids No. 3 for the three guns are connected to each other internally; the cathodes, control grids, and grids No. 2 of the individual guns use separate leads. The three heaters are connected internally in parallel. Connections to all gun electrodes are brought out through a 14-lead stem and a base filled with plastic to provide insulation between leads for high-voltage operation of the tube. A conductive coating on the inner surface of the neck is connected internally to the metal envelope and the screen assembly.

When the tube is in operation, an electrostatic electron lens is formed between the common grid-No. 4 cup and the neck coating by the potential difference between these electrodes. This lens serves to converge the three originally parallel electron beams to a point on the aperture mask of the screen assembly.[2] In performing this function, the converging lens also tends to focus the electrons within each of the three beams. The major beam-focusing action, however, which permits sharp focus of the individual beams at the point of beam convergence on the mask, is supplied by a separate lens for each beam formed between grids Nos. 3 and 4. With this arrangement it is possible to control beam focus and beam convergence separately by adjusting the voltages applied to grids Nos. 3 and 4.

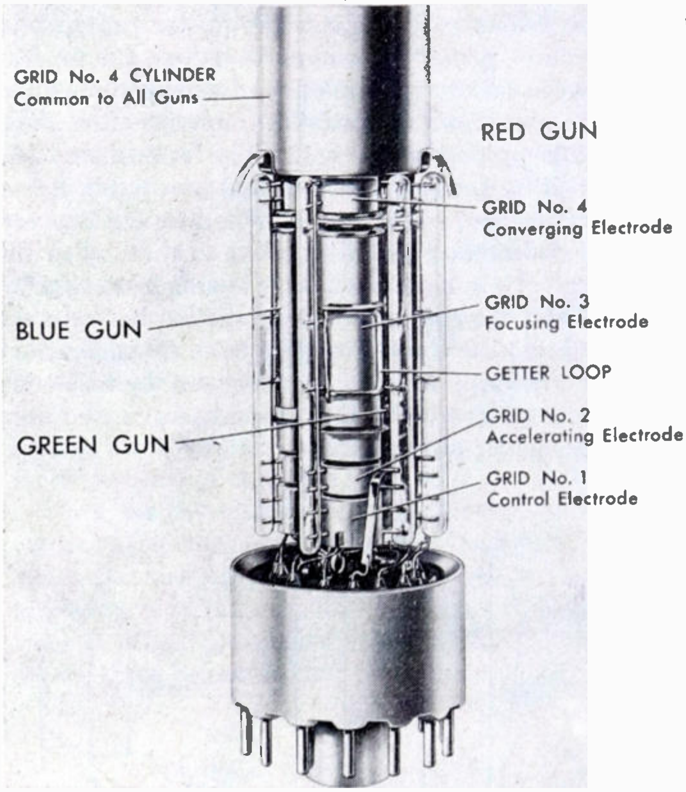

Fig. 1—Photograph of three-beam gun used in RCA color kinescopes.

Because the aperture mask and screen are flat, the distance that the beams travel between the gun and screen varies during the scanning cycle. If the converging lens potentials, which produce beam convergence at the screen center, were constant, they would tend to over-converge the beams at the edges of the screen. For this reason a dynamic convergence potential of proper wave shape, in synchronism with the scanning frequencies, may be applied to grid No. 4 in order to obtain best convergence at all points on the screen.[5] It may also be desirable to vary the grid-No. 3 voltage dynamically in a similar fashion to obtain best beam focus over the entire screen area.

The converging lens shape and, hence, its action are affected by the depth of the grid-No. 4 cup if the depth is appreciably less than the diameter of the cup. A shallow cup would permit the lens field to extend into the small-diameter portions of the electrode, and would distort the beams astigmatically. However, by having the

[3] T. R. Kennedy, Jr., "RCA shows all-electronic tube as key to color television," *N. Y. Times;* March 29, 1950. "New color television tube seen bringing color programs to the home," *Radio Age*, vol. 9, pp. 3–5; April, 1950.

[4] "Improved RCA color TV," *Tele-Tech*, vol. 10, pp. 31, 59; January, 1951. "RCA improves color in latest showing," *Broadcasting*, pp. 73, 77; December 11, 1950. See also J. Gould, "RCA exhibits improved color; complicating of the TV battle seen," *N. Y. Times;* December 6, 1950.

[5] A. W. Friend, "Deflection and convergence in color kinescopes," Proc. I.R.E., pp. 1249–1263; this issue.

depth of the cup nearly equal to or greater than its diameter, this effect is avoided because the converging lens field barely reaches the bottom of the cup, and is not appreciably affected by the three separate openings in its lower surface.

Since the proper functioning of the aperture-mask-screen assembly depends upon the accuracy with which the three beams pass through the "color centers" in the deflection plane,[6] it is important that the separation between the three gun axes, the distance from gun to deflection plane, and the distance from deflection plane to screen be properly set (Fig. 2). The latter distance is determined by the size of screen and maximum deflection angle desired for the tube. The distance between gun and deflection plane is adjusted so that, when the deflecting yoke is in position, there is sufficient space between it and the gun to avoid interaction between the yoke field and the converging lens field. Considerations governing the separation of the beams in the deflection plane (i.e., the location of the color centers) are covered in another paper in this series.[2]

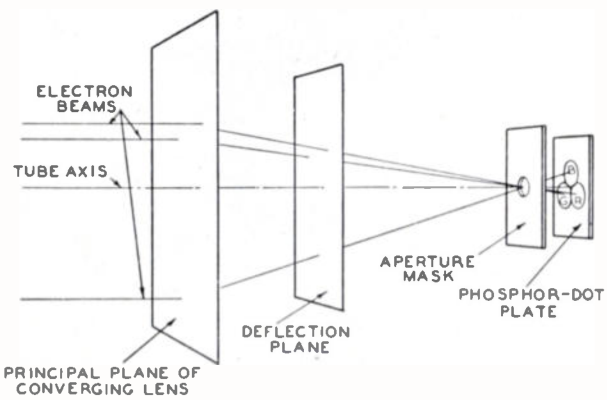

Fig. 2—Diagram illustrating three-beam convergence.

With these parameters set, then, the necessary separation between gun axes could be determined if the location of the principal plane of the converging lens were known. Actually, a reasonable value for gun separation was chosen for a first approximation and the principal plane position computed from operational measurements. A second approximation, based on these results and consisting of adjustment of either the gun separation or the distance from the gun to the deflection plane, then gave sufficiently accurate results. For the diameters and voltage ratios used for the converging lens, the principal plane of this lens lies about midway down the grid-No. 3 cylinders, some three inches below the top of the gun. Fig. 3 shows how the position of the principal plane is determined. Small errors in beam positioning may be corrected by adjustment of three small external magnets placed near the three guns.[5]

[6] D. D. Van Ormer and D. C. Ballard, "Effects of screen tolerances on operating characteristics of aperture-mask tri-color kinescopes," Proc. I.R.E., pp. 1245–1249; this issue.

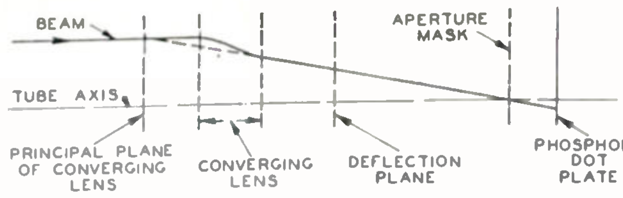

Fig. 3—Diagram of beam convergence, showing method of determining location of principal plane of converging lens.

Fabrication of the Three-Gun Assembly

The design and method of fabrication of the three-gun assembly are determined for the most part by the space considerations of the completed tube, particularly those of over-all length and neck diameter. To permit the minimum neck diameter for the desired beam spacing at the deflection plane, the beams are made mutually parallel up to the converging lens. Because of its ready availability, standard-size tubing, one-half inch in diameter, is used for the gun elements. Since the standard method of gun-element support, using either two supports 180 degrees apart or three supports 120 degrees apart, does not permit the desired beam-to-axis spacing before convergence of 0.415 inch, three standard-type guns could not be used for the assembly without certain changes.

The position of each gun axis is determined by means of an accurately machined, three-fingered fixture which uses the apertures rather than the outer parts of the electrodes for reference. This fixture permits the use of nonprecision, production-type, support elements and spacers. Thus "floating" on this positioning fixture, the cylinders are secured by glass beading or welding. The first method of intergun support considered was an all-beaded construction in which all the separate elements

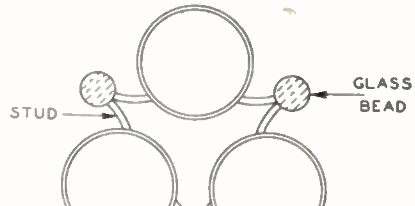

Fig. 4—Three-gun structure having all-beaded support.

of the complete gun assembly (with the exception of the common grid-No. 4 cup) are placed on the positioning fixture and beaded 120 degrees apart (Fig. 4). The grid-No. 4 cup is then positioned by another fixture and welded to the grid-No. 4 cylinders. This type of construction has the advantage that all elements of the assembly can be isolated electrically.

The method adopted later, which offers greater mechanical stability, consists of beading the individual guns with two beads each, 120 degrees apart, as subassemblies. The subassemblies are then positioned on the positioning fixture and the floating positioning system again used. With the subassembly guns positioned parallel to each other, their apertures serving as references, the guns are secured in place by welding an eyelet collar, fitted around the cylinder of a supporting gun element, to a loose-fitting support spacer. After the plane of support has been determined by welding one eyelet to its supporting gun element and welding all of the eyelets to the support spacer, the two remaining eyelets are welded to their respective gun elements. This procedure permits accurate positioning without the use of precision-made cylinders and spacer parts. In the early trials of this method it was found that the intergun supports placed between the control grids provided a loop which absorbed too much of the radio-frequency power intended for degassing the cathode-grid assemblies on exhaust. To isolate the control grids electrically and to prevent overheating due to this absorption of power, the position of the intergrid supports was changed from the No. 1 grids to the lower part of the No. 3 grids. The bottom of the grid-No. 4 cup serves as the second support spacer; the positioning procedure described above is used in placing and securing both spacers.

The heater-cathode-control-grid assembly is the standard structure used on all RCA beaded-type electron guns. Grid No. 2 is a drawn cup with its edge rounded and electropolished. The rolled edge is omitted to provide liberal electrical separation of these cups after assembly. Since this part is positioned by its aperture on the beading fixture, the lower beading stud is placed as close as possible to the bottom of the cup and made slightly longer than the upper stud in order to minimize the torque encountered when the gun is beaded. The ends of the cylinders for grids Nos. 3 and 4, which form the focusing lens for individual beams, have rolled edges of small radius. The top edge of the grid-No. 4 cup is rounded and electropolished, rather than rolled, to allow use of a cup of maximum diameter which would provide adequate breakdown separation from the neck coating.

In the color kinescope both the gun alignment and the distance between the gun and screen are controlled in production so that in operation the beams will pass through the deflection plane in such a manner[6] that both pure color and proper beam convergence are readily obtainable. For these controls, seals for both the neck tubing and gun are made with the help of fixtures which align the neck and gun properly with respect to the color-screen mounting posts.[7]

Light Output and Color Control

In the design of the gun assembly the operating characteristics of each phosphor determine the required drive characteristics of the corresponding guns. The drive characteristics of each gun are controlled so that correct color is maintained independent of changes in brightness. When a black-and-white picture is reproduced by the color kinescope, the color temperature of the whites and grays, from the high lights down to the deepest shadows, is essentially constant. Because the phosphors used in tri-color kinescopes show negligible current saturation in the range of current densities used, the achievement of constant color temperature requires only that the ratios of the three beam currents be held constant over the desired brightness range. The drive characteristics of each gun are controlled by adjustment of the potential differences between the cathodes, control grids, and grids No. 2, all of which are provided with separate base-pin connections. With this flexibility it is not even necessary to maintain close mechanical tolerances to produce the control characteristics required of each gun.

Since the drive characteristics depend directly upon certain phosphor characteristics, a consideration of the characteristics of the phosphors used in the tri-color kinescope is of interest. Table I shows the relative efficiencies of the phosphors and the relative luminosities of the three colors needed to produce white.

TABLE I

Phosphor	Relative Luminous Efficiency	Relative Luminosity to Produce 7,300°K White
Red (zinc phosphate: manganese)[8]	25.3	82.5
Green (zinc silicate: manganese)	100.0	100.0
Blue (zinc sulfide: silver and calcium-magnesium silicate: titanium)	26.6	40.0

It would appear from the above table that current equalization to produce white could be accomplished by adjusting the phosphor efficiencies. Lowering the efficiencies of the blue- and green-emitting materials might appear, at first glance, to be a simple solution. Such reduction of phosphor efficiencies would, however, require a compensating increase of total beam current to maintain light output. Even though the requisite video drive might be available for this purpose, there is a further limitation, namely, aperture-mask expansion due to the increased heating.[7]

When the phosphor efficiencies are not adjusted, the difference between the "red-gun" and the "green-gun"

[7] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask tri-color kinescopes," Proc. I.R.E., pp. 1241–1245; this issue.

[8] A. L. Smith, "Luminescence of three forms of zinc orthophosphate: Mn," *Jour. Electrochem. Soc.*, vol. 98, pp. 361–368; September, 1951.

currents needed to produce white will result in slightly different optimum focusing conditions at high current levels. However, over the range of currents used in the tri-color kinescope, independent focus control of each gun (for example, by means of separate grid-No. 3 leads) or gun modifications are not required for satisfactory results.

Developmental Three-Beam Gun Types

During the course of the development of the three-beam gun, several other types of gun construction and operating principles were investigated.

A variation of the parallel-beam type of gun consists of a single set of electrodes in which each aperture disk contains three apertures, spaced 120 degrees about the center. Three cathodes are enclosed in a common control-grid cylinder having an aperture located above each cathode; a triple-aperture disk serves as grid No. 2, and triple-aperture disks are likewise used in the grid-No. 3 cylinder, both at the lower end and near the upper end. Above grid No. 3 is a grid No. 4, consisting of a simple ring; the conductive neck coating, metal shell, and screen assembly are connected internally. A compound field produced by the potentials on grid No. 4 and the neck coating penetrates the apertures near the top of grid No. 3, providing beam-focusing action. As the beams pass into the grid-No. 4 region, they meet a common convergence field produced by the penetration into grid-No. 4 cylinder of the field produced by the neck-coating potential. Raising the grid-No. 4 voltage increases the beam-focusing action and reduces the converging action; lowering this voltage, of course, produces the opposite effects. There is, therefore, a point at some distance in front of the gun at which beam focus and beam convergence occur simultaneously; the center of the aperture mask is located at this point. This gun is especially suitable when the three beams must be so closly spaced that the use of a separate set of cylinders for each beam is not feasible. The gun requires a relatively small dynamic-convergence voltage; this voltage produces little defocusing of the beams. Fabrication of this gun presents mechanical problems, however, if separate grid-Nos. 1 and 2 controls are required for the three beams. Furthermore, the aperture method of focusing subjects the beams to spherical aberration of considerable magnitude. Masking of the beams and focusing action must be accomplished by a separate set of triple apertures in order to avoid the entrance of secondary electrons (from the edges of the masking apertures) into the convergence field.

The parallel-gun structure described at the beginning of this paper (Fig. 1) allows a considerable degree of flexibility in tube and screen dimensions, and has certain practical mechanical advantages in assembly. However, development of a special jig has recently demonstrated a practical method for accurate assembly of the guns in a tilted position with respect to the axis of the structure. The angle of tilt is adjusted so that when the gun is sealed into the tube neck at the proper distance from the deflection plane the three beams pass through the respective color centers. Minor deviations from the desired alignment may be compensated in the same way as deviations in the parallel-gun type.[6] The mechanically converged type requires no electrostatic converging lens, so that the three grid-No. 4 cylinders may be connected directly to the conductive neck coating (without use of a common cup), and thus operate at the voltage of the final electrode. Beam focusing is accomplished entirely by the lenses between grids Nos. 3 and 4. The advantages of this gun assembly as compared with the parallel-gun type are an increase in grid-No. 3 potential, with consequent improvement in gun efficiency, elimination of a converging lens, and reduction in the maximum potential on the leads brought out through the base. This gun structure, however, has a slightly increased maximum diameter. Dynamic convergence must, of course, be supplied electromagnetically.

Another type of gun, designed for a minimum neck diameter, employs electrostatic divergence of the beams before convergence. This feature permits electrical adjustment of the beam-convergence angle and of the beam spacing at the deflection plane in the finished tube. Electrostatic divergence is accomplished by a lens formed by the combination of a flat aperture disk and a cylinder. The close spacing of disk and cylinder flattens the normally converging portion of the lens so essentially only the diverging portion affects the beams.

Still another type of construction being developed is the "coincident-crossover" type gun. Its operation and construction are based on the principle that if the beams appear to originate from the same source, i.e., have coincident crossover points either real or virtual, a common electron-optical system can be used to focus and converge all beams. An additional feature of the gun is that the divergence of the beams from the crossover point can be controlled electrically, thus making it possible to adjust in the finished tube the positions of the beams in the deflection plane.

Acknowledgments

Many of our associates have contributed to the development described in this paper. For guidance and for ideas useful in three-beam gun design, the authors are particularly indebted to L. B. Headrick and L. E. Swedlund; for indispensable supporting work in means for fabricating the gun, to N. L. Graham; and for development of a practical method for assembling mechanically converged guns, to V. M. Hutchison. Much of our work would have been ineffective without the development of adequate testing equipment, for which credit is due to P. A. Richards, R. W. Hagmann, P. M. Kelly, and D. J. Ransom.

Mechanical Design of Aperture-Mask Tri-color Kinescopes*

B. E. BARNES† AND R. D. FAULKNER†

Summary—The alignment requirements of the aperture-mask color kinescope, combined with the necessity of maintaining the alignment of aperture mask and glass phosphor plate during the operation of sealing the viewing-screen assembly within the tube, have resulted in the development of new assembly methods and techniques. The aperture mask of copper-nickel alloy is stretched tightly on one side of the spacer frame and the phosphor-dot plate is loosely clamped on the opposite side; alignment of the two parts is maintained by a fixed pin at one end of the frame and a sliding pin at the other. The two-piece metal-shell construction permits insertion of alignment fixtures for glass-neck and electron-gun sealing prior to the installation of the screen assembly. A reference plane is provided for these operations by screen-assembly mounting posts inside the shell. An internal high-permeability magnetic shield is also fastened to these posts. The final envelope seal is made by welding together the flanges on the two shell sections by means of an inert-gas arc. These flanges help to protect the tube faceplate and viewing-screen assembly from mechanical and thermal damage during the welding operation.

Introduction

THE PRIMARY mechanical design task in producing a direct-view, large-screen color kinescope of the aperture-mask type was the development of methods and techniques for proper alignment of the aperture mask, phosphor-dot plate, and electron gun. This paper discusses both the techniques developed for producing the major subassemblies of viewing-screen parts and envelope parts, and also the method used for alignment, final assembly, and processing of the complete tube.

In the course of the developmental work on techniques and methods for constructing aperture-mask tricolor kinescopes, a number of developmental tubes have been made. These, in general, are similar in appearance to the RCA 16AP4, but have a welded flange near their large ends, as shown in Fig. 1. They have been made in both one-gun and three-gun versions, and with over-all lengths of either 25 15/16 inches or 33½ inches. All have a picture size of approximately 9×12 inches with rounded ends.

The one-gun tube uses either a standard 5TP4 mount or a special short mount,[1] while the three-gun tube uses a special mount with parallel beams entering an electrostatic convergence electrode.[2] The deflection angle in each case is 45 degrees. The beam-to-axis spacing in the deflection plane is approximately 0.3 inch, the distance from the deflection plane to phosphor screen approximately 14¼ inches, and the convergence angle, therefore, 1 degree 14 feet.

Fig. 1—External view of a three-gun tri-color kinescope.

The major components of the three-gun kinescope are given in the cross-sectional sketch of Fig. 2. A magnetic shield of high-permeability material is mounted inside the tube envelope to prevent beam distortion and resulting color dilution by stray magnetic fields. The phosphor screen is printed in a geometrical pattern on a flat glass plate,[3] which is assembled in conjunction with the aperture mask and then mounted within the tube.

The one-gun and three-gun tubes first demonstrated in Washington, D. C., in March, 1950,[4] used aperture masks with approximately 117,000 apertures, 0.012 inch in diameter, spaced on 0.030-inch centers. A green, blue, red phosphor-dot group was utilized with each aperture, making a total of approximately 351,000 color dots. The spacing between the aperture mask and the phosphor-dot plate was approximately 15/32 inch. The phosphors used were willemite (Zn_2SiO_4:Mn) for the green, blue-emitting silicate (CaMg $(SiO_3)_2$:Ti), and red-orange-emitting borate ($2CdO \cdot B_2O_3$:Mn). These were applied by "silk-screening" techniques,[3] and then aluminized. Didymium glass filters were used in front

* Decimal classification: R583.6×535.6. Original manuscript received by the Institute, August 15, 1951.
† Tube Department, RCA Victor Division, Radio Corporation of America, Lancaster, Pa.
[1] R. R. Law, "A one-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1194-1201; this issue.
[2] H. C. Moodey and D. D. Van Ormer, "Three-beam guns for color kinescopes," Proc. I.R.E., pp. 1236-1240; this issue.
[3] N. S. Freedman and K. M. McLaughlin, "Phosphor screen application in color kinescopes," Proc. I.R.E., pp. 1230-1236; this issue.
[4] T. R. Kennedy, Jr., "RCA shows all-electronic tube as key to color television," *N. Y. Times;* March 29, 1950.

of the tubes to improve the color of the red phosphor. These tubes were operated with the RCA color-television system in circuits previously described[5] and using special deflecting yokes.[6]

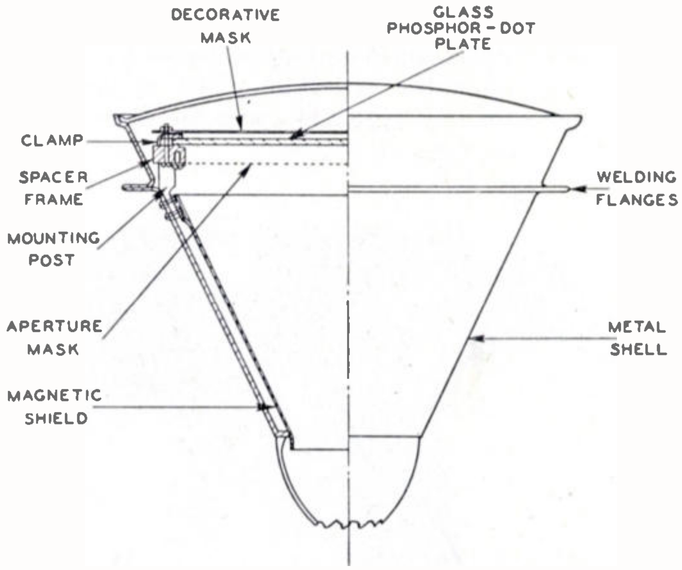

Fig. 2—Cross section of the envelope.

In December, 1950, an improved three-gun tube was demonstrated in improved circuits.[7] The number of apertures in the mask had been increased to 195,000 by reducing the aperture diameter to 0.009 inch, and the spacing between aperture centers to 0.023 inch. The resultant number of color dots was approximately 585,000. The spacing between the aperture mask and phosphor-dot plate was approximately $\frac{3}{8}$ inch. The convergence angle remained 1 degree 14 foot. The picture color and light output had been improved through the use of two new phosphors. One was a blue-emitting sulfide ($ZnS:Ag$) mixed with a blue-emitting silicate ($CaMg(SiO_3)_2:Ti$), and the other was red-emitting phosphate ($Zn_3(PO_4)_2:Mn$). The use of the new red-emitting phosphor eliminated the need for the correcting didymium glass filter. A high-light brightness of over 20 foot-lamberts was obtained, and the finer dots, together with improved receiver circuits, resulted in freedom from objectionable dot structure or noticeable moiré effects. The number of apertures, when corrected for the lost area due to the curved sides of the picture mask, correspond to approximately 215,000 for a full rectangular raster, and provided resolution capabilities in excess of those obtained with present black-and-white standards. The color pictures with this tube are bright, and have high detail resolution, good color fidelity, freedom from objectionable effects due to the dot structure.

[5] "General Description of Receivers which Employ Direct View Tri-Color Kinescopes," *RCA Rev.*, vol. 11, pp. 228–232; June, 1950.

[6] A. W. Friend, "Deflection and convergence in color kinescopes," Proc. I.R.E., pp. 1249–1263; this issue.

[7] Jack Gould, "RCA exhibits improved color; complicating of R.V. battle seen," *N. Y. Times;* December 6, 1950.

Viewing-Screen Assembly

The viewing-screen assembly consists of three major parts: the aperture mask, the phosphor-dot plate, and the spacer frame; the latter serves to hold mask and phosphor-dot plate in correct positions. These parts are shown in Fig. 3. In the initial design of the viewing-screen assembly, considerable attention was given to the registration required between the aperture mask and phosphor screen, and to those operational and processing considerations which affect this registration. Analysis of the screen-assembly problem indicated that the apertures of the aperture mask should be properly aligned with the dots in the phosphor-dot plate to insure color purity, and that the edges of the apertures should be very thin to prevent beam restriction at wide deflection angles. The required aperture-edge thinness was obtained through the use of a photoengraving process as mentioned in the accompanying paper by H. B. Law.[8] The holes are tapered to a feather edge which acts as a very thin mask with respect to the electron beam. Holes made with taper on both sides of the mask to give a feather edge in the center have been made by etching in registry from both sides.[9]

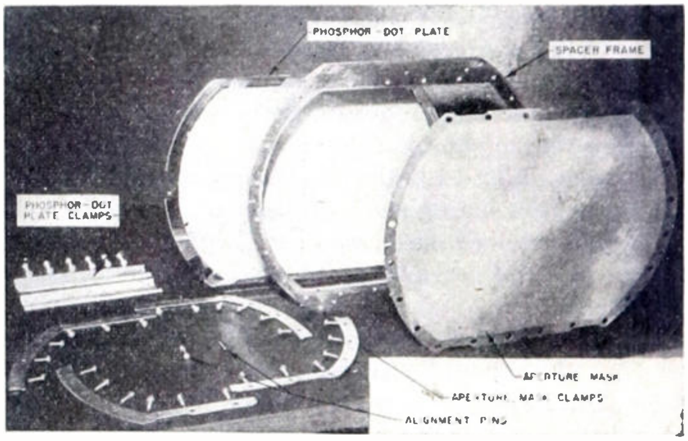

Fig. 3—Viewing-screen assembly—exploded view.

During tube operation, the aperture mask receives approximately 85 per cent of the beam current, which heats the mask and causes it to expand. If this expansion is not compensated for, the mask may buckle, and color nonuniformity may result. To overcome this problem, the "hot-blocking" manufacturing technique was developed. With a temperature difference between the aperture mask and steel frame slightly higher than that encountered in tube operation, the mask is expanded and then clamped to the frame. On cooling, the mask contracts and remains under tension.

[8] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

[9] Masks of this type have been made by the Buckbee Mears Company of St. Paul, Minn.

This operation requires a frame which is strong enough to withstand the tension of the mask without serious distortion. Because size limitations of available mask materials prevented the initial use of a circular frame with its balanced stress system, a frame, illustrated in Fig. 4, was designed. To compensate for the increased bending of the flat sides under load, they are made wider than the curved ends. The increased width of the flat sides also proved useful for mounting purposes. Because the glass phosphor-dot plate is mounted against the side of the frame opposite the aperture mask, the frame also serves as a spacer to give the correct distance between the aperture mask and the phosphor-dot plate.

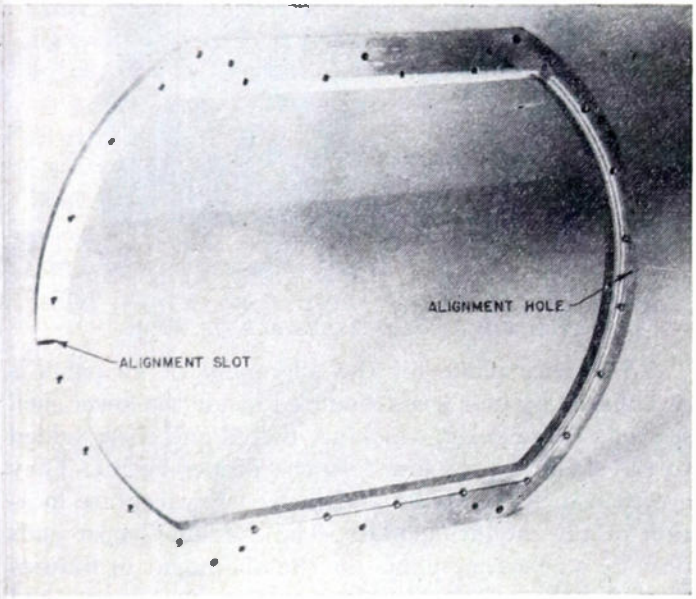

Fig. 4—A spacer frame.

Supernickel, a 70–30 copper nickel, is used for the aperture mask because it has a sufficiently high yield point to withstand the stress applied during "hot blocking." In addition, it is readily etchable by photoengraving techniques (a practical way of economically producing masks with required number of holes), and it has a coefficient of thermal expansion close to that required in the assembly. During tube exhaust, the entire envelope and screen assembly goes through a 400 degree C heating-and-cooling cycle. An aperture-mask material is therefore required which has a higher coefficient of thermal expansion than that of the low-carbon-steel spacer frame. During the heating-and-cooling cycle, the mask expansion should always be greater than the frame expansion, even though the frame temperature, due to its greater thermal mass, is considerably higher than that of the mask during cooling. If, during the cooling portion of the cycle, the aperture-mask contracts more than the frame, the possibility exists of exceeding the elastic limit of the mask material. This condition would result in distortion of the mask pattern, and, in turn, could then lead to color nonuniformity.

The proper alignment of the aperture mask and phosphor-dot plate requires special attention because of the difference in expansion of the spacer frame and phosphor-dot plate during exhaust. In some constructions, this alignment could be controlled by sealing the phosphor-dot plate directly to the spacer frame. In this

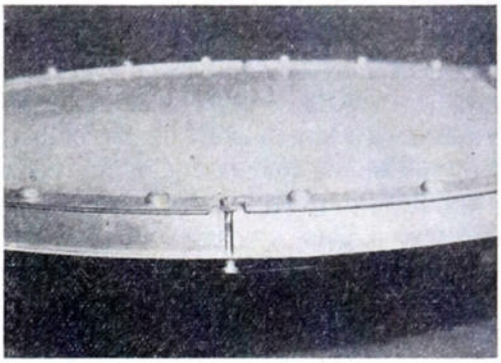

Fig. 5—Expansion joint.

instance, however, the method is not practical because of the flatness required to maintain the necessary parallel relationship between the plate and the aperture mask. The solution developed for this problem is the use of an expansion joint between the glass plate and spacer frame. As shown in Fig. 5, the joint consists of a fixed pin through the glass and frame at one end of the assembly. At the other end, a pin is fixed in the glass plate and allowed to slide in a slot in the frame. The maximum play between the glass plate and the frame is 0.001 inch. The holes are drilled in the glass plates under water with an undersized diamond drill; they are drilled halfway from one side and completed from the other. A plus tolerance of 0.0005 inch in hole diameter is held by reaming the drilled holes to size.

During "hot blocking," temporary pins in the spacer frame hold the aperture mask in proper alignment. Steel clamping segments, 1/16 inch thick, are assembled over the border of the mask by means of clamping screws. The unit is then placed in the "hot-blocking" press, which consists of two electrically heated platens, one mounted on the ram of the press and the other on the bed of the press. Air or hydraulic pressure brings the upper block down against the aperture mask; the mask is squeezed flat as it is expanded by the temperature rise. The lamping screws are then tightened to hold the aperture mask in place on the spacer frame. After the unit is removed from the press, the contraction of the mask in cooling tightens it on the frame.

This aperture mask as clamped to the spacer frame is then photographed in a unit known as a "lighthouse," which is described in an accompaning paper.[8] This photograph is then used to prepare a gelatin stencil. After the phosphor plate is printed with its phosphor-dot pattern and aluminized,[3] it is placed over the registry pin which has been fitted and pressed into the corresponding mask-frame unit. The sliding pin is then fitted into place through the hole in the glass plate and the slot in the spacer frame. Nuts are used to lock the sliding pin. Support clamps with glass-fiber cushions are used to hold the glass phosphor-dot plate snugly against the frame. The viewing-screen assembly is then ready to be placed in the tube envelope.

Envelope Assembly

The choice of materials and the techniques used to incorporate the viewing-screen assembly into a tube are determined to a large extent by the physical properties of the phosphor-dot plate. Preliminary work, in which a small-sized phosphor-dot plate $4\frac{1}{2} \times 6$ inches was sealed into a glass envelope, indicated that this method would present problems due to the stress effects of sudden changes in temperature, or the high temperature necessary to make either a direct glass-to-glass seal or a frit-type seal. In addition, the weight of a large screen assembly required a strong mounting to hold it in position during tube processing and shipment.

With these considerations in mind, two methods were investigated. The first was the use of a direct glass-to-metal seal in which the viewing-screen assembly was thermally isolated by an aluminum foil cap placed between this assembly and the sealing area. Air was circulated to cool the assembly. Although this method has possibilities, it presented difficult processing problems.

The second method was to cut the metal shell apart, insert the screen assembly in the lower portion, and then weld the two parts together without allowing the temperature inside the bulb to rise appreciably. The chief problems encountered in this development were to provide the required stress isolation between the welding area and the glass seals and to develop a technique for making vacuum-tight welds with the high-chromium steel used for the shell. Investigation showed that a shielded-arc weld using an inert gas such as helium or argon would produce vacuum-tight welds, provided that the initial fit between the parts to be welded was good. The development of a practical envelope, therefore, resolved itself into the design problem of providing a good fit between the parts and of isolating the stress between the weld and the faceplate glass seal. Butt and lap welds proved unsuccessful because the parts to be welded could not be properly backed up, and also because either type of weld provided so little stress isolation. The use of flat flanges, which could be clamped together while the edges were being welded, solved the problem.

The metal shell used for type 16AP4 had tentatively been chosen because of its availability, size, and suitability for the desired 45-degree deflection angle. In addition, the conical shape of this shell minimized the amount of stress isolation required between the weld and the faceplate. The development design finally utilized for the assembly is illustrated in Fig. 6. Two metal shells, cut to proper lengths, have flanges spun at adjacent edges and trimmed to size. During the welding of the flanges, a bending moment is produced at the faceplate seal because of thermal expansion of the flanges. This effect is minimized by the conical shape of the shell and by cooling the flanges during the welding operation by means of heavy copper rings clamped to the flanges.

Fig. 6—Metal envelope.

Alignment and Assembly of Tube

A reference plane for the alignment of all parts is established by four posts mounted inside the lower shell section. These posts, which are bolted and then welded to the shell, are machined to the proper height. They are then drilled in a jig and tapped for accurate location of the mounting bolts. The machined post ends provide a reference plane for the alignment of fixtures used for the neck-and-funnel sealing operations, and for the alignment of subassemblies in the final assembly of the tube. A master drill jig is used to drill the mounting and locating holes in the spacer frame, the mounting posts, the "lighthouse," and the assembly jigs.

After the posts are mounted and the reference plane is machined, the glass neck is sealed to the lower shell section. Since the conductive coating to be applied to the inner surface of the neck forms part of the electron-optical system, accuracy in size and roundness of the neck is required. Because of lack of demand, tubing is not currently produced in commercial quantities within the required tolerance of ± 0.001 inch on the inside diameter. It was advisable, therefore, to rework available tubing by shrinking it onto a steel mandrel. This operation is performed by heating the glass on the mandrel and using a vacuum to pull the glass into contact with the mandrel. The metal, of course, shrinks more in cooling than the glass, thus freeing the tubing. This tubing is spliced to a glass funnel and then sealed to the lower metal shell. The fixture used for neck sealing consists of a heavy metal disk and a strong central post. The fixture is bolted to the mounting posts so that the axis of the reference plane coincides with that of the fixture. The desired alignment between the axis of the neck and that of the reference plane is obtained during sealing by the fit between the neck and mandrel. After the envelope is washed, the inner walls of the glass funnel and the upper neck are coated with graphite by standard methods and baked to remove all volatile material.

The fixture used for sealing-in the electron-gun assembly is similar to that used for the neck-sealing operation, except that it has a tip which fits into the common grid-No. 4 cup of the electron gun. In use, this fixture is also bolted to the mounting posts; the gun assembly is then slipped down over the alignment fingers to the proper position. This fixture locates the gun assembly at the proper distance from the reference plane and orients it radially and axially, during the sealing operation, with respect to the positions the phosphor-dot arrays are later to take in the tube.

The magnetic shield, which is required to shield properly the electron beam from stray magnetic fields, is fastened inside the envelope to the mounting posts. This shield, made of 50 per cent nickel-iron alloy, is annealed in a dry-hydrogen atmosphere in order to obtain high permeability.

The viewing-screen assembly is then bolted to the mounting posts. A decorative mask, made of flat blackened metal, is used to frame the useful screen area and to conceal screen assembly parts which would otherwise introduce reflections when the picture is viewed. In the final assembly stage, the upper shell section with sealed-in faceplate is clamped over the mounted viewing-screen assembly. The tube is then placed in a rotating fixture for the welding operation; the seal is made by an inert-gas arc weld in one continuous operation to eliminate the possibility of leaks which might occur if the welding operation were interrupted.

The tube is then exhausted by modified conventional cathode-ray-tube methods. During the exhaust process, particular attention is paid to the heating and cooling rates to prevent the expansion of the frame from exceeding that of the mask.

Acknowledgment

In addition to help in this project from authors of other papers in this series, the mechanical design herein described was aided by ideas and suggestions of G. S. Briggs, M. J. Grimes, H. R. King, and C. P. Smith of the RCA Lancaster Plant and R. R. Law of the RCA Princeton Laboratories.

Effects of Screen Tolerances on Operating Characteristics of Aperture-Mask Tri-color Kinescopes*

DAVID D. VAN ORMER†, ASSOCIATE, IRE AND DAVID C. BALLARD†, ASSOCIATE, IRE

***Summary*—The two basic requirements for proper operation of the aperture-mask tri-color kinescope are that the deflection center and the color center of each of the three beams be coincident, and that the beams converge to a point at the aperture mask. Dimensional deviations which occur in manufacture are discussed in terms of variations from the condition of coincident deflection and color centers.**

The effects of manufacturing variations in the placement of the aperture array and phosphor arrays relative to each other are divided into two general types: the displacement of an array or part of an array within its plane, and the displacement perpendicular to the plane of an array.

If the displacement within a plane is uniform in magnitude and direction, a uniform shift of the position of the color centers within the color plane results. If the displacement is not uniform or contains a rotational component, each section of the screen has a unique color center resulting in a confused or enlarged color center for the entire screen.

With the second type, the displacements normal to the plane of the array, uniform stretching or contraction of either array can be included because these variations in dimensions cause the color centers to be displaced normal to the plane of the screen.

Complete compensation can be made in the finished tube for those manufacturing variations which affect only the position of the color centers. Such compensation is made by altering the path of each electron beam before it reaches the deflection plane so that it passes through the displaced color center, and by placing the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers. The limitations in establishing suitable tolerances for the variations are chiefly those imposed by the envelope and gun dimensions, since beam convergence and freedom from neck shadow must be maintained.

Tolerances on dimensions affecting diffusion of the color centers have been carefully considered in the design of the screen assembly because variations in these dimensions cannot be compensated for by simple means in the finished tube. An allowance for these variations has been made by the use of smaller-sized apertures. In this manner, the effects of variations in phosphor-dot size and shape on hue and intensity are, for practical purposes, eliminated.

Also discussed are the variations due to a tilt of the phosphor-dot plane, the aperture plane, or both planes with respect to the tube axis.

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Introduction

THIS PAPER discusses the effects on the operating characteristics of the aperture-mask tri-color kinescope of deviations from the design center values encountered in the manufacture of the screen assembly and the placement of the screen and gun assemblies in the envelope. The relative importance of these deviations and compensating measures possible in the completed tube are considered.

In the process of setting up the aperture-mask color kinescope, either for operation of the tube or for analysis of the screen assembly, the concept of a "color center" is useful. A color center may be defined as any point in space, determined by the geometry of the screen assembly, from which an observer could "see," through the aperture mask, only the phosphor dots of a particular color. In the tri-color tube, the positions of the three color centers, one for each color of phosphor, determine the "color plane" parallel to the plane of the screen. In the color plane there exists an array of color centers. It would be possible to see only the phosphor dots of a particular color from any one of these color centers, but only the set which is nearest and symmetrically located with respect to the central axis of the screen assembly is of interest.

If the three electron beams deflected by a common yoke field are considered, the three centers of deflection will determine the "deflection plane." If the position of each deflection center coincides with that of a color center, then each deflected beam will excite only the phosphor dots of a particular color. The manufacturing deviations in the production of the screen assembly and its placement with respect to the electron guns can be interpreted in terms of the effects on this condition of coincident deflection and color centers.

In the completed tube these centers are not accessible, i.e., they are within the tube envelope. Therefore, the relative positions of the deflection centers and the color centers must be determined from the effects produced on the viewing surface of the screen. Ideally, the projections of the electron beams through the apertures of the mask onto the phosphor plane coincide with the phosphor dots. The problem thus becomes one of interpreting a three-dimensional system in terms of the effects observed on a two-dimensional surface.

The two basic requirements for the proper operation of the aperture-mask color kinescope are that the deflection center and the color center of each of the three beams be coincident, and that the beams converge to a point at the aperture mask. These two conditions insure pure color fields in proper registry.

The effect of manufacturing deviations in the placement of the aperture array and phosphor arrays relative to each other may be divided into two general types: the displacement of an array or part of an array within its plane, and the displacement perpendicular to the plane of an array.

Uniform Displacements within Plane of Array

If the displacement of the aperture array within its plane is uniform in magnitude and direction, the dimensions of the projected array are not affected since the aperture array is made of equally spaced apertures and the two arrays are parallel. The result is merely a uniform shift of the position of the color centers within the color plane.

Fig. 1 shows a plane normal to the screen and passing through both a color center and the axis normal to the center of the screen. From this figure the following relation may be obtained:

$$\frac{d}{q} = \frac{s}{L - q}, \tag{1}$$

so that

$$\frac{\partial s}{\partial d} = \frac{L - q}{q} = \frac{\Delta s}{\Delta d}. \tag{2}$$

In these relations, d is the distance between the center of a phosphor dot and the center of the three-dot cluster or trio of which it is a part, s is the distance between the axis normal to the center of the screen and the color center, L is the distance between the color plane and phosphor plane, and q is the aperture-plane-phosphor plane spacing.

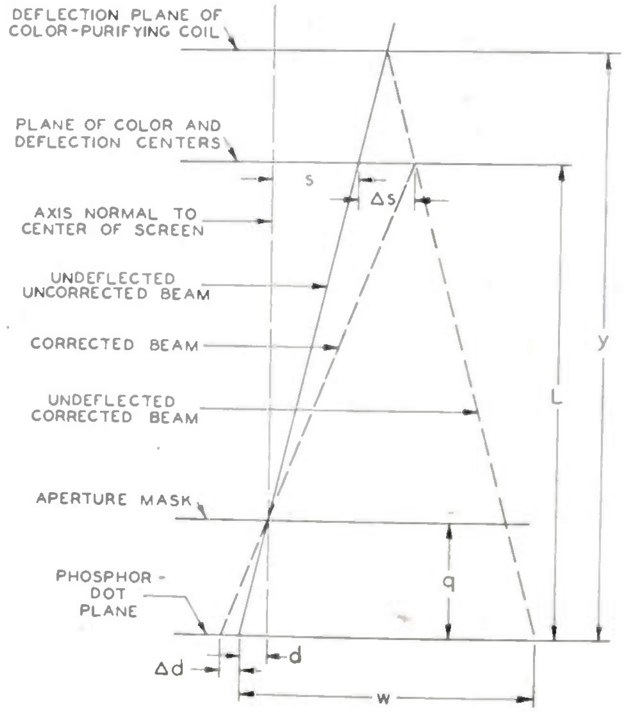

Fig. 1—Plane normal to the screen and passing through both a color center and the axis normal to the center of the screen.

The above relation shows a magnification factor between s and d such that a variation in location of a phosphor dot with respect to its masking aperture is magnified to an apparent change in s by a factor of $(L-q)/q$.

It is possible to correct for the manufacturing deviations in dimension d by deflecting the electron beam before it reaches the deflection plane in order to make it pass through the displaced color center. This correction can be conveniently made by means of the controlled magnetic field of a coil located on the neck of the tube. This coil is known as the "color-purifying" coil.

The amount of displacement of the color center is a convenient indication of the misalignment between aperture and phosphor dot.

Again, reference to Fig. 1 shows that

$$\frac{w}{y} = \frac{\Delta s}{y - L}, \quad (3)$$

where w is the distance between the undeflected focused spot of the corrected beam and the undeflected spot of the uncorrected beam, y is the distance between the phosphor screen and the deflection plane of the color-purifying coil, and Δs is the displacement of the color center resulting from a displacement Δd of the phosphor dot.

Substituting in (3) the expression for Δs in (2) gives

$$\frac{w}{y} = \Delta d \frac{L - q}{q}\left(\frac{1}{y - L}\right);$$

or if $L/q \gg 1$,

$$\Delta d = w\left[\frac{q(y - L)}{yL}\right]. \quad (4)$$

The value of the quantity in the brackets for the tubes described[1] is about 3×10^{-3}. L and q are known from the screen design, while w and y can be measured easily within the required accuracy.

The current required in the color-purifying coil to cause the beam to pass through the color center is adjusted, with the screen under examination through a microscope of approximately 40 power, so that the beam, during the scanning cycle, lands squarely on the proper phosphor dot.

If the position of each dot in a trio is correct with respect to the other two dots so that d is correct, a displacement of this trio with respect to its aperture is a displacement of the axis of the color centers from the axis normal to the center of the screen. The relative positions of the color centers remain the same, and the amount of the displacement of their axis is equal to the shift of s.

This method of analysis and correction may be used for displacements from the design center in a direction parallel to the plane of the aperture array as a result of deviations in the locations of the aperture mask, phosphor-dot plate, entire screen assembly, and the electron guns.

Nonuniform Displacements within Plane of Array

If the displacement is not uniform or if it contains a rotational component, each section of the screen has a unique color center; therefore, a confused or enlarged color center for the entire screen results. This effect can be visualized by considering for each aperture a ray passing through its center and the center of its phosphor dot. For a particular color, all such rays should meet at a single point, which has been defined as the color center. If, for example, the aperture array is now rotated with respect to the phosphor array, the rays connecting the aperture and phosphor-dot centers no longer will meet at a single point. They now define a circle of confusion in the color plane, the diameter of which depends upon the angle of rotation. Since each point within the circle will be the color center of a particular aperture, it would not be practical to have the deflection center coincident with such a "group of color centers."

Thus far, the color center has been considered as a point; however, since the electron beam passing through the color plane has a finite diameter, the system, for optimum operation, must be designed on the basis that the diameter of the color center is the same as the beam diameter.[2] This color center is composed of an infinite number of points, from each of which it is possible to "see" only a part of each phosphor dot of a particular color. When viewed from all of these points within the color center, however, the entire phosphor dot is visible. The beam, therefore, when deflected from the color center, excites the entire dot.

Since it is impractical to correct completely the entire screen for nonuniform displacements, an allowance for such deviations is made in the screen design. As referred to in H. B. Law's paper,[2] the optimum diameter of a color center is equal to M and the diameter of the phosphor dot to R. R is held to its optimum value while the diameter of the masking aperture is made slightly smaller than optimum. Changing the diameter of the aperture changes the diameter of the color center. When x is eliminated from (4), given in the paper by H. B. Law,[2]

$$\frac{M + R}{R - B} = \frac{L}{q},$$

so that

$$\frac{\partial M}{\partial B} = -\frac{L}{q},$$

where B is the aperture diameter. Therefore, decreasing the size of the aperture increases the size of the color center. When the beam diameter no longer completely fills the color center, the entire phosphor-dot area will not be excited. By allowance for a finite beam diameter in this manner, the changes in hue and intensity resulting from variations in phosphor-dot size and shape are, for practical purposes, eliminated. The ratios of the

[1] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask tri-color kinescopes," Proc. I.R.E., pp. 1241–1245; this issue.

[2] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

three beam currents are adjusted so that faithful reproduction of a given hue and intensity is obtained.[3]

Displacements Perpendicular to Plane of Array

For the second type of effect, which is the result of the manufacturing deviations in dimensions normal to the plane of the screen, uniform stretching or contraction of either array is included because the effect on the performance of the tube is the same.

From the equation[2]

$$\frac{1}{D} = \frac{1}{a} - \frac{1}{3s}$$

s is unchanged if D, the distance between centers of phosphor trios, and a, the separation of aperture centers, are unchanged. Therefore, from the equation[2]

$$q = \frac{La}{3s}$$

or

$$\frac{L}{q} = \frac{3s}{a}$$

it is evident that the ratio of L to q is a constant. For the tubes described,[1] the value of L/q is approximately 38, so that changes in the value of q mean that L must change by an amount 38 times as great. Manufacturing variations in q are compensated for by locating the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers resulting from the change in L. Without this compensation, the effect of variations in dimension q on the relative position of the projected beams with respect to the phosphor dots can be obtained from Fig. 2, which shows that

$$\frac{f + \Delta f}{L} = \frac{h}{L - (q + \Delta q)}, \tag{5}$$

where f is the distance from the axis of the color centers to the center of a particular phosphor-dot trio, Δf is the distance between the center of the phosphor trio and the center of the three projected beams, and h is the distance between the axis of the color centers and the center of the masking aperture associated with the trio. Then,

$$f = L \tan \theta$$

and

$$h = (L - q) \tan \theta,$$

where θ is the angle of deflection from the color-center axis to the phosphor-dot trio. When these expressions are substituted for f and h in (5),

$$\frac{L \tan \theta + \Delta f}{L} = \frac{(L - q) \tan \theta}{L - (q + \Delta q)}$$

or

$$\Delta f = L \tan \theta \left[\frac{\Delta q}{L - q - \Delta q}\right]. \tag{6}$$

Since Δq is very small compared to $L - q$, (6) may be written

$$\Delta f = \Delta q \left(\frac{L}{L - q}\right) \tan \theta. \tag{7}$$

Because $L/(L-q)$, the magnification of the phosphor array over the aperture array, is, for practical purposes, very nearly unity,

$$\Delta f \approx \Delta q \tan \theta. \tag{8}$$

From Fig. 2 and (8) it is apparent that an increase in spacing between the aperture mask and the phosphor-dot plate by an amount Δq produces an effect identical to that produced by an expansion of the aperture array by an amount Δh and is, therefore, equivalent to a manufacturing deviation in dimension a, the hole spacing in the mask. The correction for all of these deviations is the same, namely, placement of the deflecting yoke so that the plane of deflection coincides with the displaced plane of color centers.

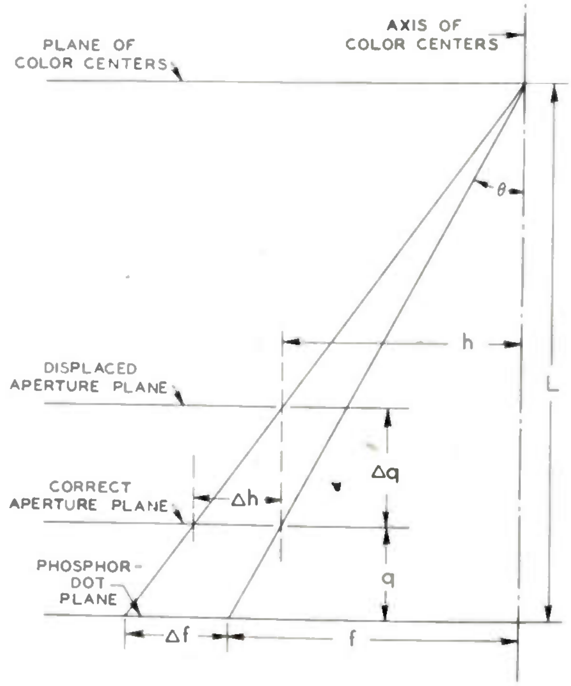

Fig. 2—Plane normal to the screen and passing through the axis of the color centers.

It follows that a tilt of the aperture mask with respect to the phosphor plane so that the two are no longer parallel (i.e., q is no longer a constant but is now

[3] H. C. Moodey and D. D. Van Ormer, "Three-beam guns for color kinescopes," Proc. I.R.E., pp. 1236–1240; this issue.

a function of θ) causes L to become a function of θ so as to keep L/q constant. The resulting diffusion of color centers makes absolute correction somewhat difficult.

A tilt of the entire screen assembly with respect to the axis of the tube, however, results in a tilt of the color-center plane and displacement of color centers in that plane. Such a tilt can, therefore, be corrected, as are other uniform displacements parallel to the plane of the array, but it requires, in addition, tilting of the deflecting yoke.

Conclusions

When the aperture-mask color kinescope is operated, the basic requirement for obtaining pure color fields is that the deflection and color centers be coincident. In order to maintain this condition of coincident deflection and color centers and, therefore, proper tube operation, manufacturing tolerances have been established for the various dimensional deviations which can occur in manufacture. Complete compensation can be made in the finished tube by adjustment of operating conditions for those deviations which affect only the position of the color centers. The limiting values of the manufacturing tolerances for these deviations are imposed chiefly by the envelope and gun dimensions in that beam convergence and freedom from neck shadow must be maintained.

The permissible deviations and resultant tolerances in the dimensions affecting diffusion of the color centers were carefully considered in the design of the screen assembly because they cannot be compensated for by simple means in the finished tube. Allowance for such deviations is made by decreasing the aperture size so that color purity is not affected.

Acknowledgment

The writers wish to express their appreciation for the advice and encouragement given by L. B. Headrick and H. C. Moodey, under whose direction this work was performed. Credit should be given to J. F. Wilhelm, A. M. Morrell, C. W. DeVoll, and R. E. Benway for their helpful assistance.

Deflection and Convergence in Color Kinescopes*

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Summary—This paper discusses the magnetic deflection of a number of closely spaced convergent electron beams as used in the three-gun shadow-mask color kinescope, or in the one-gun shadow-mask tube. The entirely different deflection problem of a line-screen color tube, which uses a raster of precisely straight lines, is also considered, but in less detail.

The shadow-mask color kinescope requires the beams to strike the same spot on the raster, regardless of which part of the deflecting field region is being traversed. A uniform magnetic deflecting field yields only approximately the desired result since large deflection angles and a plane screen complicate the problem. An experimental arrangement, for yoke design-trimming, utilized a single-beam black-and-white or color kinescope with the electron-optics of the one-gun shadow-mask color tube. A rotating magnetic field near the gun produced a conical scan. The rotating beam was next passed through a convergence lens. With adjustable dc currents through the yoke, it was possible to study the convergence at each beam position as a closed pattern on the phosphor screen; a small spot was desired at all deflection positions. Test yokes were built with distributed winding sections, each shunted by a variable resistance to adjust its contributions to the deflecting field. The dc in the coil of the convergence lens was varied as a function of the radial deflection angle to yield best convergence over the entire raster. Adjustable magnetic "compensating tabs" at the forward end of the yoke aided in achieving a final best result. After the optimum yoke configuration had been determined, both hand-wound and machine-wound types of yokes were made with the correct windings. They have been used with both one-gun and three-gun shadow-mask color kinescopes. The rotating conical scan method is also especially useful for studying aberrations of other electron-optical systems, such as lenses.

The use of a planar screen and the scanning of separated beams requires the convergence lens focus to be adjusted as a function of the deflection angle as mentioned above. This was done by a "dynamic-convergence" system, which applied specially shaped waves of the vertical and horizontal scanning frequencies to either a magnetic or an electrostatic-convergence lens.

In the line-screen color kinescope, which used a single beam, the raster lines had to coincide with the ruled phosphor lines; that is, the yoke was required to produce a raster of essentially straight horizontal scanning lines. A design similar to "antipincushion" yokes of black-and-white kinescopes was useful as a first approximation. Again, tapped sectional windings were used for empirical optimization, and a satisfactory design was evolved. On the other hand, a yoke similar to that used with the multi-beam tubes could also be used in combination with dynamic focus and "pincushion" correction systems.

Introduction

Each type of color picture tube requires the practical solution of a particular aspect of the general problem of electron beam deflection. The least complicated color kinescopes may pose very complex problems of deflection. The best over-all result requires that the tube replacement cost should be minimized while maintaining simplicity of apparatus adjustment and a satisfactory degree of excellence of reproduction of both color and black-and-white pictures.

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Utilization of the class of color kinescopes described by Baird,[1,2] Geer,[3] and Alfred N. Goldsmith[4] requires a practical solution of the very complex problem of attaining satisfactory separate deflection of each of three electron beams which converge from widely separated sources. The result must allow color registration throughout the picture. It is difficult to combine the three separately scanned color rasters to produce a color image, simply because of the geometry involved.

At the other extreme is another class of color tube which may be no more difficult to scan than a standard black-and-white kinescope. These tubes may be built with a single electron beam; the color is changed by electrical control of the beam only in the region near the screen, after the scanning action has been impressed on the beam. Such procedures, offering simplification of the deflection problems, are noted by Herold.[5] For a discussion of color tubes in this class, which require no special deflection means, refer to the accompanying papers by Forgue[6] and by Weimer and Rynn.[7]

A single beam does not, however, assure complete freedom from deflection problems. For example, color tube proposals by Rudenberg[8] and von Ardenne[9] require a very precise scanning action to cause the single beam to trace accurately a single color line of a group of parallel ruled phosphor lines on a plane screen. Such line-screen tubes and their operation are described by Bond, Nicoll, and Moore.[10] Another single-beam color kinescope, developed by R. R. Law,[11] employs the shadow-mask, direction-sensitive screen proposed by Alfred N. Goldsmith and developed by H. B. Law.[12] In this instance, the normal path of a single beam is deviated slightly so as to simulate, at any instant, any one of the beams in a multi-beam, tri-color tube.[12] If a beam-deflection system is made to deflect correctly the deviated electron beam, in any position which it may occupy within its converging conic-locus of rotation, then that system will deflect any similarly restricted, conically-converging array of electron beams upon or within that locus. This includes all tubes with one or more beams which converge toward a central axis near the screen. An important example is the shadow-mask (or aperture-mask) tri-color kinescope with three closely-spaced guns.[12] The attainment of proper deflection in such tubes is discussed in the major portion of this paper.

Both the three-gun and the one-gun shadow-mask tri-color kinescopes, which are characterized by the use of an aperture mask aligned with color phosphor dots on a plane screen, appear to offer good performance with sufficient simplicity of apparatus adjustment. The geometry of the shadow mask is arranged to allow the use of a very small angular separation between the beams to control the emitted colors. This principle is the key to satisfactory deflection of an array of electron beams. It makes possible the passage of the array of beams through a single deflection yoke with a minimum of separation. Thus, the beams may be deflected in unison by approximately the same magnetic field. It is, therefore, possible to avoid the electrical and mechanical registration problems which are encountered in separate deflection of each beam, as when a large angular difference is required between the sources.

Although the problem of separate deflection is eliminated, there remain a considerable number of effects of second order. These effects are introduced (a) by the geometry of scanning upon a plane screen, (b) by the geometry of simultaneous deflection of a number of displaced, converging electron beams, (c) by slight differences between the magnetic deflection fields traversed by each of the different beams, and (d) by manufacturing tolerances.

We are concerned with deflecting yokes and accessories which may be required to deflect electron beam arrays (such as those in the shadow-mask dot-phosphor color kinescope[11–13]) which lie in a conic locus and converge to the central axis at a common point. The development program emphasized yoke design and beam-converging devices to maintain beam convergence at a plane surface throughout the entire raster scanning process. The other circuitry and pieces of apparatus which produce the deflection are assumed to be of entirely conventional design.

Multibeam Deflection Concepts

In a conventional black-and-white television kinescope, the outer electrons of the single, focused, electron beam may converge toward the center line of the beam at an angle of perhaps 0.20°. For easier understanding of the deflection problems of the shadow-mask dot-screen color kinescope, let us assume that this angle of convergence is enlarged to between 1.0 and 2.0°, and that three, outer-surface, elemental rays of this beam

[1] J. L. Baird, British Patent 562,168.

[2] "J. L. Baird's, Telechrome," *Jour. Telev. Soc.*, vol. 4, pp. 58–59; Sept. 1944. See also *Electronic Engr.*, vol. 17, pp. 140–141; Sept. 1944; *Electronics*, vol. 17, p. 190, Oct. 1944; and *Wireless World*, vol. 50, pp. 316–317; Oct. 1944.

[3] C. W. Geer, U.S. Patent 2,480,848.

[4] Alfred N. Goldsmith, U.S. Patent 2,481,839.

[5] E. W. Herold, "Methods suitable for television color kinescopes," Proc. I.R.E., pp. 1177–1185; this issue.

[6] S. V. Forgue, "A grid-controlled color kinescope," Proc. I.R.E., pp. 1212–1218; this issue.

[7] P. K. Weimer and N. Rynn, "A 45-degree reflection-type color kinescope," Proc. I.R.E., pp. 1201–1211; this issue.

[8] R. Rüdenber, U.S. Patent 1,934,821.

[9] M. von Ardenne, British Patent 388,623.

[10] D. S. Bond, F. H. Nicoll, and D. G. Moore, "Development and operation of a line-screen color kinescope," Proc. I.R.E., pp. 1218–1230; this issue.

[11] R. R. Law, "A one-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1194–1201; this issue.

[12] H. B. Law, "A three-gun shadow-mask color kinescope," Proc. I.R.E., pp. 1186–1194; this issue.

[13] H. C. Moodey and D. D. Van Ormer, "Three-beam guns for color kinescopes," Proc. I.R.E., pp. 1236–1240; this issue.

are selected to represent the separately converging electron beams of the shadow-mask color tube, as shown in Fig. 1. Thus, it becomes apparent that the multibeam deflection problem is the same as that of a single beam, except that many of the effects, commonly termed "defocusing," are magnified by the large effective size of the composite beam. In addition, throughout the deflection process each of the beams must retain not only its separate purity of source, but also its precise relative position within the composite beam. It is desirable as well to maintain a reasonably good approximation of the original shape of the individual beam.

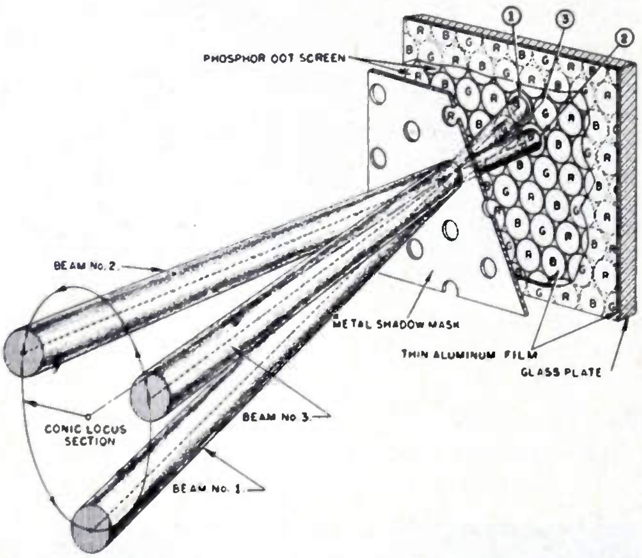

Fig. 1—Electron beams on conic locus.

Each electron beam of the three-beam group enters the deflection yoke and traverses about half the length of the yoke before it deviates appreciably from its particular sector of space wherein no other beam passes. In the forward section of the yoke the accumulating deflection of the beams causes each of them to sweep to a considerable extent through the same space. In order to deflect all beams in unison, since their initial proximity and their final broad sweep prevents any completely separate magnetic action upon the individual beams, the turns of the windings of the yoke are distributed to produce an essentially uniform magnetic field across the central transverse section of the space inside the yoke.

This creates a slightly "pincushioned" shape of raster upon the plane screen, but it seems best to concentrate upon producing a satisfactory convergence of the beams, and to consider correction of the slightly pincushioned raster separately. This shape, in which the sides of the raster are concave, may be corrected to reproduce a straight-sided raster by application of an optical correction plate, by a particular modulation of the final anode potential, or by a modulation of the deflection currents, if more simple means are not available. When the shadow-mask tri-color tubes with a 45°-deflection angle were first publicly demonstrated during 1950, none of these corrections was used, so a small amount of pincushioning remained (about a 4-per cent decrease in central width or height compared with that of the edges). In later demonstrations, however, this was eliminated by circuit modifications not discussed in the present paper.

It was assumed initially that the multibeam deflection yoke was to produce a uniform magnetic field across its central transverse section and to attain high order of uniformity and symmetry of field. Inspections and tests of production yokes for standard black-and-white television indicated that the uniformity and precision of winding distribution, as well as straightness and orientation, would not be adequate for direct adaptation to deflection of the shadow-mask color kinescope.

Consequently, in collaboration with O. H. Schade, of the RCA Victor Division (Harrison, N. J.), and others, it was decided that multi-section coils with their windings securely attached to half-cylinders of a stiff insulating material, such as phenolic resin, should provide a means for accurately fixing and maintaining the relative positions of the coils. Winding these coils in small sections provided means for repeatedly correcting the various tendencies for progressive deformation of their shapes and the random displacement of turns during the winding process.

It was decided that test samples should be made, with *both* terminals brought out from each of five or six winding sections of each coil. Thus, the ampere-turns per section of coil could be adjusted so that, from the data so obtained, the coils might be revised for optimum performance.

Preliminary Yoke Structure

A set of the windings used in the original hand-wound yokes for the tri-color kinescope is shown in Fig. 2. Each of the winding sections (after the first one) was begun by winding the wire around a set of four pins which were passed through the winding-jig and the coil-supporting half-cylinder of bakelite. The small openings between the coils were filled with hard-fibre spacers so that each coil was provided with a firm backing and fixed in position by its individual set of four pins. Even the ends of the turns of the coils were sectionalized by covering each coil layer with a piece of rayon adhesive tape. Special care was taken to assure a uniform winding.

When each winding was complete, the coil, with its base and the entire winding-jig, was impregnated with wax to fix the windings in position. The waxed coils and their base were separated from the winding form after cooling. The pin holes were then used as openings for a binding of cotton sewing thread (Figs. 2 and 3) to retain the coils in position. The larger holes in the winding shells were to admit pins for the precise orientation of each coil-supporting shell.

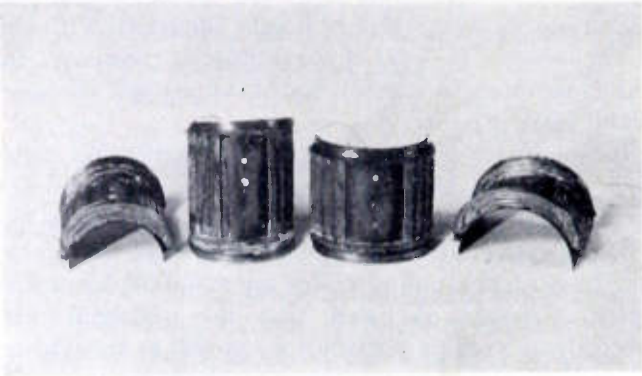

Fig. 2—Section-wound coils on half-cylinder mounts.

The horizontal-deflection coils were assembled upon an inner cylinder of bakelite tubing as illustrated in Fig. 3. The insulating strips were placed in the coil-window spaces to support the similarly mounted vertical-deflection windings, and the outer vertical-deflection

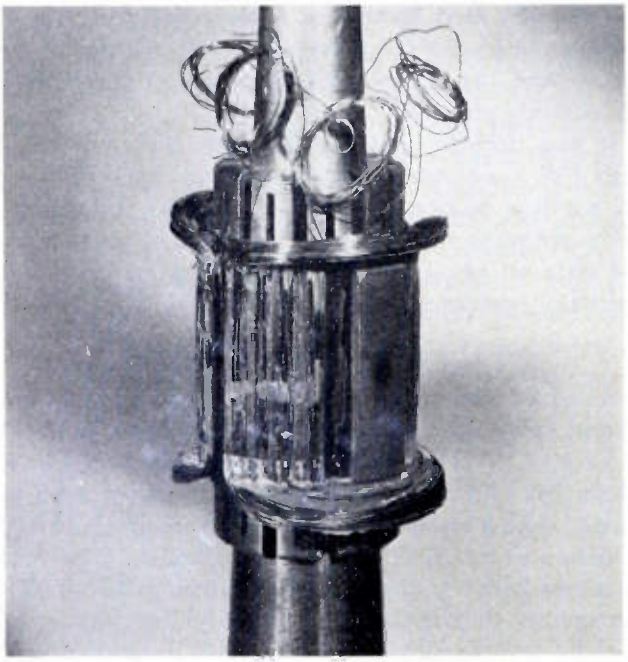

Fig. 3—Horizontal coils and half-cylinder-mounts assembled on inner cylinder.

coils were arranged at 90° about the central axis with respect to the inner coils. Over these coils a final pair of half-cylinders supported the moulded electrolytic iron or ferrite ring-cores, as can be noted in Fig. 4.

The radial insulating separators and the end covers (Fig. 4) were placed during assembly to insulate the separate coils from one another and from the core, to cover the coil ends, and to fix precisely the axial sym-

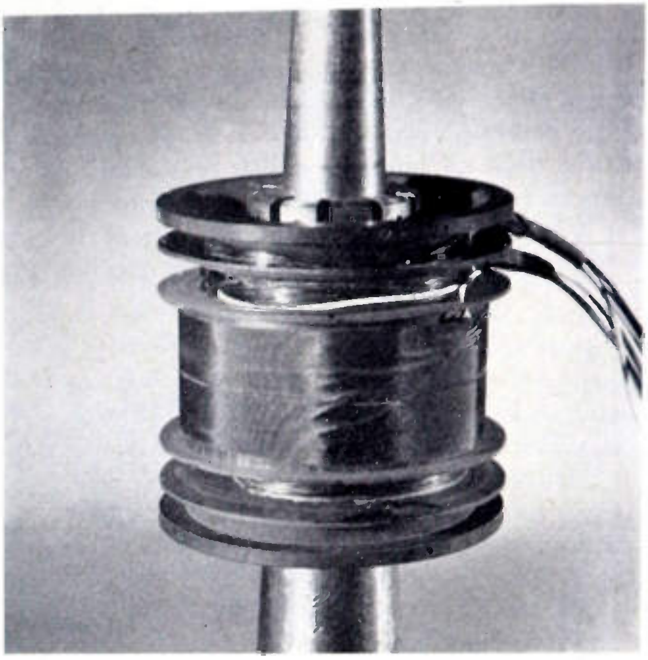

Fig. 4—Coil, core deflection, and spacer assembly of section-wound yoke.

metry of the entire structure in relation to the outer cylindrical shell. A complete assembly is shown. Fig. 5.

Fig. 5—Section-wound yoke for 45° deflection, complete with compensating trimming tabs and beam alignment magnets.

Deflection Testing of Yokes with a Conic-Locus Beam

To test and modify these yokes most effectively, apparatus was set up to produce an electron beam which could be made to sweep around a conic locus with any desired small convergence angle, as shown in Fig. 6. Means were provided to produce convergence at any desired point near the planar white screen of a deflection-testing kinescope, or near the shadowmask (or

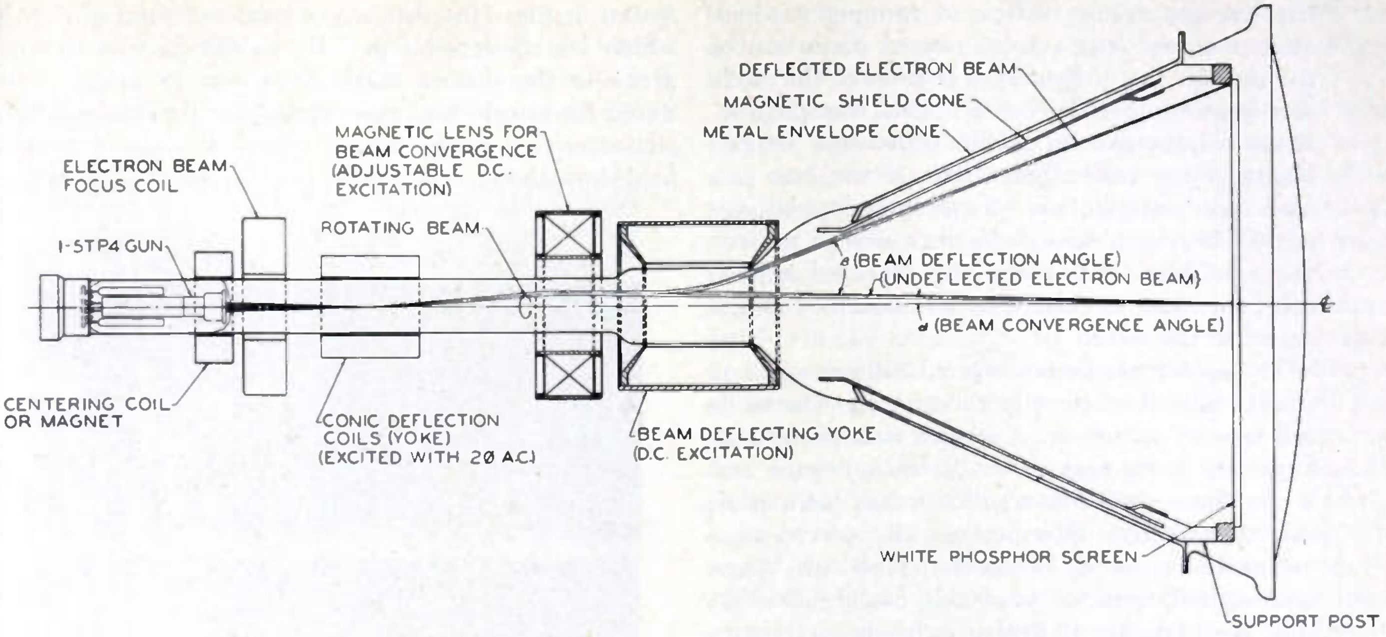

Fig. 6—Conic locus, rotating beam, system for yoke testing.

"aperture mask") of a single gun dot-phosphor color tube. To cause the beam to converge first quite near the gun in the conic-deflection region, a 5TP4 gun utilizing an electrostatic-focus element, was used with a supplementary external magnetic-focus lens coil of standard design (Fig. 6). A simpler gun and a stronger external magnetic lens were used in certain instances. A beam-centering coil or magnet was also provided for magnetic centering of the beam as it issued from the gun.

The centered and focused beam was passed through a set of coils which produced a rotating magnetic field, normal to the axis, in the crossover region of the beam. Either a standard deflection yoke or a special set of coils may be used to radially deviate and rotate the electron beam around the central axis. For most of these tests a standard production yoke was driven by two phases of 60-cycle power. When necessary, a special set of resonant coils operating at 3.58 mc was used.

A magnetic lens was employed to reconverge the beam toward the axis, as shown. This was simply an electromagnetic focus coil, with a large ($2\frac{5}{8}$ inch inside diameter) opening to make aberration and astigmatism of the effectively large beam negligible, and to allow space for adequate translation and orientation.

An especially long neck was used in this tube to allow for these various devices and the deflection yoke. This structure was combined with a planar white phosphor screen in an envelope (Fig. 6) to simulate the deflection geometry of the shadow-mask color kinescopes. Some of the tests were made with actual single-gun shadow-mask color kinescopes. These arrangements produced an electron beam which could be caused to generate a conic surface. This locus could be adjusted to contain any beam which might be used in a shadow-mask tri-color kinescope.

This system was set in operation by the following procedure:

(a) All component elements were placed upon the neck of the tube in computed positions. Each part was visually centered upon the neck and oriented co-axially therewith.

(b) The electron gun was activated at reduced beam current, or with low duty-cycle pulse keying, to avoid burning of the screen by the stationary beam.

(c) The centering coil or magnet was adjusted to cause the beam to produce a spot at the exact center of the screen.

(d) The focus coil was excited with dc and oriented to allow the spot to remain at the center of the screen.

(e) The convergence coil was similarly excited and oriented.

(f) The convergence lens was de-energized, and the conic-deflection coils were excited. The excitation currents and their phasing were adjusted to produce a true circular trace of the required diameter (perhaps 2 to 4 inches).

(g) The convergence lens was excited again and adjusted to reduce the diameter of the circular trace to perhaps $\frac{1}{4}$ to $\frac{1}{8}$ inch diameter, with the effective convergence point on the axis in front of the screen (under-converged). As the convergence angle increased, and the circle became smaller, any coma or lack of symmetry which existed in the lens system caused distortion of the circular trace. Usually a portion of the circle was bent toward the center. This was progressively eliminated by slight transverse adjustments of the convergence lens, if the lens was free from astigmatism. Symmetrical, well annealed, Mu-metal-lens shells were used to achieve this condition. Eventually, by repeated adjustments, a small circular spot was obtained at the center of the screen.

The spot could be made practically as small as that produced when only the gun and the focus coil were in operation, *if the gun structure and its alignment in the neck were sufficiently precise*, and if the focus and convergence lenses were positioned correctly. This process also served as a means for evaluation of the electron lenses. When such a small spot was produced, useful deflection tests were possible to evaluate the characteristics of the yoke.

Deflection Yoke Design Modification Procedure

In the process of determining the desirable empirical modifications of yoke design to obtain best convergence (or focus), the preliminary design-sample yokes were mounted in this test system, with means for passing an adjustable amount of dc through the deflection windings.

The beam was deflected to one corner of the picture area, for instance, by application of a sufficient amount of dc to each set of deflection coils. If a sufficiently good yoke could be made and tested in this manner, the spot would simply change to a nearly circular ellipse. The beam convergence would then occur in the space behind the plane screen. Such a pattern could be again converged to a small spot by a simple adjustment of the current through the coil of a non-astigmatic convergence lens. Theoretically, an absolutely uniform deflecting field with abrupt boundaries should produce an egg-shaped trace. The long axis should be in a radial direction, with the narrower end of the trace outward.

Tests show that with the very large equivalent beam diameter used in the shadow-mask dot-screen kinescope, usual production types of deflection yokes for black-and-white television exhibit very distorted beam patterns at the larger angle of deflection (40° to 70° total angle). These are effectively greatly magnified images of the smaller defocusing effects observed with a thin beam. They are characterized by the distorted patterns of Fig. 7(a), which were made with a total angle of 45° and a conic-beam-locus-convergence angle of $\alpha = 1°14'$, while using a yoke designed to produce an accurately rectangular picture raster ("antipincushion") for use with the line screen color kinescope. The pattern of focus obtained with a single small electron beam is shown in Fig. 7(b). In comparison, the yoke of Fig. 5, which was designed especially to obtain best convergence in the shadow-mask dot-screen kinescope, produced the simpler and more symmetrical patterns which characterize a yoke with an almost uniform magnetic field throughout its central transverse plane. The raster-

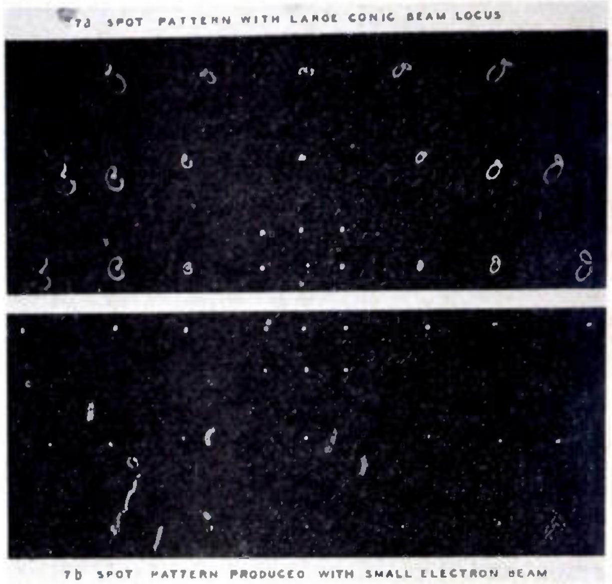

Fig. 7—Spot patterns using an "antipincushion" yoke, 45° maximum deflection angle.
(a) Upper half of raster area with large conic beam locus.
(b) Lower half of raster area with small electron beam.

quadrant photographs of Fig. 8 were taken with this yoke while using the same conic locus of electron beams used in the test of Fig. 7(a). The center dot of each quadrant pattern is placed nearest the center of the entire figure. For Fig. 8(a), optimum convergence was produced at the center only. With the same yoke, the convergence patterns of Fig. 8(b) were photographed with simulated dynamic convergence. This was done by adjustment of the beam-convergence lens to maintain best convergence as the beams were deflected away from the central axis.

During the empirical modification steps of the yoke-design process, a yoke with taps brought out at four or five points on each winding was arranged for independent variation of the currents in the several coil sections. Such variation produced the best possible convergence of the beams throughout the entire area of the raster. Measurements of the coil-section resistances and voltage drops led to computations of ampere-turns products per section which could be used to obtain design modification values.

The turned-up ends of the coils produce oppositely directed axial and other stray fields within the region of the neck-to-funnel junction of the kinescope. The former may be compensated by the addition to the system of an astigmatic lens excited by especially shaped waves of horizontal and vertical frequency. It is much simpler, however, to use movable compensating tabs of ferromagnetic material, or perhaps of highly conductive nonmagnetic material, to attain the desired trimming of the residual convergence errors. The four tabs of thin ferromagnetic nickel-iron alloy (Fig. 5), upon the front cone of the yoke, were added to provide some shielding of the widely-deflected electron beams from the large magnetic field gradients produced by the ends of the windings, and to allow experimental manipulation of the fields in that region.

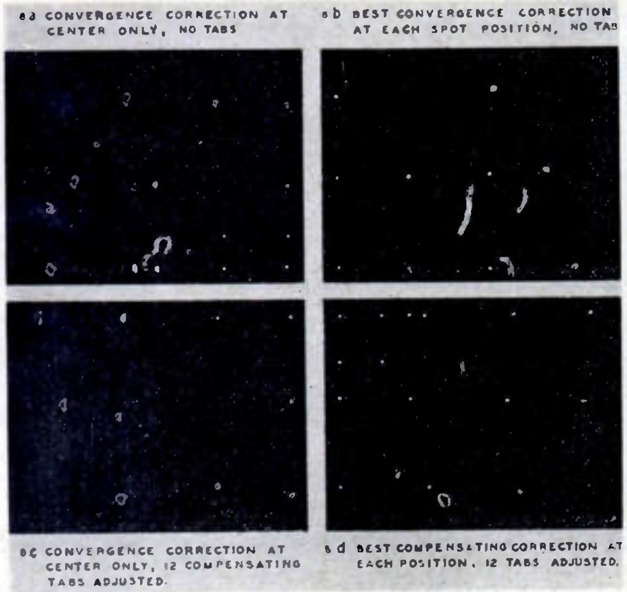

Fig. 8—Spot patterns using section-wound improved convergence yoke of Fig. 5, 45° max. deflection angle.
(a) Upper left quadrant with convergence correction at center only, no tabs.
(b) Upper right quadrant with best convergence correction at each spot position, no tabs.
(c) Lower left quadrant, convergence correction at center only, 12 compensating tabs adjusted.
(d) Lower right quadrant, with best convergence correction at each position, 12 tabs adjusted (final result).

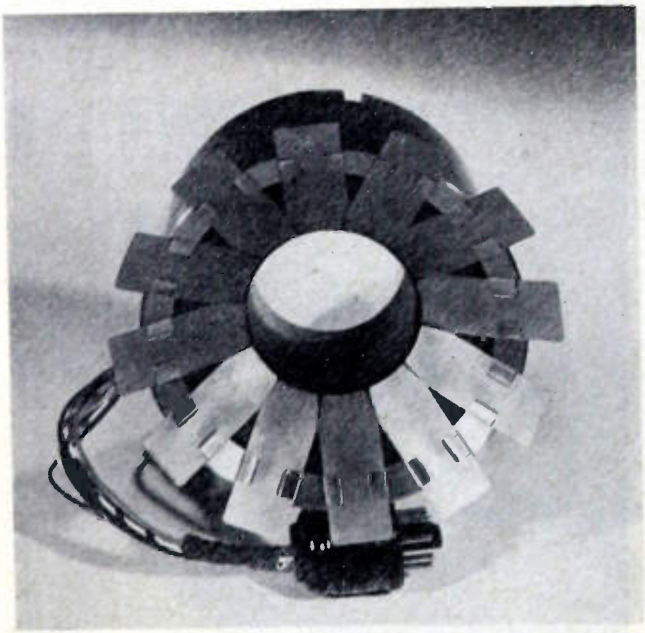

Fig. 9—Array of 12 compensating tabs on section-wound yoke of Fig. 5, approximately as used for test of Figs. 8 (c) and 8 (d).

In a more flexible version of the compensating tabs (Fig. 9), up to twelve strips of thin metal sheet material may be inserted into the holding clips, which allow freedom of movement by sliding in the radial direction or pivoting about the clip mounting screws. When these ferromagnetic "*field-compensating tabs*" were added to modify the fields at the front of the yoke, the more nearly circular trace patterns of Fig. 8 (c) were obtained *with no correction of the convergence angle*. The addition of beam-convergence correction as a function of the radial deflection angle improved the convergence to the final result for the yoke of Fig. 5, as shown by the spot pattern of Fig. 8 (d). The convergence angle was 1°14′ to correspond with that in use in developmental aperture-mask tri-color kinescopes.[14] In these yokes the transverse magnetic fields were found to be quite uniform when they were measured by means of a very small exploring coil placed within the yoke. The maximum deviation from the assumed state of uniform direction flux across the central transverse plane of the yoke was less than three degrees at the outer boundary of the deflecting space.

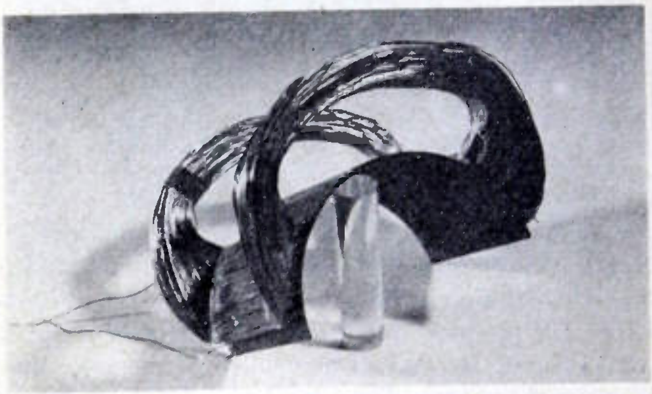

Fig. 10—Sectional-wound yoke coil with elevated turn-ends.

Originally, when these tabs were installed on the early model yokes, the use and adjustment of the entire complement of twelve tabs were required in order to produce acceptable convergence of the beams near the edges of the picture. It was decided to lift the ends of the turns radially, however, away from the deflected beams, as indicated in Fig. 10. This reduced from twelve to only four the number of tabs required to obtain best convergence of the beams at the picture edges. The remaining tabs required only partial insertion when they were correctly oriented. This very desirable change not only reduced the number of adjustments, but reduced the loss of deflection power as well and also al-

[14] B. E. Barnes and R. D. Faulkner, "Mechanical design of aperture-mask tri-color kinescope," PROC. I.R.E., pp. 1241–1245; this issue.

lowed the approximate plane of deflection to occur somewhat farther forward, thus minimizing "neck-shadow" trouble.

The windings of the yoke of Fig. 11, were produced through the cooperation of M. J. Obert and J. K. Kratz, of the RCA Victor Division. The object was to provide a design adaptable to machine winding while retaining the desirable features of the previous yokes. In this yoke, the effect of the lifted coil ends was simulated in the horizontal deflection coils by elevating the major portion of the turns of the windings and allowing only the very thin inside edges of the windings to fill the ends of the coil windows. The vertical deflection coils were made with all the turn-ends elevated. The horizontal and vertical coils were interlocked so that the magnetic-core diameter was reduced and the inside diameter of the yoke increased simultaneously. The decreased core diameter increased the deflection sensitivity, and, at the same time, the decreased radial thickness of the coils produced a larger inside diameter which allowed greater tolerance of movement of the yoke about the neck of the tube. The complete yoke in its bakelite case is also shown in Fig. 11. Four of the convergence tabs are attached to the case by the clips, as shown, in approximately their normal operating position.

Fig. 11—At left is the unmounted 45° multi-beam deflection yoke, adapted for machine winding and die forming. The completed yoke, in its case, is shown with four compensating tabs in their approximate operating arrangement, at right.

Even without the compensating tabs, this improved yoke produced a much superior convergence pattern as can be seen in Fig. 12 (b). When the *four* tabs were added the final convergence pattern of Fig. 12 (d) was achieved. These patterns may be compared with those of Figs. 12 (a) and 12 (b), which were photographed without an equivalent dynamic convergence signal, without and with tabs, respectively. Again, in each case, the nominal convergence angle $\alpha = 1°14'$ to correspond with that in use in developmental aperture-mask tricolor kinescopes.[14]

A simpler compensating-tab mount and coil cover indicated in Fig. 13, was mounted upon a deflection yoke for a 65-degree deflection model of the shadow-mask dot-phosphor color kinescope. This mounting unit was moulded of polyethylene, with a thin inner portion to allow the yoke windings to be moved to within 0.020 inch of the tube funnel when necessary. This light, injection-moulded part provides simple, low-cost, mechanical and electrical separation between the coils

Fig. 12—Spot patterns using formed-winding yoke of Fig. 11, with 45° maximum deflection angle. (The circle around the axial dot in 12 (d) indicates the required dynamic convergence amplitude.)
(a) Upper left quadrant, convergence correction at center only, no tabs.
(b) Upper right quadrant, best convergence correction at each spot position, no tabs.
(c) Lower left quadrant, convergence correction at center only, 4 compensating tabs adjusted.
(d) Lower right quadrant, best convergence correction at each position, 4 tabs adjusted (final result).

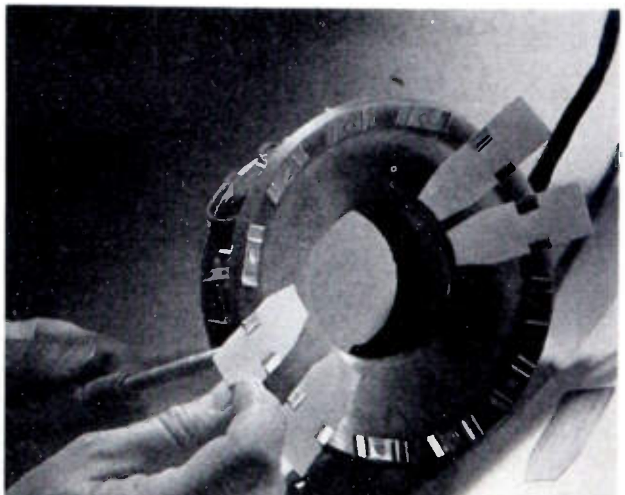

Fig. 13—Front view of 65° multi-beam deflection yoke adapted for machine winding and die forming. 4 compensating tabs are shown in place on moulded polyethylene mounting cover.

and the tabs, and its smooth surface permits easy adjustment of the tabs. The slots which are visible in Fig. 14 allow ventilation and provide flexible fingers to tuck under the combination clamp and terminal board to hold the tab mount in place. The four tabs shown in Fig. 13 are in approximately their normal positions as they might appear on the left and right sides of the kinescope. Rotation after adjustment is prevented by tightening the nuts with a socket wrench. The raster-quadrant convergence patterns for this yoke with 65-degree deflection are shown in Fig. 15. The final results in Fig. 15 (d) are as good or better than those of the earlier yokes, in spite of the increased deflection angle.

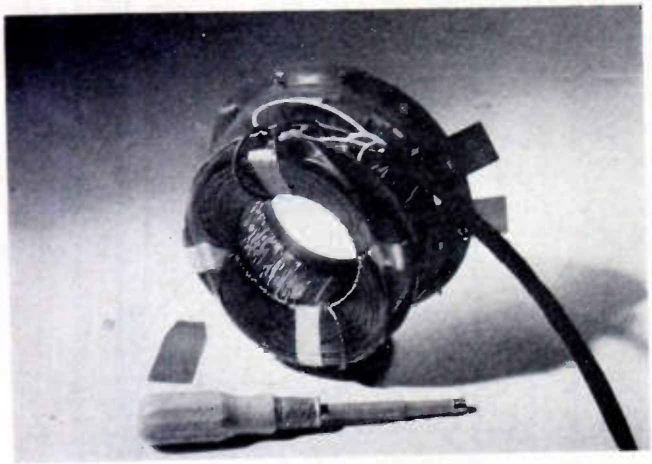

Fig. 14—Rear view of 65° deflection yoke of Fig. 13, showing tab-clip tightening nuts and mounting of front cover fingers under core clamps.

It was possible to eliminate the compensating tabs by modifying the ferrite or powdered iron ring-core structure of the deflection yoke so that it was segmented and adjustable, but the tabs are preferable for simplicity and better performance. The best experimental models of yokes previously described for application to the triple-gun shadow-mask color kinescope have been found to produce an essentially uniform magnetic field in the deflection space, but with a slightly higher flux density near the periphery. When these yokes are used with adjustable-segment cores, best adjustment is attained with the core segments pulled radially outward in the region near the four corners of the raster. The final result is a somewhat "pin-cushioned" raster, but this effect can be corrected by other means.

The present results have been achieved by a practical combination of theory and experiment. The number of variables is sufficient so that perhaps a number of similar solutions may be available. However, the requirement that a number of somewhat separated electron beams behave in a very similar manner makes it expedient to begin the analysis with the uniform field theory and to begin the experimental work under essentially the same conditions. Well chosen minor adjustments and, *above all*, precise construction and assembly of the kinescope and the associated adjustment and deflection components, are the factors which lead to a useful final result.

Simplified Geometry of Deflection of Multiple Convergence Electron Beams

The convergent electron beams of the conic locus in Fig. 1 must be bent in unison to scan the surface of a plane phosphor screen in a television raster. A simple deflection field, e.g. a uniform magnetic field, causes a serious geometric distortion of the locus, producing an elongated and complex convergence region rather than

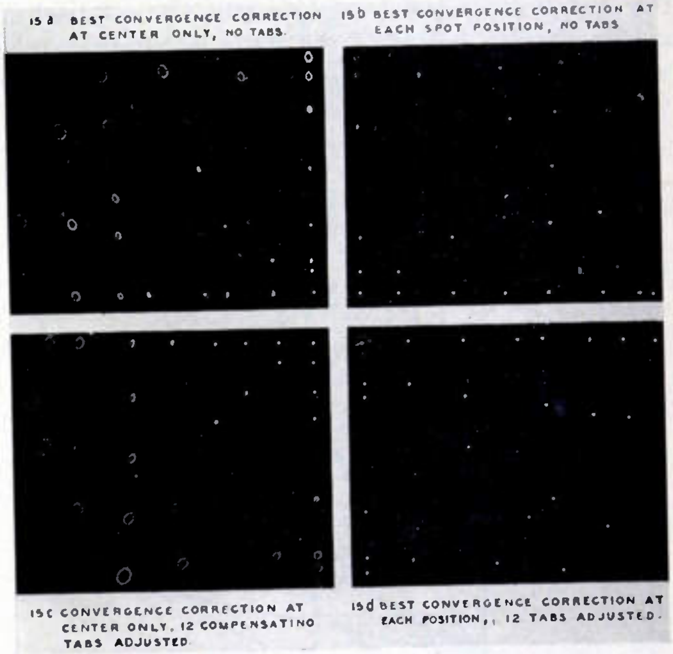

Fig. 15—Spot patterns using formed-winding yoke of Figs. 13 and 14, with 65° maximum deflection angle. (The circle around the axial dot in 12(d) indicates the required dynamic convergence amplitude.)
(a) Upper left quadrant, best convergence correction at center only, no tabs.
(b) Upper right quadrant, best convergence correction at each spot position, no tabs.
(c) Lower left quadrant, best convergence correction at center only, 12 compensating tabs adjusted.
(d) Lower right quadrant, best convergence correction at each position, 12 tabs adjusted (final result).

a simple convergence point. A portion of this geometric effect is the movement of the convergence region backward from the plane screen so that its distance from the approximate deflection plane is proportional to the cosine of the deflection angle which is illustrated in Fig. 16. A simple planar surface, at which all beams are deflected through an angle β_0, is to be assumed normal to the central axis for the preliminary considerations. In this instance, two opposite beams in the conic locus have been assumed, for convenience of illustration, by taking an axial section through the locus and deflecting it normal to the plane of the section. The deflected central axis is also shown for reference. The convergence point Q_B traces a simple circular arc so that the axial distance (X_{QB}), from the plane of deflection to the beam convergence point (Q), varies in proportion to the cosine of the angle of deflection (β_0), as measured from the central axis. The ratio of X_{QB} to the axial convergence distance X_P, between the plane of deflection and the aperture mask, is

$$\frac{X_{QB}}{X_P} = \cos \beta_0. \tag{1}$$

This phase of the problem treats deflection normal to a plane (B), in which these beams lie. The deflected central axis lies in a plane (A), which passes through the central axis normal to plane (B). The assumed opposing electron beams of the conic locus always converge at the same point on the deflected axis, in plane (A). This point is deflected in a circular arc.

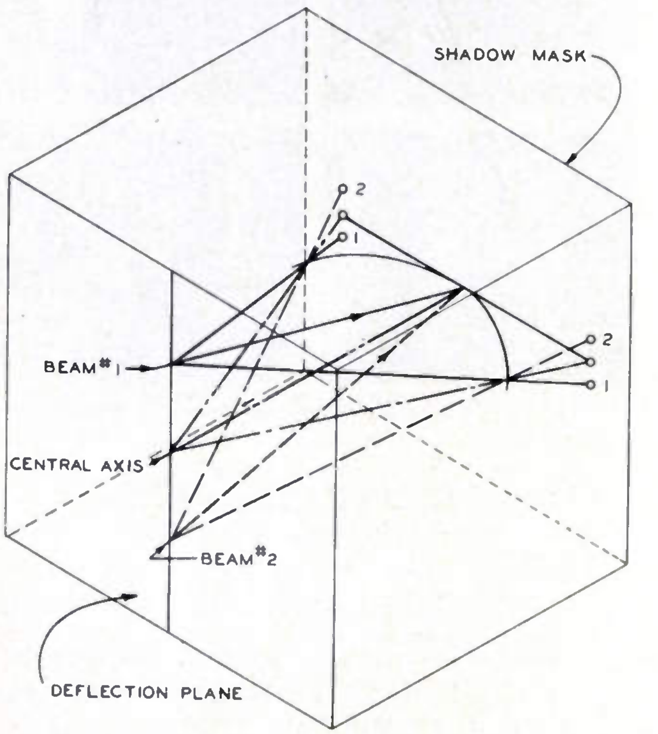

Fig. 16—Deflection normal to plane of beam convergence.

Fig. 17 is introduced to initiate a study of the problem of convergence of a second pair of assumed oppositely converging beams, which lie in the plane (A). Again, the figure is greatly simplified by the assumption of the equal, abrupt bending through an angle (β_0) of each beam which passes through the assumed plane of deflection. Each beam crosses the deflected central axis at a different point, Q_{A01} and Q_{A02}, and they converge at a third point Q_{A12}, further from the undeflected axis. The ratio of X_{QA} (the axial distance from the plane of deflection to the intersection of each beam with the deflection axis) to x_p (the axial distance from the plane of deflection to the center of the aperture mask) is

$$\frac{X_{QA}}{X_P} = \frac{1}{2}\left[1 + \cos(\alpha + 2\beta_0)\right], \tag{2}$$

where α is the angle of convergence of the beams of the conic locus toward the central axis.

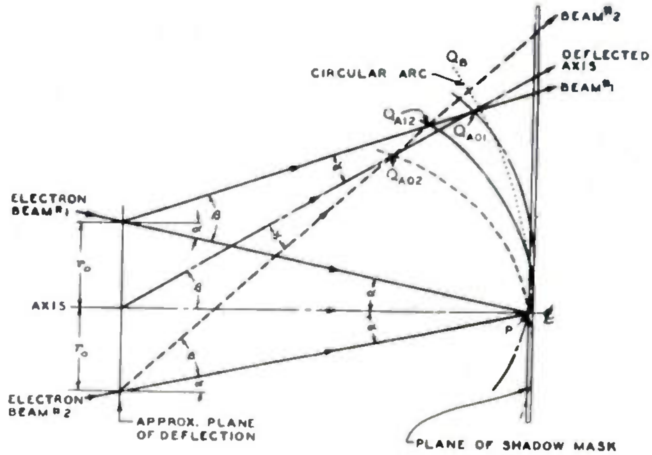

Fig. 17—Simplified geometry of multi-beam deflection system.

Plots of X_{QB}/X_P and X_{QA}/X_P from (1) and (2) are shown in Fig. 18. In this case, $\alpha = 1°00'$, and the angle of off-axis deflection β_0 is the variable. The axial distance X_{QA}, from the deflection plane to the point of convergence of each beam with the deflected axis, decreases at a much more rapid rate with increase of β_0 than does X_{QB}. When $\beta_0 < 10°$ the difference is relatively small. It is obvious, however, that for practical maximum values of β_0, such as 20° to 35°, a correction must be made to produce a useful convergence of the beams.

The plane (A) in which deflection of the axis always occurs was chosen as *a radial plane through the central axis*. Plane (B) was assumed to be also through the central axis of the locus of beams, but normal to the plane (A). If a full conic locus of electron beams, which converge at an angle $\alpha = 1°14'$, was deflected at an angle of $\beta_0 = 32.5°$ from the axis to a point six inches from the center of a plane screen, the magnified trace which would occur, due to the over-converged beams, is shown in Fig. 19. The major axis of the egg-shaped trace lies along the radial line from the center of the screen, extending outward farthest from the deflected axis position (0, 0) in the radial direction. This pattern was computed under the assumption of a uniform magnetic field, which yields a constant finite radius of beam curvature within an equivalent deflecting space bounded by two infinite planes normal to the axis, with a separate distance Y, the equivalent yoke length. The patterns obtained with the experimental yokes were somewhat flattened on the side nearest the axis and distorted as shown in Fig. 8 (a), due to the edge effects in the actual field.

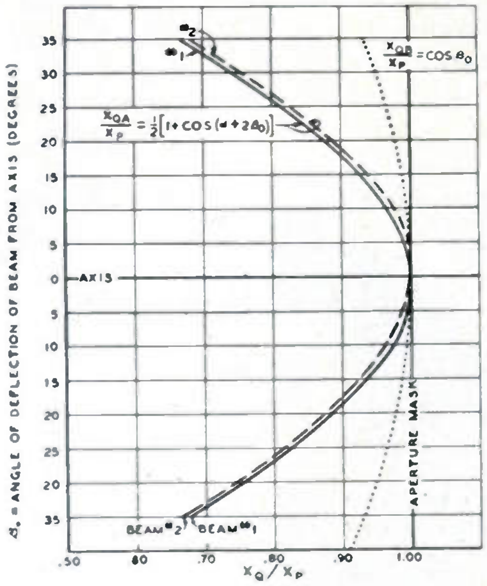

Fig. 18—Fractional distance to convergence point (Q) as a function of deflection angle (β_0), $\alpha = \pm 1°$.

This analysis indicates that the axial distance between the geometrical center-plane of the deflection yoke, normal to the axis, and the instantaneous apparent center of beam deflection is very closely approximated by relation

$$g_0 = \frac{Y}{2} \tan^2 \frac{\beta_0}{2} \tag{3}$$

where: Y is the effective length of the yoke, and β_0 is the angle of deflection from the undeflected position of the beam. It is found, for instance, that for a 70° deflection angle ($\beta_0 = 35°$), $g_0 = 0.049$ inch. Thus it is evident that the "plane of deflection" is actually a curved *surface of deflection*, which is the locus of the apparent center of deflection. This and numerous other higher-order effects contribute to the micro-geometry of deflection and convergence of multiple electron beams.

Dynamic Convergence Procedures

An improved state of convergence at the plane aperture mask can be attained by dynamic modulation of the convergence angle (α) of the conic locus of the electron beams by ac excitation of the beam convergence lens, by modulation of the single-beam rotation amplitude, or by dynamic modification of the angles of convergence α of the individual beams with respect to the central axis, in accordance with functions of the angle of beam deflection β_0 from the axis.

As a first approximation it is possible to produce a symmetrical decrease of the convergence angle of the converging beam locus which enters the deflection yoke as a function of the angle β_0. For best results, this function must be such that the values of X_Q/X_P are intermediate between those of (1) and (2).

A symmetrical lens of either the magnetic or electrostatic type may be used to produce the desired variation in beam convergence. During the deflection yoke tests, with adjustable dc deflection, the change in convergence was readily produced by a simple change in the current which passed through the coil in the beam convergence lens as in Fig. 6.

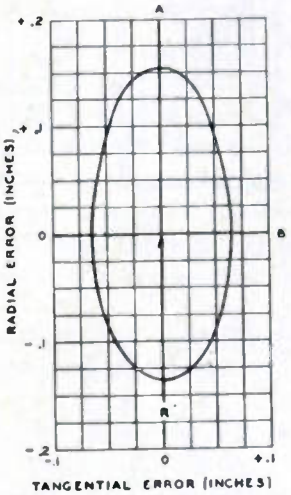

Fig. 19—Computed beam-convergence error pattern plot (32.5° off axis on 12-inch screen).

During actual scanning of a television raster, the convergence angle α must be modulated at a rapid rate by a combination of signal components synchronized and correctly phased with the sawtooth waves of horizontal and vertical deflection current. A separate dynamic convergence lens coil was added to accommodate the signals of scanning frequency and their first several harmonics, when dynamic convergence was used with the single gun shadow-mask dot-screen color kinescope.[11] For optimum results this lens should be made with two separate elements of opposite sense. This avoids the rotational effect introduced by a single magnetic lens, which causes a slight twist in the beam orientation.

The same magnetic lens system may be used with a three-gun dot-screen color kinescope. The tubes of this type demonstrated in 1950 were made with an internal, electrostatic, beam-convergence lens, so that the electron beams issuing from their parallel-axis guns could be bent toward the central axis to converge at the aperture mask. This afforded a simple means for apply-

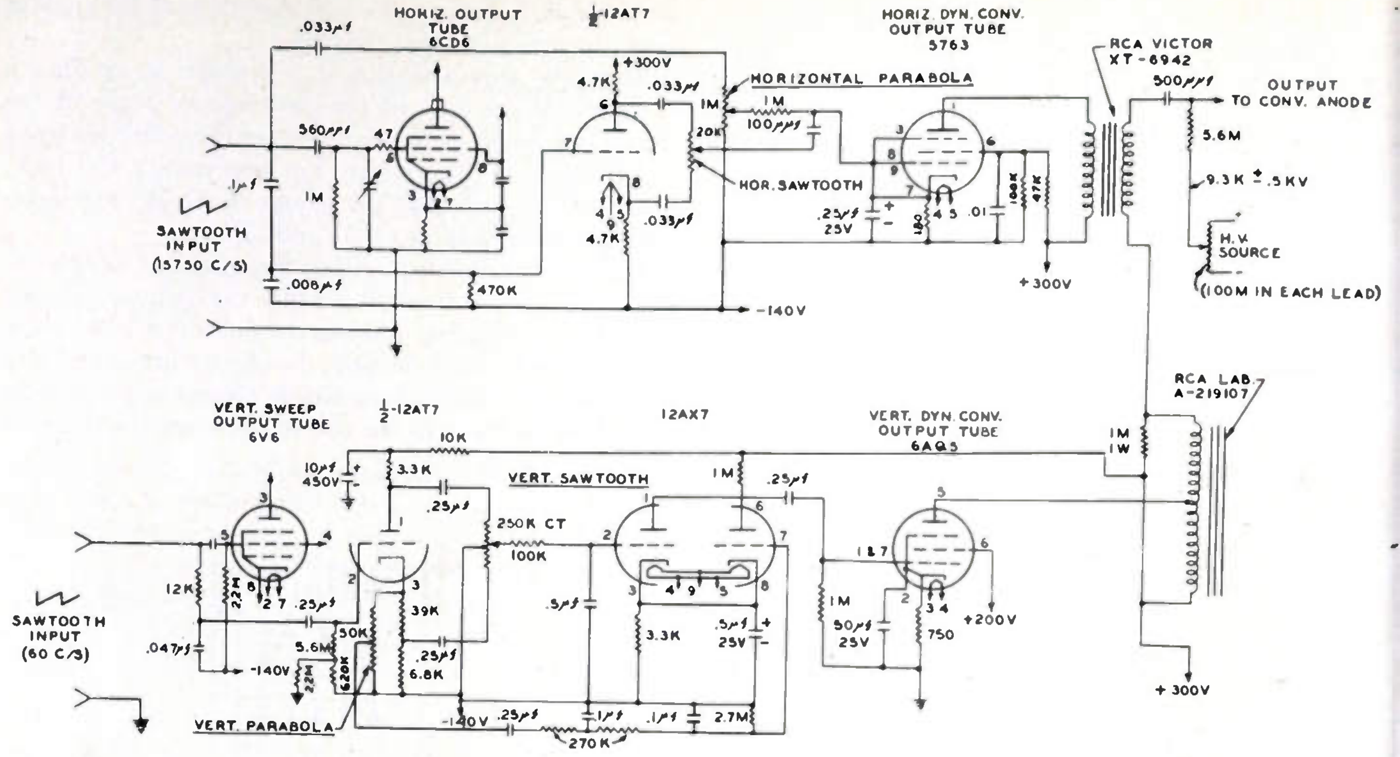

Fig. 20—Dynamic convergence system for three-gun shadow-mask color kinescope

ing the required dynamic convergence as a voltage signal added to the 9 to 10 kv dc potential of the convergence anode.

It was found that a parabolic voltage wave applied across the elements of the convergence lens produced an acceptable approximation of the desired compromise dynamic convergence signal. Such a wave may be produced quite readily by integrating a sawtooth wave from the deflecting circuits. Unbalance conditions, which may arise from manufacturing tolerances in the tube and its accessories, may be corrected by simply adding to the parabolic waves appropriate amounts of the original sawtooth wave or its inverted counterpart. These parabolic and sawtooth signals are required at both the horizontal and vertical scanning frequencies.

The schematic diagram of Fig. 20 indicates one arrangement which has been used for deriving these signals from common types of horizontal and vertical deflection circuits. The sawtooth input signals to the horizontal and vertical deflection output tubes are of the correct relative phase and shape for adaptation to produce the required dynamic convergence. In both the horizontal and vertical dynamic convergence channels an inverter stage is used in combination with an attenuator to provide sawtooth signals of variable amplitude and of *either* relative polarity.

In the channel which operates at the horizontal deflection frequency (15,750 cps) a portion of the sawtooth input signal is passed through a single integrating *RC* circuit and then amplified after combination with the modified sawtooth signal of similar frequency. The output of these signals from the amplifier is coupled, via a suitable voltage-increasing transformer, to the convergence anode of the kinescope. Approximately 1,200 volts peak-to-peak signal is provided from this circuit, of which perhaps 900 to 1,100 volts may be required for present tubes.

Since a voltage-step-up output transformer, correctly designed to minimize distortion of the low-frequency vertical-deflection dynamic-convergence signals is much too heavy and expensive, a considerably smaller differentiating transformer is used. In order to counteract this differentiation the signal of the vertical-sawtooth channel is integrated once and the vertical-parabola signal is integrated twice. Later, each is amplified by an additional amount to compensate for the considerable loss of amplitude in the integrating circuits. The same effect may be attained by an integrating feedback amplifier. The output from this vertical convergence transformer should be approximately 1,000 volts, maximum peak-to-peak, of which about 700 to 900 volts is generally adequate. Similar performance has been obtained by use of a high-voltage resistance coupled output amplifier, with no output transformer. The output of both the vertical and the horizontal dynamic convergence signals are added together and to the necessary dc component required by the second (convergence) anode of the shadow-mask color kinescope.

When dynamic convergence is produced by magnetic lenses, the output transformers may be modified or eliminated and the output signal currents simply passed through one or more magnetic lens coils. This system has been used in tests of tri-color kinescopes with both the three-gun three-beam array and with the single-gun rotating beam. In the three-gun kinescope the magnetic lenses are most useful when each of the guns is aimed mechanically in a manner which does not quite converge the undeflected electron beams at the center of the aperture mask, so that convergence is produced at the maximum deflection angle. Both the convergence anode and its required high (10 kv) dc potential supply may thus be eliminated. A similar gun arrangement was used in the original tubes built by H. B. Law.[12]

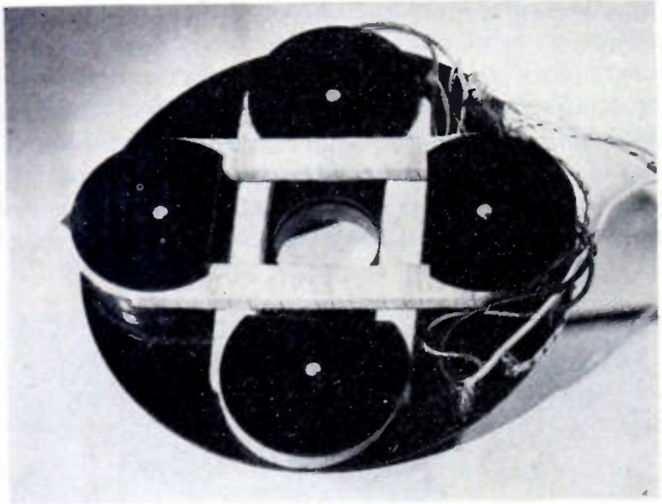

Fig. 21—Double astigmatic magnetic lens assembly for dynamic convergence of electron beams.

It is noteworthy that, at the expense of additional complication it is possible to apply crossed horizontal and vertical astigmatic convergence lenses to produce a somewhat more accurate dynamic convergence. This is done by taking into account the differences between the convergence error effects illustrated by (1) and (2) and the plots of Fig. 17. For instance, if a locus of beams is deflected solely in a horizontal direction, as the vertical deflection passes through zero, the radial deflection vector is horizontal. Fig. 17 shows that the degree of overconvergence in the radial deflection direction is greater than in the tangential (vertical) direction, but a symmetrical lens produces the same correction in both directions. An astigmatic lens may be used to compensate for this difference by producing less correction in the vertical direction. Thus an equivalent spherical and cylindrical lens combination is required to be excited at only the horizontal scanning frequency. Similarly, a like lens oriented about the axis at right angles is needed to produce the correction for vertical deflection of the beams. The two combine their actions as required for their respective components when both horizontal and vertical deflection are simultaneously present.

In a possible magnetic lens system for this purpose, (Fig. 21), the two elongated coils are made to approximate the desired relative corrections in the two directions. Two of these dual-coil units may be used to attain the most precise results. They may be connected in opposing sense to cancel their beam-rotation effects. If desired, such coils may be provided with a housing which acts as an external ferromagnetic return path. Materials such as ferrite or moulded powdered iron may be used to reduce the required driving power. Alternatively, the coils may remain circular and ferromagnetic adjustment elements may be provided to modify the lens to introduce the desired astigmatism.

It is apparent from Fig. 19, that even the double-astigmatic dynamic-convergence correction (magnetic or electrostatic) is not complete because of the small residual differences of deflection which occur between oppositely converging electron beams or their components in the plane (A). *Absolute* convergence upon the deflected central axis in this plane requires a differential modulation of the deflection of the opposing beams or components, in addition to the more simple dynamic corrections. Among the simpler procedures for accomplishing both this and the required adjustments for the stray fields from the ends of the deflection yoke windings are various methods of modifying the magnetic paths within and about the yoke. It is also possible to apply individual beam controlling means and their associated circuits.

The voltage waves generated for application to the electrostatic convergence lens may be modified in amplitude and applied to the beam focusing elements of the electron lenses to maintain essentially optimum focus throughout the entire area of the raster. Likewise, similar waves, of greater amplitude, may be applied to the final anode to eliminate "pincushion" effect caused by scanning upon a plane shadow mask or screen. Similar effects may be produced with magnetic lenses.

Auxiliary Components and Adjustments for Operation of the Three-Gun Shadow-Mask Dot-Phosphor Color Kinescope

A three-gun shadow-mask dot-phosphor color kinescope may contain a triangular array of three parallel electron guns which should project their beams symmetrically into a "convergence anode" cylinder.[13] From this anode space they pass through a convergence lens formed by the opening of the end of the convergence anode cylinder and into the final (accelerating) anode portion of the tube neck, which is provided with a conductive coating on the inside. A dc potential of about 10 kv is applied across these convergence lens elements to cause the three beams to converge at the center of the screen. Manufacturing tolerances make it difficult to produce triple-gun assemblies in which the guns are precisely parallel to each other and to the central axis of the tube. A uniform transverse magnetic field produced by a "color purity coil," may be applied to all the electron beams to orient the *system* of beams as desired. This coil uses either a rotatable yoke-like single pair of coils, or two fixed pairs of coils at right angles, fed from an adjustable source of dc. The *individual* beams can also be adjusted separately by use of small permanent beam-alignment magnets. The arrangement is shown on the neck of the three-gun shadow-mask dot-phosphor color kinescope in Fig. 22. Another arrangement for mounting the beam alignment magnets at the rear of the deflection yoke was shown in Fig. 5. The structure of the swivel-type adjustable mounts is apparent in both photographs.

It may not be sufficient to use the "color-purity" coil simply to cause the axis of the beam locus to coincide with the central axis of the kinescope. The tolerances of manufacture of the aperture mask and dot-screen assembly may make it desirable that the undeflected axis of the beam system approach them at an angle which differs slightly from ninety degrees, to compensate for very slight relative transverse shifts of these elements. To adjust the approach angle of the beam system for color purity, the dc in the transverse magnetic field of the color purity coil, which is in the vicinity of the electron-gun structure, is adjusted to deflect the beams very slightly. The beam axis can then be re-centered by the application of a transverse dc "centering" field in the deflection yoke to achieve a slight angle of incidence of the central axis of the beams with the plane of the aperture mask. Rotation of the field and adjustment of the excitation current in the color purity coil, in combination with adjustments of the centering currents of the deflection yoke, and the axial positioning of the yoke, makes it possible to satisfactorily simulate any required movement of the equivalent array of electron guns.

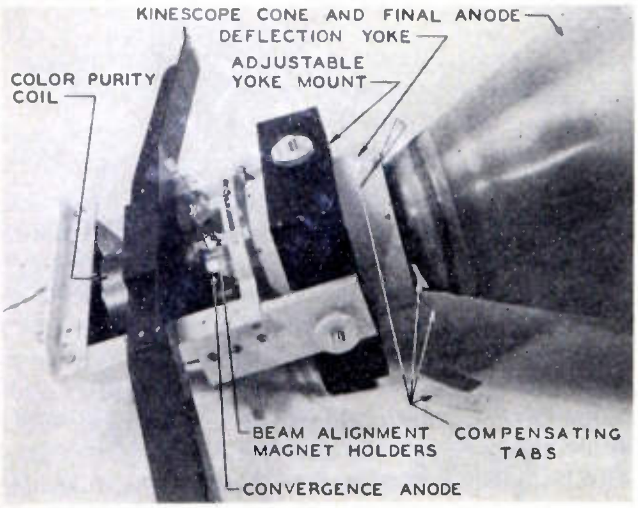

Fig. 22—Assembly of deflection and convergence components on neck of three-gun shadow-mask color kinescope.

The correctly oriented array of beams is caused to pass symmetrically through the deflection yoke by adjustment of the transverse position and orientation of the yoke to bring into coincidence the central axes of the yoke and the undeflected system of beams. The final adjustment is made after a test pattern of horizontal and vertical bars has been applied to the shadow-mask color kinescope and after the dynamic convergence signals have been adjusted to produce straight, parallel lines in the red, green, and blue patterns. The yoke orientation adjustments are made to improve further the parallel adjustment of the sets of color bars of the test pattern. Additional adjustments of the small beam alignment magnets may be made next to produce equally-spaced spots of the three colors at the intersections of similarly colored lines so that they fall at the corners of equilateral triangles. When this process is completed, the dc convergence control provides means for completing the color-raster convergence to produce essentially white lines, except for possible residual convergence errors, which sometimes occur very near the edges of the raster and which are eliminated by adjustment of the field-compensating tabs.

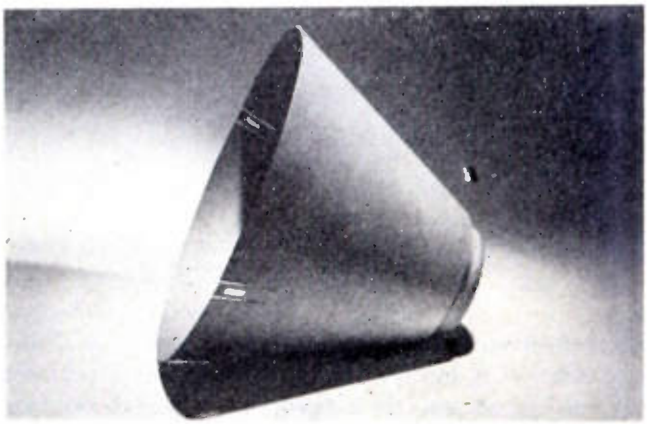

Fig. 23—Internal magnetic shield cone for shadow-mask color kinescope.

The compensating tabs of ferromagnetic material are provided at the end of the yoke to assure good convergence, even near the edges of the raster. They are inserted between the uplifted conductors at the forward end of the deflection yoke and the cone (or "funnel") section of the kinescope envelope. The important regions are those nearest the beams as they pass out of the yoke to scan the four corners of the picture, and to a lesser extent those near the regions where they pass to scan the entire left and right edges of the raster. The convergence tabs should be adjusted in both radial insertion depth and orientation about the pivot points of the tab holders.

To prevent effects due to surrounding magnetic fields, such as small residual magnetism of the chrome-steel cone of the kinescope, a cone of Mu-metal, or possibly of 50 per cent nickel-iron alloy, shaped as in Fig. 23, is installed *within* the metal cone of each shadow-mask color kinescope. The small end of the shield cone is made to extend backward beyond that of the outer metal envelope cone to attenuate the fields across the small opening, where they might otherwise produce their maximum effect.

Yoke Winding Design for Single-Beam Line-Screen Tubes

Deflection means for the electron beam of a line-screen color tube, such as that described by Bond, Nicoll, and Moore,[10] introduce an entirely different set of requirements. A single, very narrow, electron beam must be deflected quite accurately along a straight line. It is desirable to provide a dynamic focus means, similar to the dynamic convergence apparatus, to assure the smallest possible spot size throughout the raster. In addition, the horizontal scanning lines must be essentially straight. Satisfactory results have been achieved by very precise sectional winding and by experimental modification of the magnetic field distributions of previously developed black-and-white television yokes which have been designed to eliminate pincushion effects.[15] O. H. Schade provided valuable assistance in making a number of these tests and in recommendations for modification of the windings. The final turns distribution was adjusted by taps, while the yoke was in operation, in order to provide the straightest possible scan lines. The result was a much more concentrated sort of winding than that used for deflection of the shadow-mask dot-screen color kinescope. Electrostatic lenses and external circuit arrangements were used by Bond, Nicoll, and Moore[10] to produce the final corrections. The system of associated circuitry which is required to maintain a precisely uniform deflection rate across the phosphor-line structure is described in detail in the same paper.[10]

A yoke similar to that developed for the shadow-mask tri-color tube might be used with advantage in the future to allow maintenance of optimum focus. The "pincushion" of the raster could then be eliminated by means separate from the deflection yoke. This may be done by the appropriate cross-modulation and mixing of horizontal and vertically synchronized corrective signals in the deflection yoke, by similarly modulating the potentials of various anode elements of the kinescope, or by extending the application of post-deflection electrostatic lens techniques within the kinescope.[10]

Conclusions

A group of three closely spaced, converging, electron beams may be deflected satisfactorily in unison by a single magnetic deflection yoke to excite a dot-phosphor color screen through an aperture mask, as in the tri-color kinescope. In the reproduced color or black-and-white image it is found that the accuracy of beam convergence at the maximum radius of deflection may be readily held to within less than one-half of one per cent of the raster height. Closer tolerances are attainable, but with more difficulty. Very carefully design and precise construction of the deflection yoke are required to produce equivalent deflections of the different beams. There should also be means for producing slight adjustments of the magnetic fields near the front of the yoke to produce minor corrections of convergence near the edges of the picture and to compensate for tolerance errors. Dynamic modulation of the beam convergence angles, or an equivalent process, is essential to compensate for geometrical effects involved in the scanning process. Rather simple means are available for the production of satisfactory wave shapes for the "dynamic convergence" process from signals already available in the deflecting circuits. The application of similar waves in a "dynamic focus" system is found also to be applicable for maintenance of the best possible focus over the entire picture raster. Similar waves may be applied to the final anode to counteract any "pincushion" effect.

The mathematics of the simplified deflection geometry is useful in predicting the design of the required dynamic convergence, focus, and pincushion control apparatus and their essential operating conditions. It is also applicable to more precise iterative solutions of deflection problems.

A single-gun kinescope with a conically-deflected and reconverged electron beam has proved to be an extremely valuable tool for the adjustment and evaluation of electron lens and beam deflection systems. Since the original draft of this manuscript was prepared, essentially the same experimental methods have been discussed by others.[16]

The line-screen tube poses the problem of the precise scanning of a straight line. In the first approximation, the deflection problem seems less difficult of solution than that for the dot-screen shadow-mask tube. Somewhat more complicated circuitry is required, however, in addition to the yoke, to produce and to maintain the required linearity of deflection. The multibeam deflection yoke may also be used for this purpose to obtain best focus. Pincushioning of the raster must then be corrected by other means.

Acknowledgment

In addition to those mentioned in this and the accompanying papers, it is a pleasure to acknowledge the assistance of J. B. Zirker, of the RCA Laboratories Division, in some of the early work in the mechanical design of test apparatus. T. R. Bashkow, also of the RCA Laboratories Division, has participated actively in the more recent work in the improvement of the dynamic convergence circuits, deflection coils, and adjustment procedures.

[15] K. Schlesinger, "Anastigmatic yoke for picture tubes," *Electronics*, vol. 22, no. 10, pp. 102–107; October, 1949.

[16] D. E. George, R. G. E. Hutter, and M. Cooperstein, "The rotating beam method for investigating electron lenses," IRE National Convention, Paper no. 69, March 20, 1951, New York, N. Y.; also *Sylv. Tech.*, vol. 4, no. 2, pp. 41–43; April, 1951.

Recent Improvements in Band-Shared Simultaneous Color-Television Systems*

B. D. LOUGHLIN†, MEMBER, IRE

Part I—The Constant-Luminance System and Related Improvements

Summary of Part I—A number of improvements in band-shared simultaneous color systems (the previously proposed "dot-sequential" system being one of this class) are described. These improvements reduce susceptibility to interference and permit color pictures to be obtained through a total bandwidth of only 4 mc. These color pictures are comparable to those obtained with a nonband-shared simultaneous color system using 4-mc bandwidth for each color. In order to explain these system improvements the simultaneous nature of the so-called "dot-sequential" system must first be developed. Then the constant-luminance system, in which the color subcarrier information does not affect the brightness of the picture, may be described. Additional improvements consist of an improved subcarrier pattern to reduce crawling effects in the picture and sampling of the brightness signal at the transmitter to reduce "shimmer" resulting from cross talk of high video-frequency components into the chromaticity channel. The manner in which this group of system modifications can be used to improve substantially both compatibility and the color picture is explained.

I. Introduction

During the past few years there have been at least two major engineering advances in color-television systems, namely, the mixed-highs theory and the so-called "dot-sequential" form of band-shared simultaneous color system using mixed-highs. The mixed-highs principle is based on the well-established fact that the eye is insensitive to color in fine detail; consequently, it is wasteful of the spectrum to transmit three separate color signals for fine-detail information. This theory was proposed by Bedford[1] and has been clearly illustrated by color slides in recent talks given by Loughren and Hirsch.[2]

The second major advance, the "dot-sequential" color system using mixed highs, as proposed by RCA,[3] is one form of band-shared simultaneous color system and, as such, it has formed the foundation for a compatible high-resolution color system. The purpose of this paper is to describe system improvements which reduce the visibility of certain interference and spurious patterns produced in this early form of band-shared system. These system modifications permit reproduction of high-resolution color pictures without "shimmer" and permit the compatibility of the system to be improved.

* Decimal classification: R583. Original manuscript received by the Institute, May 11, 1951.

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[1] A. V. Bedford, "Mixed highs in color television," Proc. I.R.E., vol. 38, pp. 1003–1009; September, 1950.

[2] A. V. Loughren and C. J. Hirsch, "Comparative analysis of color-television systems," *Electronics*, pp. 92–96; February, 1951.

[3] "A six-megacycle compatible high-definition color-television system," *RCA Rev.*, pp. 504–524; December, 1949.

II. Simultaneous Nature of the "Dot-Sequential" System

A. The "Dot-Sequential" Signal

While the system proposed by RCA has been called a "dot-sequential" color system using mixed highs, an alternate point of view can be developed, which indicates that the system is substantially simultaneous. However, it should be noted that while "dot-sequential"

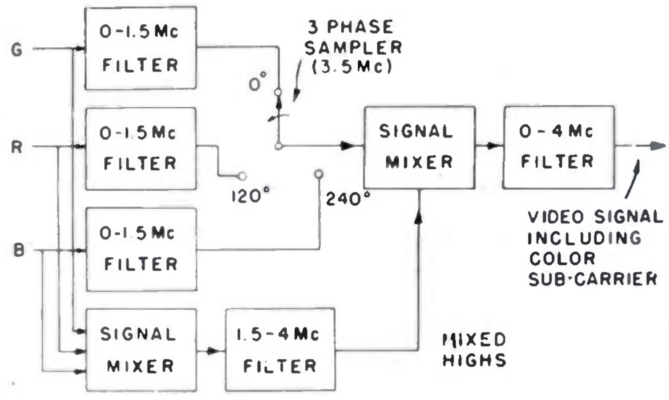


Fig. 1—"Dot-sequential" color transmitter.

receiving apparatus was originally demonstrated by RCA, this *apparatus* should not be confused with the *system* fundamentals now to be reviewed.

The encoding or sampling portion of a "dot-sequential" transmitter is shown in Fig. 1. This is substantially similar to the arrangement originally proposed by RCA.[4] The three-color signals *G*, *R*, and *B*, representing the green, red, and blue signals, are obtained from a color camera and applied to 1.5-mc low-pass filters. The resulting reduced-bandwidth color signals are applied to a symmetrical three-phase sampling system. This three-phase sampling system rapidly and symmetrically measures the amplitude of the reduced-bandwidth *G*, *R*, and *B* signals, and repeats its cycle of measurement at a rate of approximately 3.5 mc. Then a "mixed-highs" signal, containing an equal weighting of the green, red, and blue signal components in the 1.5 to 4-mc range, is added to the output of the sampler to give the desired composite video signal.

B. The Sampling Process

The nature of the "dot-sequential" output signal and spectrum can be deduced from a brief inspection of the

[4] See Fig. 1 on page 505 of footnote reference 3. The present arrangement differs mainly in using 0 to 1.5-mc filters before sampling instead of 0 to 2-mc filters. This simplifies the analysis since the sampling rate is higher than twice the bandwidth of the signal that is sampled. Also, the sampling rate, as stated here, is about 3.5 mc.

sampling process, as shown in Fig. 2. This figure illustrates one channel, i.e., the green channel, of the

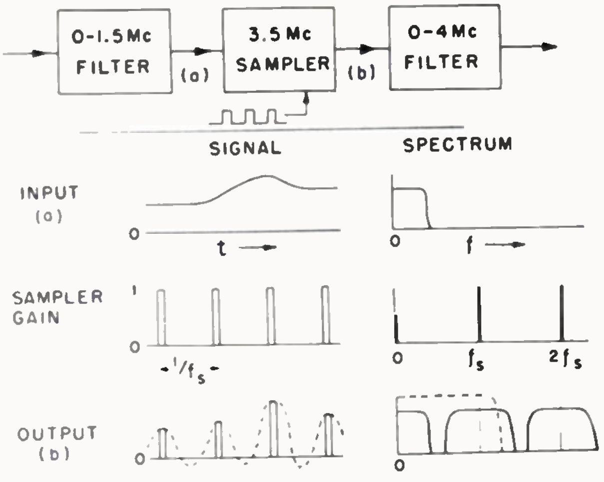


Fig. 2—The sampling process.

three-phase sampler. The reduced-bandwidth signal at point (*a*) is applied to the sampler. The sampling action is merely equivalent to the periodic closing of a switch at a 3.5-mc rate for short intervals of time. Thus, the output of the sampler at point (*b*) is a pulse train with a 3.5-mc repetition rate which has an amplitude proportional to the signal at (*a*); that is, the pulse train is *modulated* in amplitude by the reduced-bandwidth input signal at (*a*).

Considering the Fourier series expansion of the modulated pulse train, it is seen that each harmonic component of the pulse train is modulated by the input signal. Thus, because of the dc component of the pulse train the output signal contains a component equivalent to the input signal; and because of the fundamental and harmonics of the pulse train the output signal contains a series of modulated carriers at the fundamental and harmonics of the sampling rate, which are modulated by the input signal. In other words, the average transmission of the sampling switch results in an output signal equivalent to the input signal, and the heterodyning action of the sampling switch results in the fundamental and harmonics of the sampling rate, which are modulated by the input signal.

In a practical system a bandwidth limitation is required because of the finite bandwidth of the television rf channel (represented here by a 4-mc low-pass filter), so that only the output terms, due to the average transmission of the switch and the fundamental frequency of sampling, are used. Thus, in the proposed "dot-sequential" system the net output of a sampler is merely the low-frequency video signal plus a 3.5-mc modulated subcarrier.[5]

C. The "Dot-Sequential" Spectrum

The "dot-sequential" transmitter includes three samplers, similar to Fig. 2, which operate at 120-degree phase relation and individually sample the green, red, and blue signals. The output signals resulting from the average transmission of these three samplers produce a 0- to 1.5-mc signal which has equal weighting of the original green, red, and blue signals (i.e., $\frac{1}{3}G+\frac{1}{3}R+\frac{1}{3}B$). This is illustrated by the low-frequency portion of the output spectrum, shown in Fig. 3. The modulated carrier output of these three samplers have 3.5-mc subcarriers which are displaced 120 degrees from each other because of the relative timing of the three samplers. Thus, the net carrier signal may be represented by a three-phase vector diagram, as shown above the 3.5-mc component in Fig. 3. When narrow-angle

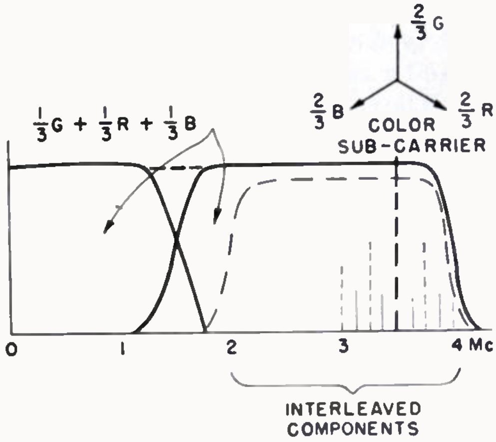


Fig. 3—Spectrum of "dot-sequential" color signal.

sampling is used, the low-frequency components and modulated carrier components have the 1-to-2 relation represented by the $\frac{1}{3}$ and $\frac{2}{3}$ values shown.[6] Also note that the 3.5-mc signal disappears on white (that is, when $G=R=B$) because the vector diagram has symmetrical values.

The total output from the three-phase sampler system is seen to be a composite low-frequency signal plus a composite-color carrier signal. Now, in addition, mixed-highs containing equal weighting of the three color components in the 1.5 to 4-mc range are supplied through the shunt path of Fig. 1. The 1.5 to 4-mc mixed-highs signal combines with the 0 to 1.5-mc signal (resulting from the average transmission of the three-phase sampler) to produce a wide-band 0- to 4-mc (brightness) signal, which is similar to the normal video signal of present-day black-and-white transmission. As will be seen, it is convenient to call this "normal" video signal a "brightness" signal.

It should be noted that as a result of the conventional scanning process the normal brightness video signal consists mainly of bunches of energy clustered about harmonics of the horizontal scanning frequency.[7] The horizontal scanning-frequency harmonics in the

[5] It should be noted here that the above Fourier series-type analysis of sampling may not be particularly useful when the input signal varies *rapidly* compared with the rate of sampling. However, in the "dot-sequential" system the sampled signal is a reduced-bandwidth signal which is sampled at a fast rate; in this case the Fourier series expansion helps to clarify the actual operation.

[6] For example, the output signal due to G is: $G[\frac{1}{3}+\frac{2}{3}\cos(2\pi f_s t)]$ Also, see pages 507–508 of footnote reference 3.

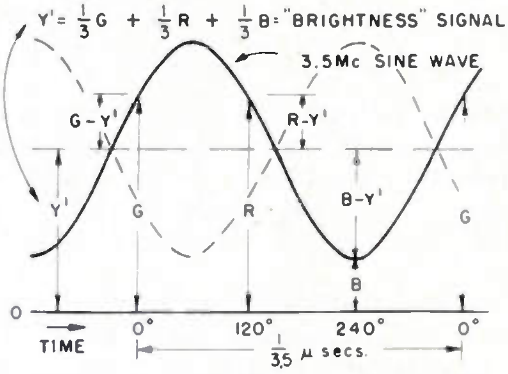
[7] P. Mertz and F. Gray, "A theory of scanning and its relation to the characteristics of the transmitted signal in telegraphy and television," *Bell Sys. Tech. Jour.*, pp. 464–515; July, 1934. Also, P. Mertz, "Television—the scanning process," Proc. I.R.E., pp. 529–537; October, 1941.

3- to 4-mc region are represented by the fine solid lines in the spectrum of Fig. 3. In the "dot-sequential" arrangement the sampling frequency is an odd multiple of one-half the horizontal scanning-frequency, and thus falls half way between the clusters of energy in the normal video signal.[8] In other words, the color subcarrier and its sidebands (represented by the dotted spectrum lines) are interleaved between the high-frequency components of the brightness signal in the 2- to 4-mc range. Since this subcarrier energy is interleaved with the brightness or normal video signal, it tends to integrate out or have low visibility in a receiver reproducing the normal video signal.[9]

From the above analysis, it is evident that the "dot-sequential" system is really one form of *band-shared simultaneous* system, having a wide-bandwidth brightness signal and a narrower-bandwidth color or chromaticity signal. The chromaticity information is thus transmitted as a modulated subcarrier of approximately 3.5 mc, the components of which share the 2- to 4-mc band with, and interleave between, the high-frequency components of the brightness signal.

D. Color-Difference Signals

A further look at the nature of the color subcarrier will be useful. Fig. 4 illustrates a greatly enlarged oscillo-



SIGNAL FOR FLAT YELLOW-COLORED AREA

Fig. 4—"Dot-sequential" signal.

gram of the output signal of a "dot-sequential" transmitter when a flat area, yellow in color, is scanned. The composite signal is represented by a 3.5-mc sine wave (solid-line curve) superimposed on some average or brightness signal (Y'). On alternate frames the sine-wave phase is reversed (as shown by the light dotted line) since the sampling frequency is an odd multiple of one-half horizontal scanning frequency and there is an odd number of lines per frame.

In accordance with the "dot-sequential" concept, narrow-angle sampling of the composite signal at 0, 120, and 240 degrees, that is, measuring the instantaneous amplitude at these times, gives output signals proportional to G, R, and B. Now, suppose the low-frequency component of the brightness signal Y' is thrown away in a filter and only the 3.5-mc component is applied to a sampler. In this case, the output signals, resulting from sampling at 0, 120, and 240 degrees, will be proportional to the instantaneous amplitude of the sine wave at these times and will be $G-Y'$, $R-Y'$, $B-Y'$. (Note that one or two of these signals will have a negative value.) In other words, sampling of the subcarrier alone gives *color-difference* signals which indicate how the G, R, and B signals differ from the average or low-frequency signal Y'. Thus, the 3.5-mc subcarrier signal carries color-difference signals or chromaticity information, and the low-frequency signal Y' might be considered to be a black-and-white brightness signal. It will be noted that when using symmetrical sampling of the subcarrier alone, the sum of the three resulting color-difference voltages is always equal to zero since the subcarrier is a sine wave. Thus, such a symmetrical system might be called a "constant-amplitude system" since the sum of the resulting G, R, and B *voltages* is independent of the 3.5-mc color subcarrier signal.

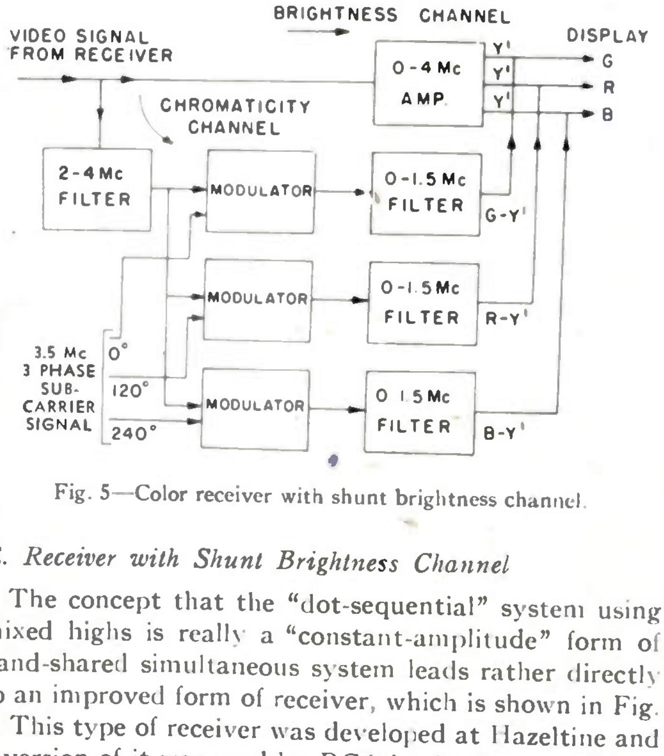


Fig. 5—Color receiver with shunt brightness channel.

E. Receiver with Shunt Brightness Channel

The concept that the "dot-sequential" system using mixed highs is really a "constant-amplitude" form of band-shared simultaneous system leads rather directly to an improved form of receiver, which is shown in Fig. 5. This type of receiver was developed at Hazeltine and a version of it was used by RCA in the demonstrations given in Washington, D.C., during December, 1950. The wide-band brightness signal is applied equally to the green, red, and blue channels of a three-color display (such as a three-gun tricolor picture tube) to produce a *high-resolution* black-and-white picture. The high-frequency portion of the signal, which includes the color subcarrier signal, is selected by the 2- to 4-mc filter in the chromaticity channel, and output signals proportional to the 0-, 120-, and 240-degree values of the modulated subcarrier wave may be obtained from either desamplers or modulators. These correspond to the color-difference signals $G-Y'$, $R-Y'$, and $B-Y'$. Since the color information is limited to a 1.5-mc bandwidth

[8] Typical sampling frequencies might be: 441×15.75 kc/2 = 3.47 mc or 455×15.75 kc/2 = 3.58 mc. Also, see footnote references 2 and 3 for more details.

[9] For a more complete discussion on this, see footnote reference 2.

at the transmitter, 1.5-mc low-pass filters can be included in the color-difference channels at the receiver. The resulting narrow-bandwidth color-difference signals are then applied to the appropriate channels of the display, thus *adding color* to the high-resolution black-and-white picture produced through the shunt brightness channel. The receiver is seen first to produce a high-resolution black-and-white picture similar to that obtainable with present-day black-and-white receivers, and then to "color" the picture from information obtained from the 3.5-mc subcarrier signal.

The simultaneous nature of the system is evident from this form of receiver. Even if narrow-angle desamplers were used, the three narrow-band color-difference signals, $G-Y'$, $R-Y'$, and $B-Y'$, are simultaneous signals which are *not* chopped up by sampling. The reason for this is that the 0- to 1.5-mc filter, which has a bandwidth of less than half the sampling rate, can be thought of as acting as a smoothing filter to fill in the gaps between samples. Furthermore, the brightness channel makes a normal video signal. Thus, the resulting G, R, and B signals are really simultaneous and not sequential in nature. However, the brightness signal and the chromaticity signal share the same frequency band, and *interference* "dots" can be produced between the signals. This interference will be treated in more detail.

Even if narrow-angle desamplers were used instead of modulators, it should be noted that because filters are located before and after the desamplers they would merely produce a *synchronous detection* action. Therefore, the narrow-angle desamplers needed in accordance with the "dot-sequential" concept can be replaced by *sine-wave* modulators since it is merely necessary to keep the correct relative gains in the brightness and chromaticity channels. The possible use of sine-wave modulators is a substantial practical advantage, and their use will be indicated in all of the improved systems to be described.[10]

Also, it should be noted that the presence of the color subcarrier signal in the brightness channel may tend to desaturate the reproduced colors because of nonlinear characteristics of the picture tube. This is particularly true if the subcarrier amplitude in the brightness channel is large. Thus, when using the system proposed by RCA, it may be desirable to reduce the bandwidth of the brightness channel in the color receiver from the 0- to 4-mc value shown down to 0 to 3 mc in order to eliminate the direct 3.5-mc signal and its desaturation effects. This would not be necessary if the color carrier is transmitted at a lower amplitude, as will be proposed later.

F. Spurious Signals Produced in Receiver

Now let us look at some of the difficulties encountered in the constant-amplitude form of band-shared simultaneous color system. Annoying spurious signals can be produced in the chromaticity channel of the receiver because this channel takes high-frequency video components and reduces them to more visible low-frequency components due to heterodyne action in modulators. For example, consider a particular 3-mc component in the video signal which might be a desired high-frequency component of the brightness signal, or possibly an undesired 3-mc beat note resulting from oscillator radiation from a neighbor's receiver. The 3-mc signal will go through the brightness channel and appear as a fine-structured black-and-white signal. In addition, the 3-mc component will appear in the chromaticity channel and will heterodyne with the 3.5-mc subcarrier, in the modulators, to produce more visible 0.5-mc beat notes. With the constant-amplitude system, using symmetrical sampling angles and equal gains in the three modulator channels, the 0.5-mc beat notes appearing in the three color-difference channels will be equal in amplitude and will differ in phase by 120 degrees. This is illustrated by the left-hand symmetrical voltage vector diagram in Fig. 6(a), and by the corresponding voltage waveforms in Fig. 6(b).

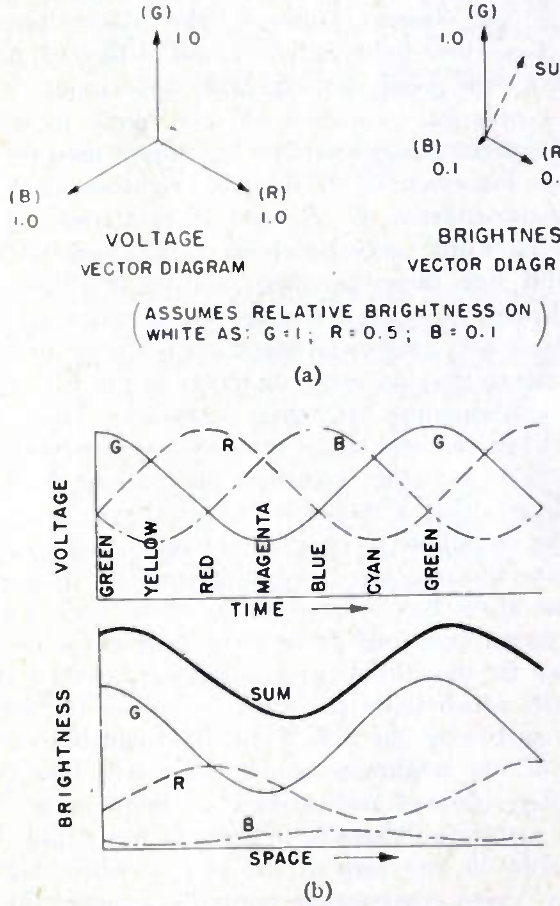


Fig. 6—Beat-notes in the constant-amplitude system. (a) Beat-note vector diagrams. (b) Beat-note waveforms.

While the electrical sum of the three beat notes would add to zero, the visual effect does not, and a colored beat note results. Moreover, since the eye is more sensi-

[10] When using sine-wave modulators instead of narrow-angle samplers, the three-phase signal, referred to in Fig. 5, is properly termed a three-phase *reinserted subcarrier signal*. For brevity, the word "reinserted" will not be used in the block diagrams.

3- to 4-mc region are represented by the fine solid lines in the spectrum of Fig. 3. In the "dot-sequential" arrangement the sampling frequency is an odd multiple of one-half the horizontal scanning-frequency, and thus falls half way between the clusters of energy in the normal video signal.[8] In other words, the color subcarrier and its sidebands (represented by the dotted spectrum lines) are interleaved between the high-frequency components of the brightness signal in the 2- to 4-mc range. Since this subcarrier energy is interleaved with the brightness or normal video signal, it tends to integrate out or have low visibility in a receiver reproducing the normal video signal.[9]

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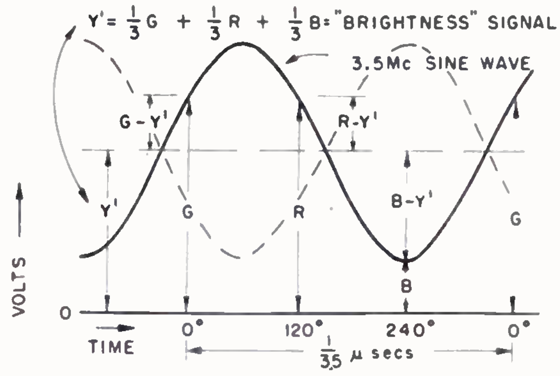

SIGNAL FOR FLAT YELLOW-COLORED AREA

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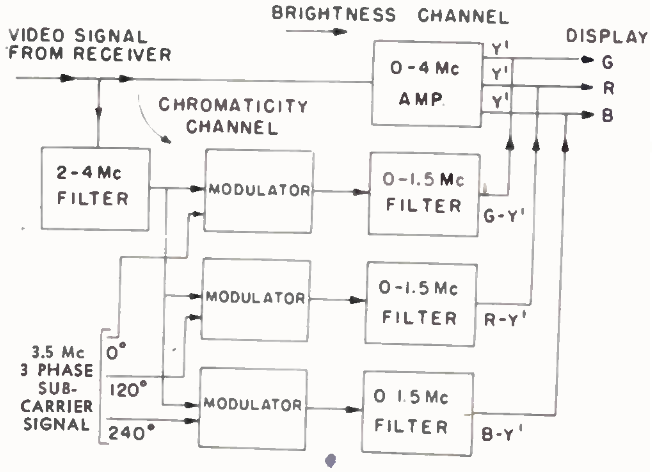

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at the transmitter, 1.5-mc low-pass filters can be included in the color-difference channels at the receiver. The resulting narrow-bandwidth color-difference signals are then applied to the appropriate channels of the display, thus *adding color* to the high-resolution black-and-white picture produced through the shunt brightness channel. The receiver is seen first to produce a high-resolution black-and-white picture similar to that obtainable with present-day black-and-white receivers, and then to "color" the picture from information obtained from the 3.5-mc subcarrier signal.

The simultaneous nature of the system is evident from this form of receiver. Even if narrow-angle desamplers were used, the three narrow-band color-difference signals, $G-Y'$, $R-Y'$, and $B-Y'$, are simultaneous signals which are *not* chopped up by sampling. The reason for this is that the 0- to 1.5-mc filter, which has a bandwidth of less than half the sampling rate, can be thought of as acting as a smoothing filter to fill in the gaps between samples. Furthermore, the brightness channel makes a normal video signal. Thus, the resulting G, R, and B signals are really simultaneous and not sequential in nature. However, the brightness signal and the chromaticity signal share the same frequency band, and *interference* "dots" can be produced between the signals. This interference will be treated in more detail.

Even if narrow-angle desamplers were used instead of modulators, it should be noted that because filters are located before and after the desamplers they would merely produce a *synchronous detection* action. Therefore, the narrow-angle desamplers needed in accordance with the "dot-sequential" concept can be replaced by *sine-wave* modulators since it is merely necessary to keep the correct relative gains in the brightness and chromaticity channels. The possible use of sine-wave modulators is a substantial practical advantage, and their use will be indicated in all of the improved systems to be described.[10]

Also, it should be noted that the presence of the color subcarrier signal in the brightness channel may tend to desaturate the reproduced colors because of nonlinear characteristics of the picture tube. This is particularly true if the subcarrier amplitude in the brightness channel is large. Thus, when using the system proposed by RCA, it may be desirable to reduce the bandwidth of the brightness channel in the color receiver from the 0- to 4-mc value shown down to 0 to 3 mc in order to eliminate the direct 3.5-mc signal and its desaturation effects. This would not be necessary if the color carrier is transmitted at a lower amplitude, as will be proposed later.

F. Spurious Signals Produced in Receiver

Now let us look at some of the difficulties encountered in the constant-amplitude form of band-shared simultaneous color system. Annoying spurious signals can be produced in the chromaticity channel of the receiver because this channel takes high-frequency video components and reduces them to more visible low-frequency components due to heterodyne action in modulators. For example, consider a particular 3-mc component in the video signal which might be a desired high-frequency component of the brightness signal, or possibly an undesired 3-mc beat note resulting from oscillator radiation from a neighbor's receiver. The 3-mc signal will go through the brightness channel and appear as a fine-structured black-and-white signal. In addition, the 3-mc component will appear in the chromaticity channel and will heterodyne with the 3.5-mc subcarrier, in the modulators, to produce more visible 0.5-

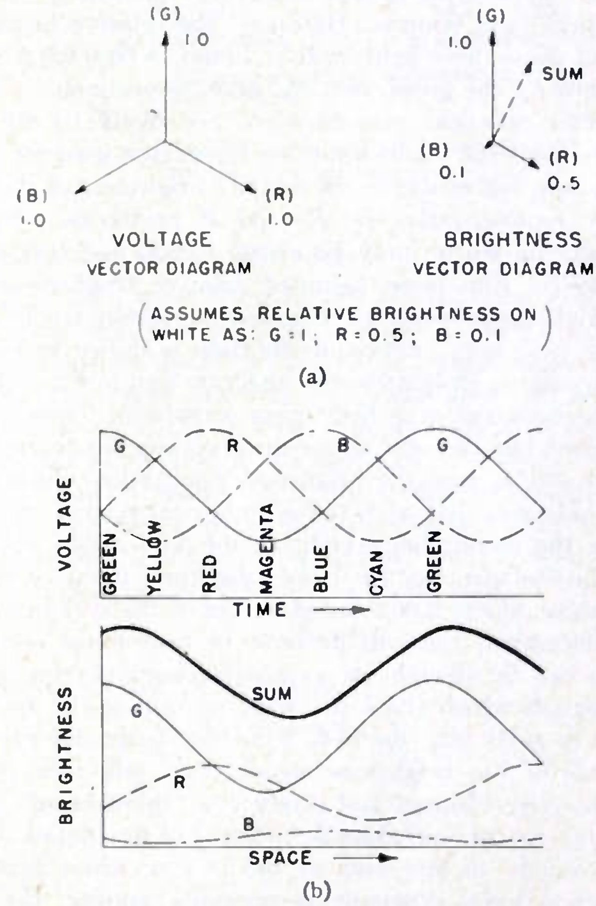

Fig. 6—Beat-notes in the constant-amplitude system. (a) Beat-note vector diagrams. (b) Beat-note waveforms.

mc beat notes. With the constant-amplitude system, using symmetrical sampling angles and equal gains in the three modulator channels, the 0.5-mc beat notes appearing in the three color-difference channels will be equal in amplitude and will differ in phase by 120 degrees. This is illustrated by the left-hand symmetrical voltage vector diagram in Fig. 6(a), and by the corresponding voltage waveforms in Fig. 6(b).

While the electrical sum of the three beat notes would add to zero, the visual effect does not, and a colored beat note results. Moreover, since the eye is more sensi-

[10] When using sine-wave modulators instead of narrow-angle samplers, the three-phase signal, referred to in Fig. 5, is properly termed a three-phase *reinserted subcarrier signal*. For brevity, the word "reinserted" will not be used in the block diagrams.

tive to brightness changes than to chromaticity changes, the brightness component of this colored beat note should be particularly considered.

Equal voltage fluctuations in the G, R, and B channels of the display do not represent equal brightness fluctuations. For example, when rather representative primaries are used to reproduce a white picture, turning off the blue primary will change the picture from white to yellow, but hardly change the visual brightness of the picture. In other words, the blue channel mainly affects color or chromaticity and has only a small effect on brightness.

The difference in brightness between the primaries may be illustrated by considering three monochromatic lights of wavelengths 540 mμ (G), 610 mμ (R), and 470 mμ (B). With these three colored lights, a white light of about 4,800 degrees K is produced by equal *energy* from the three light sources. However, the relative brightness of these three lights will be found to be 0.95, 0.50, and 0.09 for the green, red, and blue, respectively.

Actual practical primaries are not likely to differ widely from the monochromatic lights just used for illustration. For example, the relative brightness of three rather representative G, R, and B primaries, when reproducing white, may be about 1, 0.5, and 0.1, respectively. For these assumed relative brightnesses, the brightness-variation versus space resulting from the 0.5-mc beat note under consideration is shown in Fig. 6(a) by the right-hand vector diagram and in Fig. 6(b) by the corresponding brightness waveform. Thus, we see that while the sum of the three voltage fluctuations would add to zero the brightness fluctuations do not. This indicates that with the symmetrical system a signal in the chromaticity channel not only causes color fluctuations but may also cause brightness fluctuations.

Because of the band-shared nature of the system under discussion, spurious patterns or beat notes result which can be thought of as interference between the two signals which share the same portion of the spectrum. In particular, the 2- to 4-mc high-frequency components of the brightness signal cross talk into the chromaticity channel and produce a "shimmering" or crawling pattern on edges or in areas of fine detail. In other words, in any area of the picture where high-frequency video components normally appear, there will also appear spurious patterns because of these components getting into the color channel of the receiver.

Now, since the band-shared components are interleaved, the interference has opposite polarity on successive picture frames. This tends to make the interference cancel out visually; however, because of nonlinearities and of inadequate integration of the eye over the 1/15th second involved in two successive picture frames, these spurious patterns are still somewhat visible. In particular the *brightness* component of these spurious patterns is the most visible. Experience indicates these spurious patterns, resulting in the symmetrical arrangement, need to have their visibility reduced.

III. The Constant-Luminance System

A. Color Versus Brightness Fluctuations

The eye is less sensitive to changes in chromaticity, that is, changes in hue and saturation, than it is to changes in brightness. When these are changes versus space, this statement is merely a rephrasing of the mixed-highs principle.[11] But the statement also applies to changes versus time, as is indicated by the flicker photometer. In the flicker photometer two beams of light are alternated at about 40 times per second, and they appear to flicker as long as there is any brightness difference between them. However, if the flicker rate has been set properly, no flicker will result from a difference in hue or saturation.[12] Thus, the flicker photometer illustrates that a flicker produced by brightness modulation is far more readily perceptible than is a flicker of equal energy content representing a change in hue and saturation only.

B. Proportioning of Chromaticity Channel for Constant-Luminance Operation

Since the spurious signals mentioned before result mainly in the band-shared chromaticity channel, it seems reasonable to expect that they would be less visible if this chromaticity channel did not affect the brightness of the reproduced image. This has been found to be true, and such an arrangement, in which the brightness is determined by the direct shunt path of the receiver and the chromaticity channel has been so proportioned that it does not affect the brightness or luminance of the image, has been called the "constant-luminance system."[13]

While an exact constant-luminance-system can be constructed, an "approximate" or simplified system, in which the luminosity of the blue-reproducing primary is assumed to be substantially zero, results in some simplifications and will, therefore, be described here. For example, Fig. 7 illustrates a color receiver for a simplified system in which the green and red primaries are assumed to have a relative brightness of 2 to 1 and the brightness of blue is considered to be zero (that is, blue merely affects color). It will be noted that this receiver is similar to the one previously shown for the symmetrical system, except that some of the angles and gains are changed.

For the moment, let us ignore the problem of how to obtain correct color signals and consider merely the spurious signals produced in the chromaticity channel. Since the green and red color-difference channels de-

[11] As a good example of brightness versus chromaticity, see R. M. Evans, "An Introduction to Color," John Wiley and Sons, Inc., New York, N. Y., Plate VI, opposite p. 144.

[12] See page 200 of footnote reference 11.

[13] In a similar sense, the symmetrical three-phase system is called a "constant-amplitude system" because the sum of the three color-difference *voltages* from the chromaticity channel equals zero.

modulate 180 degrees from each other, any signal coming through the chromaticity channel will produce opposite signals in the green and red channels. Also note that the relative gain of the green color-difference channel is one-half that of the red color-difference channel. Thus, for any signal appearing in the red color-difference channel, an opposite polarity signal of one-half amplitude appears in the green color-difference channel. For the assumed case of relative brightness of the primaries, one unit voltage fluctuation in the green channel produces one unit brightness fluctuation, but one unit volt-

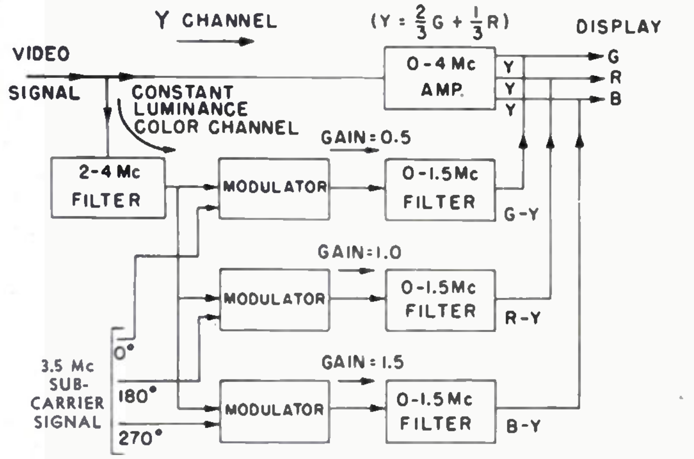

Fig. 7—Color receiver for simplified constant-luminance system.

age fluctuation in the red channel produces only one-half unit of brightness fluctuation. Thus, for the arrangement shown, any signal in the chromaticity channel results in equal and opposite *brightness fluctuations* from the green and red images produced by the display. Thus, the brightness or luminance is independent of signals in the chromaticity channel since the resulting green and red brightness changes cancel, and the brightness of blue has been assumed to be zero.

Since blue has been assumed to have negligible luminosity, the phase angle and gain of the blue color-difference channel are not determined by constant-luminance considerations. For simplicity in the arrangement shown, the system has been designed so that the blue color-difference signal can be obtained in quadrature to the red and green color-difference signal and requires a relative gain of 1.5 times. (The value of 1.5 was chosen since it appears to give optimum performance when using the group of improvements to be described later.)

Fig. 8 illustrates the beat-note vector diagrams for the simplified constant-luminance system. Again these may be considered to represent the vector relations of the 0.5-mc beat notes occurring in the three channels when a 3-mc signal is applied to the chromaticity channel. The left-hand vector diagram represents the voltage fluctuations and the right-hand vector diagram the brightness fluctuations. As shown, the brightness fluctuations from the green and red color-difference channels cancel each other. If the blue primary actually has some small relative brightness, such as 0.1, it is seen that only a very small net brightness fluctuation is produced.

Experience with the simplified constant-luminance system just described indicates that the susceptibility of the receiver to interference and spurious signals produced in the chromaticity channel is reduced by 6 to 8 db, compared with the previously proposed symmetrical system.

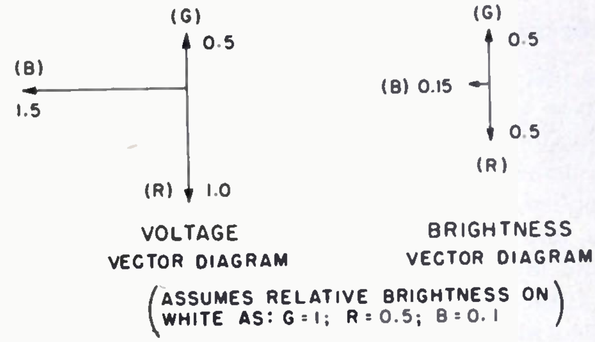

Fig. 8—Beat-note vector diagram in simplified constant-luminance system.

C. Obtaining Correct Color Signals

How the correct color signals are obtained will now be considered briefly. In a constant-luminance system the brightness signal (Y) should be proportional to the visual brightness and thus should contain G, R, and B, weighted according to relative brightness. This is true since the chromaticity channel does not affect brightness. Thus, the shunt or brightness channel must determine brightness and the signal it receives must therefore be proportional to brightness. For the simplified system under consideration this means that

$$Y = \tfrac{2}{3}G + \tfrac{1}{3}R.$$

Using this value we find that

$$R - Y = \tfrac{2}{3}R - \tfrac{2}{3}G$$

and

$$G - Y = \tfrac{1}{3}G - \tfrac{1}{3}R.$$

Thus,

$$G - Y = -\tfrac{1}{2}(R - Y).$$

In other words, in such an approximate system, $G-Y$ and $R-Y$ can be detected 180 degrees from each other, or one can be obtained from the other by a phase inverter. The direct relationship between $G-Y$ and $R-Y$ results since Y contains only the two colors, G and R. Thus, one additional independent quantity containing only G and R (such as $R-Y$) will permit solution for each color signal.

It will be noted that in a color-television system there are three independent quantities to be transmitted. In the simplified constant-luminance system these three quantities may be considered to be Y, $R-Y$, and $B-Y$. One quantity, Y, is transmitted as the normal video signal, and the other two quantities can be considered to be the in-phase component of the 3.5-mc subcarrier $(R-Y)$ and the quadrature component of the 3.5-mc subcarrier $(B-Y)$. Since these three means of transmission are independent of each other, the transmitted signal can be decoded and the three original signals, G, R, and B, can be separated from each other at the receiver to obtain correct color signals.

D. Receiver with Quadrature Desampling

As just pointed out, $G-Y$ is $-\frac{1}{2}(R-Y)$. Thus, the receiver of Fig. 7 can be replaced by using only two modulators plus a video phase inverter. Such a tricolor tube arrangement is illustrated in Fig. 9. The Y-signal is applied to the grids of the three guns of the tricolor tube, and negative color-difference signals are applied to the individual cathodes. This produces individual grid-cathode voltages of G, R, and B. For further simplicity, this receiver is illustrated as using only 1-mc bandwidth in the color-difference channels since this may be adequate and permit more gain per stage.

E. Transmitter (Encoder)

A rather straightforward transmitter arrangement for the simplified constant-luminance system is shown in Fig. 10. The G, R, and B signals are combined to give a wide-band Y signal and narrow-band $R-Y$ and $B-Y$ signals. The Y signal is transmitted as the normal video signal and the $R-Y$ and $B-Y$ signals modulate 3.5-mc subcarriers in quadrature.

F. An "Exact" Constant-Luminance System

The system just described is a simplified or an "approximate" constant-luminance system, in which the blue reproducing primary has been assumed to have

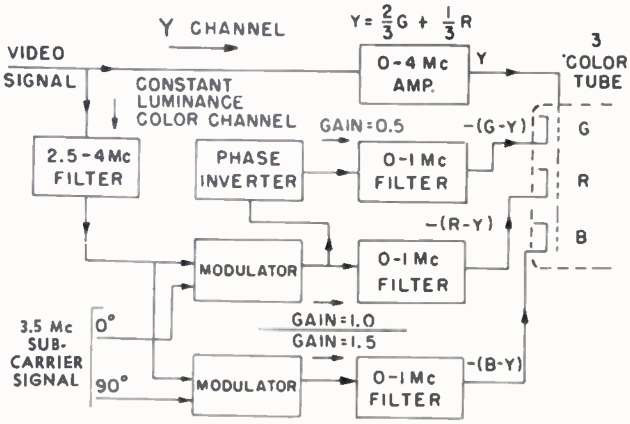

Fig. 9—Simplified receiver for constant-luminance system.

zero luminosity. The construction of a more exact constant-luminance system can be accomplished, if desired, by arranging the chromaticity channel of the system so that the green and red fluctuations do not exactly cancel, but have instead a small net brightness fluctuation which is equal and opposite to the small brightness fluctuation produced by the blue channel. For example, the system could be arranged so that the green and blue color-difference channels have gains and

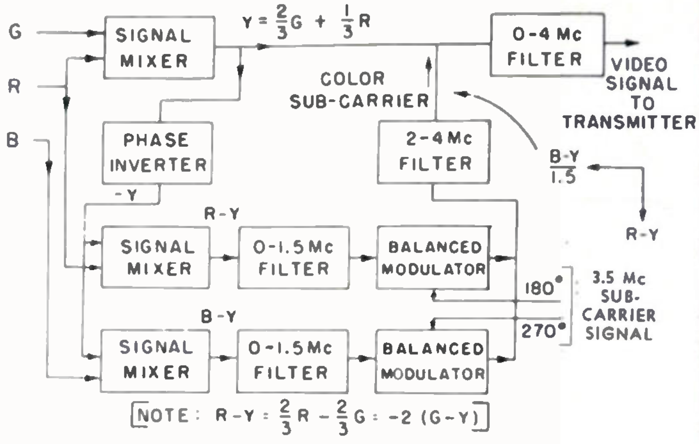

Fig. 10—Color transmitter for simplified constant-luminance system.

angles, as in Figs. 7 and 8, and so that the red color-difference channel has a gain of 1.04 and angle of 163.3 degrees. In this case, the red fluctuation will cancel the sum of the green and blue fluctuations. However, in view of other system limitations, such as nonlinear picture-tube characteristics of brightness versus voltage, the "exact" constant-luminance arrangement is really not exact. Thus, the practical benefits may be small in using the "exact" arrangement in the receiver as compared to the simplified arrangement previously described.

G. Advantages of the Constant-Luminance System

Since imperfections (noise or interference) in the chromaticity channel signals are less visible in the constant-luminance system than in the constant-amplitude system, a number of advantages result:

1. High-frequency beat-note interference, such as may be produced by oscillator radiation, is less visible.
2. Noise through the chromaticity channel as well as the color-sync channel is less visible.
3. Cross talk of high-frequency video components into the color channel is less visible (less "shimmer").
4. Color "cross-talk" effects produced by single side-band transmission of color subcarrier information and by mixed highs are less visible since the brightness of reproduced images is correct in spite of the color errors.
5. Nonuniform amplitude and phase characteristics near the color subcarrier frequency do not affect brightness of image. Thus, distortions produced by these nonuniform characteristics are less visible.

It is interesting to note that the above advantages appear great enough to be preferable to exact color rendition. While observing recent constant-amplitude transmissions, it was noted that if these transmissions were viewed on a constant-luminance receiver the result was a more pleasing picture than when observed on a constant-amplitude receiver. This gave incorrect chromaticity and brightness for certain colors, but a phase of reinserted subcarrier could be found which gave very acceptable color rendition. (Note that since the original scene was not available for comparison small deviations from true reproduction were not apparent.) The noise and spurious patterns were substantially less with the constant-luminance system receiver and printing was more legible because of reduction in visibility of spurious patterns on edges. Phase distortion near the color subcarrier frequency produced a noticeable misregistration of lips with the constant-amplitude receiver, but this misregistration substantially disappeared with the constant-luminance receiver since no brightness misregistration was then reproduced. This limited observation indicated that the advantages of the constant-luminance system are more important than *exact* color balance. But, of course, substantially correct color balance can be obtained in addition to the benefits described above by transmitting a constant-luminance signal.

An additional advantage results because the transmitted brightness signal is proportional to visual brightness. This produces a preferred form of picture on black-and-white receivers tuned to the color transmissions because colored areas are reproduced with an intensity proportional to their original brightness as seen by the normal human eye.

IV. Related Improvements

A. Compatibility

A few words about compatibility now seem to be appropriate. Within the original "dot-sequential" system, a rather large 3.5-mc sine wave is transmitted in areas of saturated colors. While this sine wave tends to integrate out since it is an odd multiple of one-half horizontal scanning frequency, it is nevertheless desirable to reduce the transmitted amplitude of the 3.5-mc signal to improve compatibility, that is, to permit reproduction of unimpaired images in black-and-white receivers. Any such reduction at the transmitter must be accompanied by a corresponding increase in gain in the chromaticity channel of the color receiver in order to maintain correct saturation of the colors. Then, the increased gain in the chromaticity channel makes this channel *more* susceptible to interference and spurious patterns.

Any improvement, such as the constant-luminance system, can be used *either* to reduce the visibility of the spurious patterns in the color pictures *or* to improve the compatibility of the system as seen on black-and-white receivers. Laboratory experience with high-resolution color pictures and wide bandwidth black-and-white receivers indicates that both the compatibility and the color pictures should be improved. Besides the constant-luminance system, there are additional means that should be considered to reduce the visibility of the spurious patterns in the color receiver.

B. Subcarrier Pattern

The phase of the beat notes in the chromaticity channels depends upon both the phase of the input signal and the phase of the reinserted subcarrier signal. Thus, the form of the spurious *patterns* depends upon the subcarrier signal *pattern*. If the subcarrier is an odd multiple of one-half horizontal scanning frequency and then has its phase shifted by 90 degrees on every other field, a pattern with reduced visibility is obtained. The predominant upward crawl of the originally proposed signal, shown in Fig. 11(a), is eliminated in the pattern of Fig. 11(b). The difference in apparent motion is illustrated by the arrows in Fig. 11. This difference in motion appears to give a small reduction in visibility of spurious patterns in the color picture plus a small reduction in visibility of the 3.5-mc signal on black-and-white receivers.

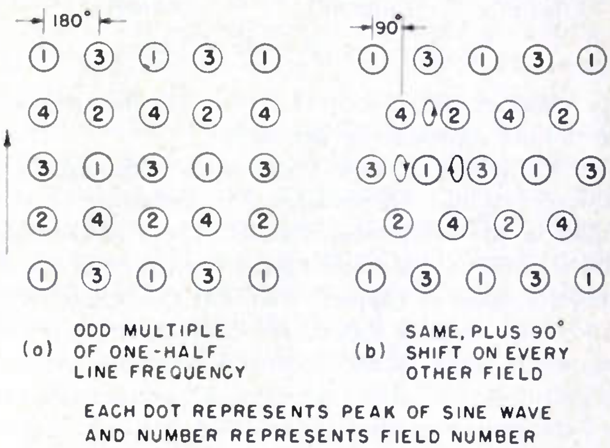

Fig. 11—Dot patterns.

C. Compensation for Spurious Patterns

The visual effect of the cross talk of high-frequency brightness components into the chromaticity channel can be further reduced. Consider for the moment a brightness signal component at 3.3 mc. With a 3.5-mc subcarrier, this would produce 200-kc beat notes in the chromaticity channel. Now assume that every time a 3.3-mc signal is transmitted an additional component is transmitted at 3.7 mc. This would produce a second 200-kc beat note that might be made to add or subtract from the first beat note in specific color channels. For example, consider Fig. 12 and specifically consider the vector relations in the green channel. The 3-5-mc reinserted subcarrier vector in the green channel is illustrated together with the 3.3-mc vector which is rotating with respect to the 3.5-mc subcarrier vector. The vector of the added 3.7-mc component rotates in an opposite direction to the 3.3-mc component. If it is correctly phased, the two components can add to produce a fluctuation in *quadrature* to the green reinserted subcarrier signal. Then the net cross talk into the green color-difference channel will be zero, that is, the two beat notes will cancel.

Note that with the simplified constant-luminance system the condition for cancelling the cross talk in the green color-difference channel also results in cancellation in the red color-difference channel. However, the cross talk in the blue color-difference channel is doubled. This transferring of all the spurious patterns to the blue channel can be made to give a net reduction in visibility of the cross talk of highs into the chromaticity channel because of the very low brightness of typical blue reproducing primaries.

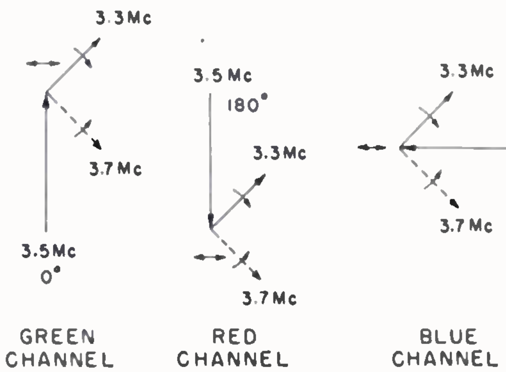

Fig. 12—Cross-talk vector diagrams.

Fig. 13 illustrates how these extra components are produced at the transmitter by including a 7-mc sampler in the brightness channel. The 7-mc sampling signal is obtained by doubling the frequency of the 3.5-mc color subcarrier frequency so that the original video components, such as the 3.3-mc component, and extra components, such as the 3.7-mc component, are symmetrically disposed about the color subcarrier frequency. The 7-mc sampling phase is selected to produce cross-talk cancellation in the green and red channel of the color receiver. In addition, the brightness signal may be limited slightly in bandwidth by passing it through a 3.5-mc filter before sampling to prevent the combination

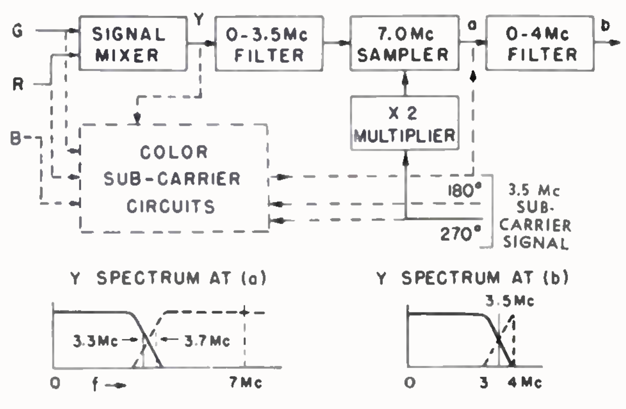

Fig. 13—Sampling of brightness signal for cross-talk compensation.

of the original and added high-frequency components from being excessive in amplitude.

To make the above system practical, the additional components transmitted for cross-talk compensation should be of low visibility so that the black-and-white receivers are free from spurious patterns. This condition is satisfied if the 3.5-mc subcarrier pattern uses the additional 90-degree shift on every other field, as shown in Fig. 11(b). The resulting 7-mc sampling pattern is a checkberboard pattern which repeats in 1/30 of a second. The pattern is like that of Fig. 11(b), with the 3's and 4's replaced by 1's and 2's, because 180-degrees shift at 3.5 mc is equivalent to 360-degrees shift at 7.0 mc. It will be noted that the phase of the pattern on adjacent lines in space differs by 180 degrees, thus giving low visibility.

To prevent excessive rectification effects in the blue channel due to the extra cross talk in this channel, it is desirable to limit the bandwidth of the blue color-difference channel in the receiver to about 0.5 mc. In addition, it may be desirable to include a limiter in the blue color-difference channel to prevent high-amplitude short-duration pulses of cross talk from causing excessive rectification and "blooming" in the blue picture tube.

D. Proportioning of Bandwidths

Besides the improvements previously mentioned it is probably obvious that the susceptibility of the chromaticity channel to interference and spurious signals can be reduced by narrowing the bandwidth of the channel *at the receiver*. The optimum bandwidth of the color-difference channels is not known at this time, but it appears that some reduction can be made without appreciable degradation of the color picture. A reduction to 1-mc bandwidth, or possibly even to 0.5-mc bandwidth, appears necessary to reduce the susceptibility to interference. Note that reducing the band-pass filter in the chromaticity channel to a 3- to 4-mc pass band will give a 0.5-mc bandwidth for the color-difference signals. This also produces a frequency-response characteristic for the chromaticity channel that is symmetrical about the 3.5-mc color carrier frequency, thus permitting optimum benefits from the brightness signal sampling arrangement previously described.

Spurious patterns produced in the chromaticity channel by cross talk from high-frequency components of the brightness signal can be eliminated by reducing the bandwidth of the brightness signal at the *transmitter*. While this eliminates spurious patterns, it also reduces the resolution of the system. Such a reduction in resolution may be unnecessary in view of the compensation arrangement, just described, which is included *at the transmitter*.

V. Summary of Improvements ("20-db Package")

Fig. 14 gives a tabulation of the approximate improvements in interference reduction obtained by the various items mentioned in this paper. It will be noted that the first two items in the tabulation, namely, the constant-luminance system and the narrower bandwidth in the chromaticity channel, reduce the probable visibility of external high-frequency interference, such as noise or oscillator radiation, as well as reduce the cross talk of highs into the color channel. The last two items, namely, the 90-degree subcarrier pattern and the brightness channel sampling, are effective only in reducing the visibility of cross talk of highs into the color channel.

It will be noted that the group of modifications described result in a reduction of spurious shimmering patterns due to cross talk of highs into color by an amount which is of the order of 14 to 20 db (i.e., of the order of 5 to 10 times). This package of improvements can be used to improve the color picture or the compatibility of the system, or may be divided between these two items. It is recommended that 6 to 10 db be used for improving compatibility, that is, the color subcarrier signal level should be transmitted at a level that is 6 to 10 db below that corresponding to the "dot-sequential" arrangement. Then the rest of the "20-db package" can be used for reducing the shimmer in the high-resolution color pictures.

MODIFICATION	APPROXIMATE IMPROVEMENT	
	FOR EXTERNAL HIGH FREQ. INTERFERENCE	FOR CROSSTALK OF HIGHS INTO COLOR
CONSTANT LUMINANCE	6-8 db	6-8 db
NARROWER BANDWIDTH CHROMATICITY CHANNEL	1-2 db	1-2 db
90° PATTERN	——	1-2 db
SAMPLING OF BRIGHTNESS	——	6-8 db
TOTAL APPROXIMATE IMPROVEMENT	7-10db	14-20 db

RECOMMENDED USE OF CROSSTALK IMPROVEMENTS } 6-10db FOR COMPATIBILITY; REST FOR COLOR PICTURE

Fig. 14—Tabulation of interference reduction.

VI. Conclusions (Part I)

Because of the band-shared nature of the systems under consideration, spurious signals result in the chromaticity channel of the receiver. In order that these spurious effects have minimum visibility, the system should be designed so that the wide-band signal is proportional to visual brightness and the subcarrier does not affect the visual brightness of the picture but merely adds color. In other words, a constant-luminance system should be used. When using such a system, the visibility of cross talk within the system due to band sharing can be further reduced by using an extra sampling in the transmitter in the brightness signal channel. Additional shimmer reduction can be accomplished by selection of the subcarrier pattern and by limiting the bandwidth of the chromaticity channel at the receiver. By combining the above modifications, a highly compatibility color-television system may be obtained which will reproduce good high-resolution color pictures without shimmer. Laboratory experience with a color-television system using the described improvements shows that color pictures, comparable to those obtained with a *12-mc* simultaneous color system in which a 4-mc bandwidth for *each* color is used, can be obtained through a 4-mc bandwidth.

Part II—Color-Television Systems with Oscillating Color Sequence

Summary of Part II—An additional improvement in band-shared simultaneous color systems is described which reduces the visibility of phase errors in the subcarrier channel of the system. This improvement is obtained by periodically reversing the phase sequence (timing order) of the color subcarrier information, for example, after each scanning field so that phase errors may produce opposite types of color errors on adjacent lines in space. At normal viewing distances the human eye averages the color of adjacent elemental areas, thus giving a first-order correction for chromaticity errors due to phase errors in the color subcarrier channel. While this permits a greater tolerance on the phase of the reinserted subcarrier at the receiver, the major advantage results because vestigial sideband transmission of the color subcarrier information is made practical. The manner in which this latter feature can be used to improve both compatibility and the reproduced color pictures is described. The extent to which the improvements of Part I can be used with a system having an oscillating color sequence is also discussed.

I. Introduction

The first part of this paper was directed toward band-shared simultaneous systems having superior compatibility and reduced visibility of interference and spurious patterns compared with the "dot-sequential" system. Because of the relatively sharp cut-off characteristic of the IF amplifiers of most television receivers, compatibility may be substantially improved by increasing the color subcarrier frequency. The second part of this paper will describe a system improvement which will permit the use of a higher color subcarrier frequency. Thus, it appears desirable to discuss this additional improvement and the manner in which it affects the other improvements mentioned in Part I.

In the type of band-shared simultaneous color-television system which has been considered in detail in Part I, the color subcarrier is used to transmit two quantities which represent chromaticity information. These two quantities can be considered as the in-phase and quadrature components of the subcarrier signal. To prevent cross talk between these two quantities in the previous system, the phase of the transmitted subcarrier signal and the reinserted subcarrier reference at the receiver must be accurately maintained. Also, to prevent cross talk, double sideband transmission of the transmitted subcarrier signal is required. This part of the report describes a band-shared simultaneous color system in which the phase sequence of the color subcarrier information is periodically reversed, for example, after each scanning field. By using such an oscillating color sequence (OCS), a first-order correction is obtained for chromaticity errors that would normally result, because of phase errors, in the color subcarrier channel; vestigial sideband transmission of the color subcarrier information is then made practical. While the sequence reversal rate is not limited to a reversal after each scanning field, the present discussion will be limited to this reversal rate, for simplicity.

In order to understand fully the improvements made by using an oscillating color sequence, it is desirable to study the exact nature of color cross talk resulting from phase errors. While the oscillating color-sequence principle can be applied to the constant-amplitude system, it appears most attractive when applied to the simplified constant-luminance system using quadrature demodulation, as described in Part I. Thus, the color cross talk produced by phase errors in the simplified constant-luminance system will be considered in detail.

In order simply to illustrate the principle of operation of systems using an oscillating color sequence, the result of an incorrect phase of the reinserted subcarrier at the receiver will be considered in detail. However, it should be noted that such phase errors can be controlled and that the major practical improvement results because color cross talk due to vestigial sideband transmission of the color subcarrier is substantially eliminated.

II. Color Cross Talk Due to Phase Errors

If the phase of the reinserted subcarrier reference at the receiver relative to the transmitted subcarrier signal is not correct, color cross talk is produced. If the average value of the relative phase is in error because of the misphasing of the reinserted subcarrier, a ***large-area*** color contamination results. However, even if the average value of the relative phase is correct, the instantaneous relative value may be incorrect because of the unintentional phase modulation of the received subcarrier signal. Such phase modulation can result when the color subcarrier signal passes through a channel having nonuniform amplitude and phase characteristics. These nonuniform characteristics may result from purposeful vestigial sideband transmission, from phase distortion in the color receiver, or from multipath transmission (i.e., echoes). The spurious phase modulation produced by these nonuniform characteristics results in color cross talk ***near edges*** of colored areas.

A. Large-Area Color Errors

Consider the output produced by one of the color demodulators of a color receiver with a shunt brightness channel (Fig. 7), under the conditions of incorrect phase of the reinserted subcarrier. The output of a demodulator is proportional to the product of the input signals. Thus, if the color subcarrier information has a desired in-phase component of A and a quadrature component of B, and the reinserted subcarrier has a phase error of δ, the output of the demodulator is proportional to[14]

$$[A \cos \omega_s t + B \sin \omega_s t][2 \cos (\omega_s t + \delta)].$$

Expanding the above relation and using the following trigonometric relations,

$$\cos x \cos y = \tfrac{1}{2} \cos (x - y) + \tfrac{1}{2} \cos (x + y)$$

$$\sin x \cos y = \tfrac{1}{2} \sin (x - y) + \tfrac{1}{2} \sin (x + y),$$

we obtain an output signal from the demodulator of

$$A \cos \delta + A \cos (2\omega_s t + \delta) - B \sin \delta + B \sin (2\omega_s t + \delta).$$

The terms involving $2\omega_s t$ represent second harmonics of the subcarrier which are eliminated in the low-pass filters in the output of the demodulator; therefore, the useful output is

$$A \cos \delta - B \sin \delta.$$

When $\delta = 0$, the desired color signal A is given by the term $A \cos \delta$. Note, that when a small phase error exists, the output *due to* the desired component A is hardly in error, but the error in the output signal is caused mainly by contamination or ***cross talk*** (represented by $B \sin \delta$) ***from the quadrature component B***.

Now consider the operation of the complete chromaticity channel of the color receiver under conditions of the wrong phase of the reinserted subcarrier. The vector relations in this channel are shown in Fig. 15.[15] From the equations shown above, it is apparent that the output of the $R-Y$ and $B-Y$ demodulators is proportional to the projection of the transmitted signal vectors upon the respective reinserted subcarrier vectors, as indicated in Fig. 15. Now, the net output for any color channel of the receiver is equal to the signal through the brightness channel plus the signal through the respective color-difference channels (see Fig. 7). Using primes to

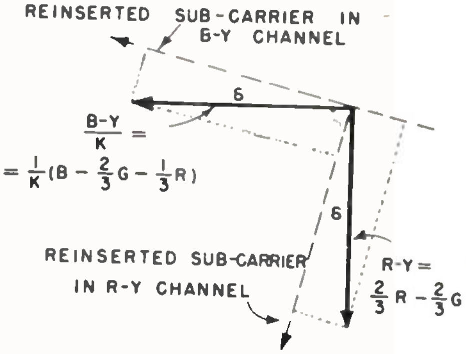

Fig. 15—Vector relations in color demodulators when reinserted subcarrier is at wrong phase.

[14] The coefficient "2" in front of the reinserted subcarrier term is selected to be equivalent to peak detection.

[15] In this section, the transmitted amplitude of the $B-Y$ component is considered to have the general value of $B-Y/K$, where K is some constant having a value probably between 1 and 5. In Part I of this paper, K was chosen as 1.5 since this appeared to give optimum performance with the "20-db package" of improvements tabulated in Fig. 14.

represent the signals produced under conditions of misphasing, we have

$$R' = Y + (R - Y)'$$

$$B' = Y + K\left(\frac{B - Y}{K}\right)'.$$

Since $G - Y = \frac{1}{2}(R - Y)$ (see Section III, C, of Part I),

$$G' = Y - \tfrac{1}{2}(R - Y)'.$$

The values of the various color-difference signals can be found from the projections of the respective vectors in Fig. 15. This gives the following:

$$R' = Y + (R - Y)\cos\delta + \left(\frac{B - Y}{K}\right)\sin\delta$$

$$\approx R + \frac{\delta}{K}\left(B - \frac{2}{3}G - \frac{1}{3}R\right)$$

$$G' = Y - \frac{1}{2}(R - Y)\cos\delta - \frac{1}{2}\left(\frac{B - Y}{K}\right)\sin\delta$$

$$\approx G - \frac{\delta}{2K}\left(B - \frac{2}{3}G - \frac{1}{3}R\right)$$

$$B' = Y + K\left(\frac{B - Y}{K}\right)\cos\delta - K(R - Y)\sin\delta$$

$$\approx B - \delta K\left(\frac{2}{3}R - \frac{2}{3}G\right).$$

Here it has been assumed that δ is small so $\cos\delta \approx 1$ and $\sin\delta \approx \delta$.

Note from the equations that the error signal produced in any color channel is proportional to δ. Also note that the error signal in the red and green channels is reduced as K is increased (i.e., as the $B - Y$ component is transmitted as a lower relative amplitude). However, at the same time, the error signal in the blue channel is increased since more gain (K) is required in the blue color-difference channel. This gives one possible basis for choosing a value for K. By weighing the subjective effects of voltage errors in the three channels (equal voltage errors do *not* produce equally tolerable subjective effects), a value for K can be chosen which gives the minimum subjective color error for a given misphasing of the reinserted subcarrier.

The color errors produced by misphasing can be evaluated from the above equations. If a saturated red is transmitted ($G = B = 0$) and δ has a positive value, a positive error appears in the green channel and a negative error appears in the blue channel so that the red is reproduced with a slight orange tinge (red+small green). If a saturated green is transmited ($R = B = 0$) and δ has a positive value, a positive error appears in the blue channel and a negative error appears in the red channel so that the green is reproduced with a slight bluish tinge. Thus, the colors have been slightly rotated about the color triangle. In other words, the *phase of the reinserted subcarrier* directly *determines the hue* of the reproduced color. Actually, a phase shift of the order of 5 to 10 degrees produces a noticeable hue shift, particularly in colors near yellow.

B. Color Errors Near Edges

Nonuniform transmission characteristics in the vicinity of the color subcarrier can produce spurious phase modulation which results in color errors near edges of colored areas, or in areas of fine color detail. This effect can be illustrated by a special example shown in Fig. 16. In this figure the pattern being transmitted has a white background with alternate bluish and yellowish areas. This pattern represents constant green and red signals, with a sinusoidal variation superimposed on a

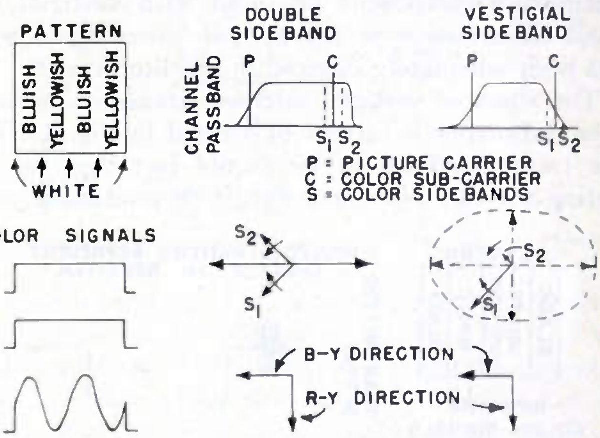

Fig. 16—Vector diagrams showing cross talk due to vestigial sideband transmission of color subcarrier.

constant level for the blue signal. With such a signal, the sinusoidal variation does not appear in the brightness signal ($Y = \frac{2}{3}G + \frac{1}{3}R$) in the simplified constant-luminance system, and the color subcarrier information should merely produce a variation in the blue color-difference channel of the receiver. The sinusoidal variation of the blue signal at the transmitter will produce a pair of sidebands about the color subcarrier. As illustrated by the center portion of Fig. 16, these sidebands (S_1 and S_2) should add to produce a fluctuation *along* the *$B - Y$ axis* (90- to 270-degree axis). This sum of the two sidebands should be along a line ***perpendicular*** to the ***$R - Y$ axis*** so that none of this sinusoidal variation is seen in either the red or green channel.

If the channel pass band is narrow so that the color subcarrier falls on a sloping characteristic, the conditions at the right of Fig. 16 apply. Assuming that the color subcarrier is about 6 db down on the side, the color-difference channel will need about 6 db more gain to obtain correct large-area saturation of colors. Then the sideband S_1 will appear larger and the sideband S_2 smaller than before. The resultant of these two unequal sidebands will now move along an ellipse instead of a line. In other words, besides the desired output variation in the $B - Y$ direction, there will be a quadrature component (spurious phase modulation) which is in the $R - Y$ direction, and cross talk into the green and red channels will result.

Over a uniformly sloping amplitude characteristic, the color cross talk resulting from vestigial sideband transmission of the color subcarrier is proportional to the modulating frequency. This is true because the greater the modulating frequency, the greater the difference in amplitude between the two sidebands. Actually, if no phase distortion is present, the quadrature component (cross talk) can be shown to be proportional to the first derivative of the modulating signal. Correspondingly, if the amplitude characteristic is flat but a small curvature (equivalent to a square law term) exists in the phase characteristic, the quadrature component can be shown to be proportional to the second derivative of the modulating signal. This quadrature component that we have just discussed is similar to the quadrature component produced with vestigial sideband transmission of the normal video signal, which has been adequately covered in the literature.[16]

The effect of vestigial sideband transmission of the color subcarrier is further illustrated in Fig. 17. Here the transmitted subcarrier should just turn off blue during the short subcarrier burst to produce a yellow

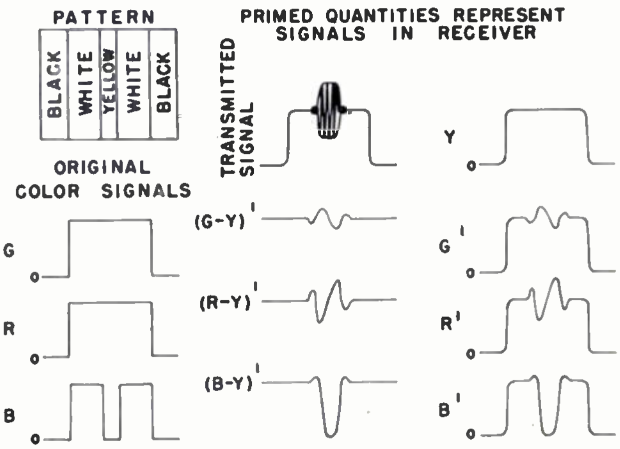

Fig. 17—Waveforms showing color cross talk due to vestigial sideband transmission of color subcarrier.

bar. However, a quadrature component is produced which appears as a differentiated signal in the green and red channels. Thus, in the reproduced image, the yellow bar has a greenish-yellow bar to the left and an orange bar to the right.

III. Oscillating Color Sequence (OCS) to Cancel Color Cross Talk

From the previous material, we have seen that errors in a particular output signal produced by phase errors in the color subcarrier channel are due mainly to cross talk from the subcarrier component which is in quadrature to the desired component required for the particular signal under consideration If this quadrature component is reversed in polarity, the cross-talk error produced is also reversed. Reversing one component of the color subcarrier is equivalent to reversing the color sequence (i.e., instead of the color sequence being green, red, and blue with increasing phase angle, the color sequence is changed to green, blue, and red). Thus, by periodically reversing the color sequence, the color cross-talk errors due to misphasing can be made to be of opposite sign during successive periods of time.

The resolution of the human eye for chromaticity changes at constant brightness is less than 40 per cent of the resolution for brightness changes.[17] Thus, at normal viewing distance, the chromaticity of adjacent lines in space will ***automatically be averaged*** by the eye. If the color errors due to misphasing are ***opposite*** on ***adjacent lines*** in space, such as would be produced by reversing the color sequence after each field, the eye will automatically average the errors so that they ***visually cancel*** out. This is equivalent to using the mixed-highs principle in the vertical direction. Of course, for the eye to do a good job of averaging the color of adjacent lines and to prevent flicker, it should be only the ***chromaticity*** that is in error and ***not*** the brightness. Phase errors in the constant-amplitude system can produce brightness as well as chromaticity errors, but as a first-order approximation only chromaticity errors are produced in the constant-luminance system. Thus, the oscillating color-sequence principle appears most attractive when applied to the constant-luminance system, and particularly attractive when applied to the simplified constant-luminance system using quadrature demodulation.

A. Apparatus for System for OCS

Before describing the cancellation effects in detail, it will be useful to illustrate the equipment needed to practice OCS. Consider a simplified constant-luminance system in which the color sequence is reversed after each field by reversing the direction of the transmitted $B-Y$ component. The transmitted subcarrier signal for such a system is illustrated in Fig. 18, where the vector diagram on the left may apply to odd-numbered fields and the vector diagram on the right to even-numbered fields.

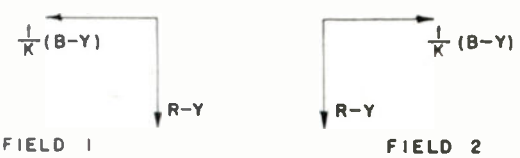

Fig. 18—Vector diagram of color subcarrier for constant-luminance system with oscillating color sequence.

A possible transmitter for this system using OCS is shown in Fig. 19. This is similar to the transmitter shown in Fig. 10 for the simplified constant-luminance system, except that a phase inverter is added to the $B-Y$ subcarrier circuit on every other field to reverse the color sequence. Also, it will be noted that a higher subcarrier frequency (near 4 mc instead of 3.5 mc) is indicated. This will be discussed in more detail later.

The receiver for a signal having OCS requires some arrangement to accommodate the periodic reversal of

[16] Nyquist and Pfleger, "Effect of the quadrature component in single sideband Transmission," *Bell Sys. Tech. Jour.*, pp. 63–73; January, 1940.

[17] See footnote reference 1.

the $B-Y$ signal. This can be accomplished in a number of ways: First, the phase sequence of demodulation can be periodically reversed (i.e., the $B-Y$ component can be demodulated alternately with a reinserted subcarrier

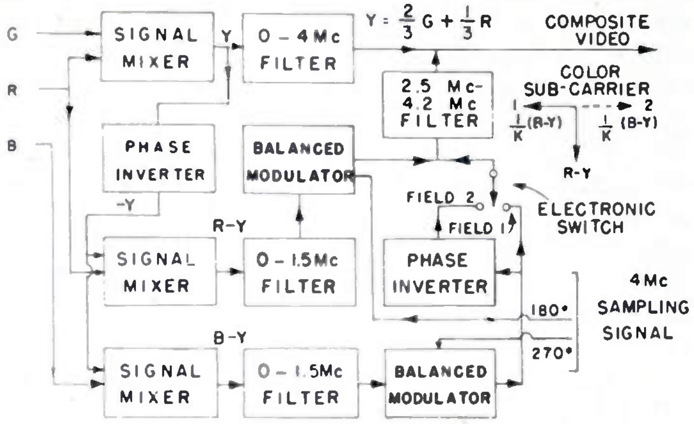

Fig. 19—Transmitter for constant-luminance system with oscillating color sequence.

at 90 and 270 degrees). If the reinserted subcarrier phase shifts are obtained from a delay line, this reversal of phase sequence of demodulation can be accomplished by connecting the reinserted subcarrier signal to opposite ends of the delay line during alternate periods. Second, the phase of the $B-Y$ signal can be periodically reversed in the video channel after demodulation. Third, the phase of the received subcarrier signal can be reversed before application to the $B-Y$ demodulator. This latter arrangement, which has a number of practical advantages, is illustrated in Fig. 20. The form of receiver shown in this figure is similar to the simplified receiver shown in Fig. 9, except that a balanced output is obtained from the band-pass filter, and the $B-Y$ demodulator is alternately connected to the two sides of the balanced output.

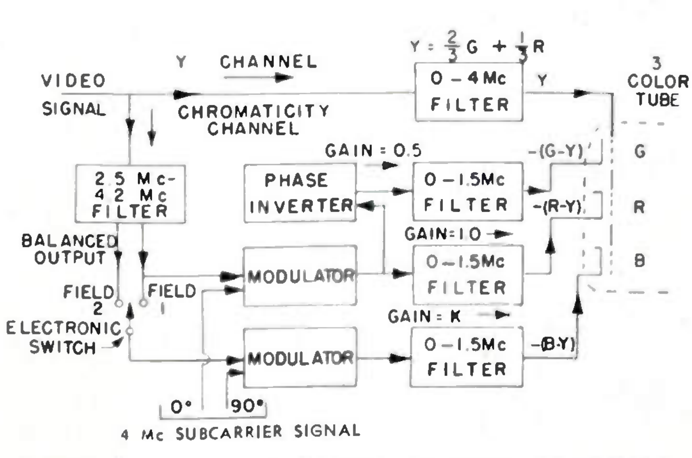

Fig. 20—Receiver for constant-luminance system with oscillating color sequence—using subcarrier channel switching.

Another circuit arrangement for a system with oscillating color sequence is shown in Fig. 21. This arrangement can be inserted directly in the color subcarrier channel of the receiver before the signal goes to either the $R-Y$ or $B-Y$ demodulators. This circuit directly reversed the color sequence of the *complete* subcarrier by using the beat note between the original color subcarrier and a signal at twice the subcarrier frequency.[18] The direct and reversed phase-sequence subcarriers are chosen on alternate fields, thus cancelling the phase reversal applied at the transmitter so that the subcarrier can be applied to a set of normal $R-Y$ and $B-Y$ demodulators.

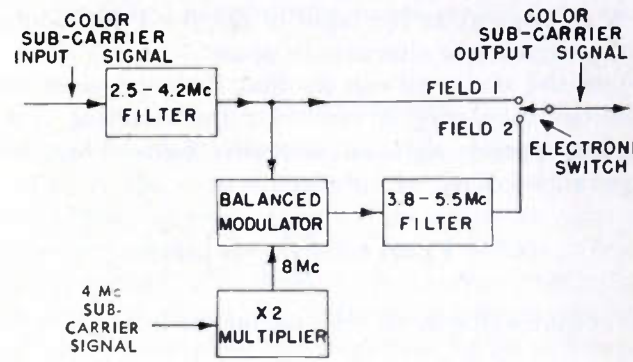

Fig. 21—Circuit for reversing phase sequence of color subcarrier.

It should be noted that the arrangement of Fig. 21 is rather universal. By adjusting the phase of the 8-mc signal applied to the balanced modulator, the phase of the axis about which the signal is inverted can be chosen. Also, the circuit can be used in the chromaticity channel of either the receiver or transmitter. In addition, the circuit can be used with OCS applied to the constant-amplitude system as well as to the simplified constant-luminance system just described.

B. Cancellation of Large-Area Color Errors

Consider the detailed operation of a system using OCS. Fig. 22 shows the vector relations in the receiver

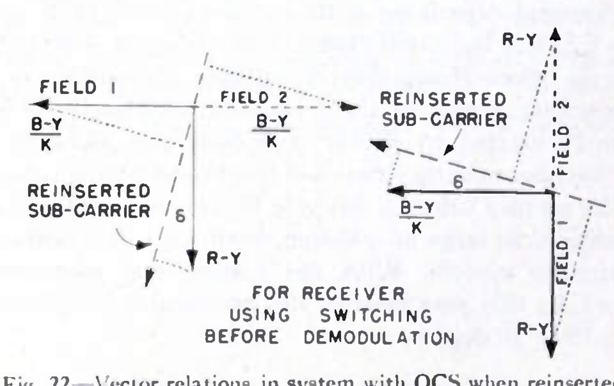

Fig. 22—Vector relations in system with OCS when reinserted subcarrier is at wrong phase.

of such a system when the reinserted subcarrier is at an incorrect phase. The relations existing in the $R-Y$ channel are shown by the left vector diagram. For illustration, it will be assumed that the receiver (such as the receiver in Fig. 20) uses switching before demodulation, and then the right vector diagram represents the

[18] Note that the phase of the beat note will retard when the phase of the original subcarrier is advanced.

relations existing in the $B-Y$ channel at the input of the $B-Y$ demodulator *after* switching. The phase of the color subcarrier signal is reversed after each field by the electronic switch so that the $B-Y$ component now appears at a fixed phase; this means, of course, that the $R-Y$ component appears to have opposite phase on successive fields. Thus, for this form of receiver, the $B-Y$ component at the input of the $R-Y$ demodulator appears to alternate in phase, and the $R-Y$ component at the input of the $B-Y$ demodulator also appears to alternate in phase.

From the above we can see that if the phase of the reinserted subcarrier is incorrect, the resulting cross talk has opposite signs on successive fields. Thus, the output signal of $(R-Y)$ modulator is

$$(R - Y)\cos\delta \pm \left(\frac{B - Y}{K}\right)\sin\delta.$$

The output signal of $(B-Y)$ modulator is

$$K\left(\frac{B - Y}{K}\right)\cos\delta \mp K(R - Y)\sin\delta,$$

where the + and − signs apply on alternate fields. If the system is linear, these opposite-sign chromaticity errors should visually cancel because successive fields correspond to adjacent lines in space. Then the only visual effect of misphasing should result from the cos δ terms which cause a gradual desaturation in the reproduced color due to a loss in detection efficiency for the desired color-difference components. Thus, in an *ideal linear* constant-luminance system using OCS the *phase* of the reinserted subcarrier should not affect the hue of the reproduced image, but should merely *change the saturation* of the color according to a cosine function. (Of course, when the cosine function becomes negative, this corresponds to a complementary color.)

Practical experience with a system using OCS (and $K=1.5$) has indicated that a misphasing of ± 20 to 30 degrees gives reasonably acceptable chromaticity reproduction. However, the permissible misphasing is frequently limited by flicker considerations. Because of the nonlinear characteristics of brightness versus voltage of the picture tubes, a 30-cycle flicker can result under conditions of large misphasing, even with the constant-luminance system. With the system just mentioned ($K=1.5$), this *may* restrict the permissible misphasing to ± 15 to 20 degrees.

C. Cancellation of Color Errors Near Edges

Color errors near edges due to vestigial sideband transmission of the color subcarrier have been previously described and illustrated in Fig. 17. When OCS is used, these color errors are opposite in sign on successive fields (i.e., on adjacent lines in space) and thus they tend to cancel visually. This effect is illustrated by Fig. 23.

The elimination of color distortion due to vestigial sideband transmission of the color subcarrier is the major advantage of OCS, and permits a substantial improvement of the color system. A higher subcarrier frequency can be used, thus improving compatibility. By changing the color subcarrier frequency from approximately 3.5 mc to approximately 4.0 mc, a very substantial improvement in compatibility may be obtained because of the relatively sharp cut-off characteristic of the IF amplifiers of most television receivers. Also, by using a higher subcarrier frequency, the spurious patterns produced in the color receiver can be minimized by a very slight reduction in bandwidth of the transmitted brightness signal. In addition, a higher subcarrier frequency permits a wider chromaticity bandwidth to be used.

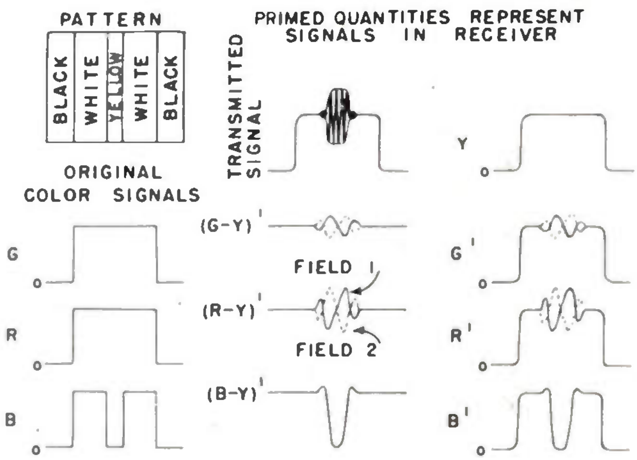

Fig. 23—Cancellation of color cross talk due to vestigial sideband transmission of subcarrier when using OCS.

IV. Summary of Advantages of OCS

The following is a summary of advantages obtained by using an oscillating color sequence:

1. Permits the use of a higher color subcarrier frequency.
2. Permits a wider chromaticity bandwidth.
3. Permits a greater tolerance on the phase of reinserted subcarrier at the receiver.
4. Simplifies the design of the IF channel of the color receiver since the IF characteristics need not be flat near the subcarrier frequency.
5. Makes color convertors more practical since good color can be obtained even when the color subcarrier is way down on the side of the IF characteristic.
6. Increases the probability of obtaining good color under conditions of multipath transmission.

V. Possible Values for a Practical System Using OCS

If desired, OCS could be directly applied to the improved system outlined in Part I of this paper. However, since vestigial sideband transmission of the color subcarrier is practical when using OCS, this possibility should be further explored. When vestigial sideband transmission of color subcarrier is used, sampling of the brightness signal at the transmitter (shown in Fig. 13) to reduce spurious patterns in the receiver is not very effective. This compensation scheme, which was described in Part I, relies on substantial double sideband transmission about the color subcarrier frequency. Thus, if the color subcarrier frequency is raised, when using OCS, some compromise other than the complete "20-db package," previously tabulated in Fig. 14, needs to be used. In a possible arrangement suggested below, the transmitted color subcarrier is only slightly reduced in amplitude (3 to 6 db) compared to the amplitude corresponding to the "dot-sequential" arrangement and the remaining improvement in compatibility is obtained by the higher subcarrier frequency. Then, to reduce spurious patterns, the constant-luminance system is used and the transmitted brightness component is slightly limited in bandwidth.

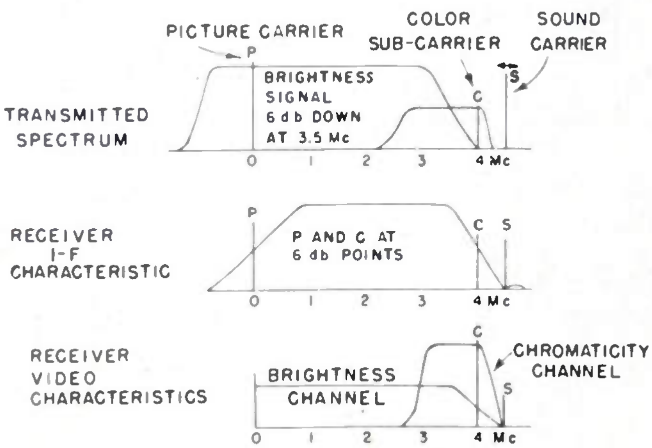

Fig. 24—Pass-band characteristics for suggested system using oscillating color sequence.

The pass-band characteristics for such a suggested system are shown in Fig. 24. Suggested system characteristics are the following:

1. Color subcarrier frequency about 3.99 mc (such as $507 \times 15.75/2$ kc $= 3.99$ mc).
2. Subcarrier transmitted at a slightly reduced amplitude compared to the amplitude corresponding to the "dot-sequential" arrangement (such as 3 to 6 db down).
3. Brightness signal to be transmitted with slightly limited bandwidth—flat to 3 mc, 6 db down at 3.5 mc, substantially zero at 4.0 mc.
4. Color receiver designed to be 6 db down at color subcarrier frequency.
5. Simplified constant-luminance system used (with $K = 1.5$).

VI. Conclusions

While the oscillating color-sequence principle can be applied to the constant-amplitude system, it appears most attractive when applied to the simplified constant-luminance system described in Part I of this paper. If OCS is applied to a constant-luminance system using a subcarrier of about 3.5 mc, the arrangement described in Part I of sampling the brightness signal to compensate for spurious patterns can be used. However, if OCS is used to permit a higher subcarrier frequency of about 4 mc, the compensation scheme is of little benefit; the combination of the constant-luminance system with slight bandwidth restriction of the brightness signal suffices to reduce the visibility of spurious patterns under conditions of adequate compatibility. While good, compatible, high-resolution color-television pictures can be obtained through a 4-mc bandwidth with either of the above proposals, further consideration may be required to determine which arrangement is most attractive commercially.

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Analysis of Dot-Sequential Color Television*

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Summary—**A mathematical analysis of the pulse sampling and sorting processes is presented. Color distortion and cross talk introduced by sideband clipping of the sampled color functions is examined. A color multiplexing arrangement using cisoidal functions is described which can produce results equivalent to the pulse sampling and sorting method, and which is more economical circuitwise than pulse sampling. The use of mixed highs is reviewed and is shown to produce negligible effects on the color presentations, while providing resolution for the color picture equivalent to present monochrome standards in the same bandwidth.**

Introduction

A CONSIDERABLE amount of work has been and is being directed toward the solution of the technical problems involved in achieving acceptable color-television systems. Although some of these problems have arisen from limitations imposed by other than technical sources, the present discussion will confine itself to the engineering aspects of the situation. Only compatible dot-sequential systems[1] will be considered in order to preserve the unity of the paper in the allotted space. Although many references to time-sharing multiplex techniques[2] appear in the literature, the particular sampling and sorting processes employed by the dot-sequential system demonstrated by RCA before the FCC are emphasized. The end results are expressions for color cross talk and distortion which include the effects of mixed highs. Although pulse sampling and sorting methods are quite standard, an alternative method is described that makes use of cosine functions and which gives results identical with those obtained by pulse methods.

The Typical System

Elements of the typical dot-sequential system previously mentioned appear in Figs. 1 and 2. The primary color camera outputs are each channeled to a common adding circuit and to separate low-pass filters. This adder circuit output is filtered to pass only the higher video frequencies from 1.79 to 4 mc, which carry the fine detail of the color picture and which are called, appropriately enough, the "mixed highs." The low-frequency video signals from the low-pass filters are sampled in sequence by a low-duty-cycle electronic switch, the output of the switch being filtered, as shown, and then added to the mixed highs to form the complete video signal. At the receiver, the reverse process occurs, with the high-frequency 1.79-to-4-mc portion of the incoming signal being applied to all three color-channel outputs. The complete 0-to-4-mc input is sampled by a switch synchronized with the switch at the transmitter. The three outputs of the sampler are filtered to remove the dot structure, caused by the sampling rate, and then applied to the corresponding color grid.

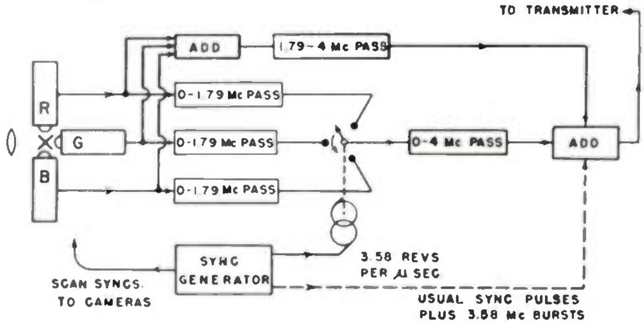

Fig. 1—RCA dot-sequential color camera chain.

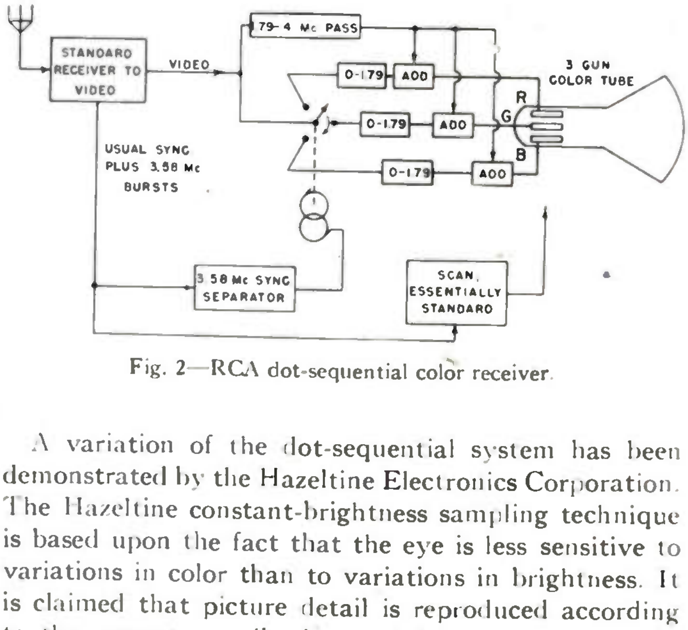

Fig. 2—RCA dot-sequential color receiver.

A variation of the dot-sequential system has been demonstrated by the Hazeltine Electronics Corporation. The Hazeltine constant-brightness sampling technique is based upon the fact that the eye is less sensitive to variations in color than to variations in brightness. It is claimed that picture detail is reproduced according to the correct contribution to brightness of the color components and that the visible effects of cross talk, noise, and sampling instability are greatly reduced.

The Pulse-Sampling and Filtering Process

A set of unmodulated rectangular pulses, each having a width d, period T, and amplitude B, may be defined by the Fourier series

$$G(t) = Bd/T\left[1 + 2\sum_{n=1}^{\infty} a_n \cos n\beta t\right]. \qquad (1)$$

* Decimal classification: R583. Original manuscript received by the Institute, February 1, 1951; revised manuscript received, July 11, 1951.

† Sylvania Electric Products, Inc., Physics Laboratories, Bayside, N. Y.

[1] RCA Laboratories Division, "A six-megacycle compatible high-definition color-television system," *RCA Rev.*, vol. 10, pp. 504–524; December, 1949.

[2] W. R. Bennett, "Time division multiplex systems," *Bell Sys. Tech. Jour.*, vol. 20, pp. 199–221; April, 1941.

where

$$\beta = 2\pi/T,\ a_n = \frac{\sin(n\pi d/T)}{n\pi d/T},\ (n = 1, 2, 3 \cdots).$$

If the width of the pulse is very small, so that $d/T \ll 1$, and if the pulse set is filtered so that the filter output $F(t)$ consists of only the dc plus fundamental terms, the output of the filter will pass through zero at $\beta t = 2\pi/3$ and $\beta t = 4\pi/3$, as in Fig. 3(a).[3] If the pulse has

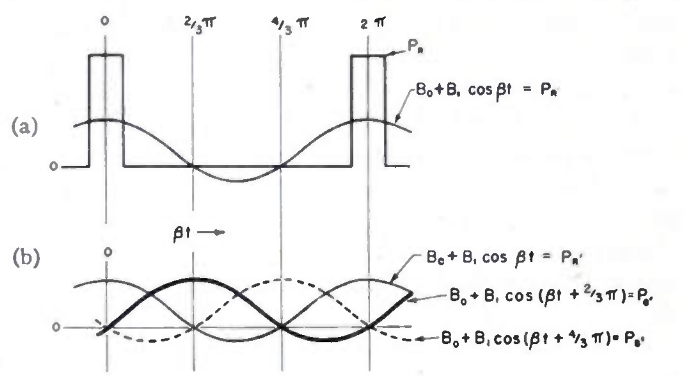

Fig. 3—(a) Periodic pulse, $G(t)$, and its dc plus fundamental components, $F(t)$. (b) dc plus fundamental functions of three similar pulse sets shifted by 120 degrees.

a finite width, the function will not be zero at these points but, instead, will have a positive value which will lead to cross talk. However, with a duty cycle of 13 per cent or less, the value of the function at these points will be less than 1 per cent of the maximum value of $F(t)$, and can then be neglected for most applications. A plot of the value of the error at these

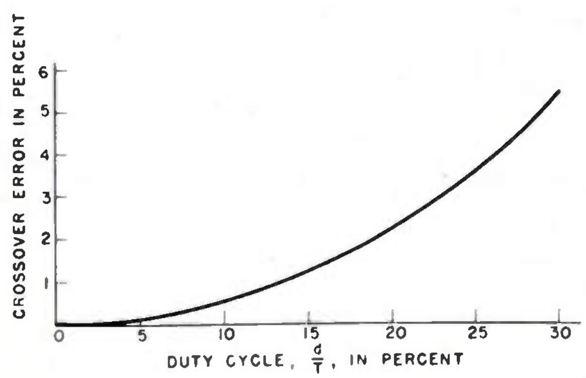

Fig. 4—Value of $F(t)$ at $T/3$ and $2T/3$ as a function of pulse-duty cycle, in per cent of maximum value of $F(t)$.

points appears in Fig. 4. This phenomenon suggests that two other similar sets of pulses might be added at the points where $F(t)$ is zero: At the time one narrow pulse occurs, the dc plus fundamental terms of the other two pulse sets are essentially zero; hence, but little cross talk would exist between the three functions.

[3] The filtered output of (1) becomes $B[d/T+(2/\pi \sin \pi d/T) \cos 2\pi t/T]$. As $d \to 0$, then $\sin \pi d/T \to \pi d/T$, giving $Bd/T(1+2 \cos 2\pi t/T)$.

It has been shown in the literature[4] that the highest frequency that can be recovered, after being sampled at regular intervals, has a period essentially equal to twice the interval. If we sample a function defined as

$$f(t) = A(1 + m \cos \omega t), \qquad (2\omega < \beta), \qquad (2),$$

where m is the modulation index, by a pulse set defined by (1), then the result is merely amplitude modulation of the pulses and is expressed by the product of (1) and (2). The function $f(t)$ will be used as part of the video signal from one of the cameras. If the modulated pulse train is passed through a low-pass filter having the admittance characteristic of Fig. 5, the output of the filter may be expressed for two conditions: (a) the double-sideband case, when the modulation frequency is low so that both modulation sidebands of the fundamental sampling frequency are passed (e.g., in the RCA case, where $\beta/2\pi = 3.58$ mc, $X/2\pi = 4$ mc, double sideband transmission holds when $\omega/2\pi$ is less than 0.42 mc); and (b) the single-sideband case, when the modulation frequency is high so that only the lower sideband of the fundamental sampling frequency is passed (e.g., in the RCA case, when $\omega/2\pi$ is between 0.42 and 1.79 mc).

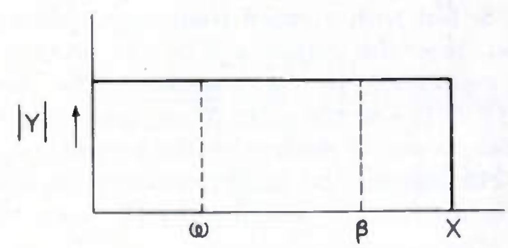

Fig. 5—Idealized low-pass filter response characteristic.

The output of the filter for the double-sideband case is

$$\begin{aligned} ABd/T\{1 &+ m \cos \omega t + 2a_1 \cos \beta t \\ &+ ma_1[\cos(\beta - \omega)t + \cos(\beta + \omega)t]\}, \\ &= ABd/T\{(1 + m \cos \omega t)(1 + 2a_1 \cos \beta t)\}, \end{aligned} \qquad (3)$$

where $\beta + \omega < X < 2\beta - \omega$.

For the single-sideband case, the filter output is

$$\begin{aligned} ABd/T\{1 &+ m \cos \omega t + 2a_1 \cos \beta t + ma_1 \cos(\beta - \omega)t\} \\ &= ABd/T\{(1 + m \cos \omega t)(1 + 2a_1 \cos \beta t) \\ &\quad - ma_1 \cos(\beta + \omega)t\}, \end{aligned} \qquad (4)$$

where $\beta < X < \beta + \omega$.

In both (3) and (4), the value of the coefficient a_1 is substantially equal to unity, for sampling pulses with a duty cycle less than 13 per cent.

Expressions (3) and (4) give the signal that can be transmitted to a receiver where it would be sampled;

[4] C. E. Shannon, "Communication in the presence of noise," Proc. I.R.E., vol. 37, pp. 10–21; January, 1949.

the information recovered would be given by (2), except for the multiplying constant. Equation (2) is shown here for simplicity as a function of a single frequency only, and may be considered as one of many terms, the sum of these terms being a complete Fourier series which would describe the camera video signal.

Inspection of (3) shows that its maximum values (proportional to the modulation function) occur at values of βt equal to integral multiples of 2π, and its zeros for corresponding values of βt of 120 and 240 degrees. When (3) is transmitted to a receiver through a channel having a delay θ, and is sampled there by a pulse train identical with the transmitter sampling pulse train (except for amplitude), the output of one channel of the sorter is the product of (3) and the receiver sorting function (similar to (1)).

$$ABd/T\,(1 + m\cos\omega t')(1 + 2a_1\cos\beta t')B'd/T \left(1 + 2\sum_{n=1}^{\infty} a_n'\cos n\beta t'\right), \quad (5)$$

where $t' = t + \theta$. When $\beta t' = n2\pi$, the output of this channel of the sampler consists of narrow pulses whose amplitudes describe the original modulation. Accordingly, if this sorter pulse output is passed through a low-pass filter with an admittance characteristic given by Fig. 5, but with a cutoff frequency bounded $\omega < X < (\beta - \omega)$, then the output will be the original modulation multiplied by a constant. The result is $3BB'(d/T)^2A(1+m\cos\omega t')$. When the receiver-sorter pulse train is out of phase with the incoming signal by 120 or 240 degrees, the receiver-sorter pulse output is zero since the function described by (5) is zero at those times.

As a consequence, three synchronized pulse trains of the type described by (1), differing in phase by 120 degrees and independently modulated, may be added together to transmit three channels of information without cross modulation or loss of information if double-sideband transmission is employed. At the receiver, three sets of similar, synchronized, narrow pulse trains sample the transmitted signal, and the original modulations (except for multiplying constants) appear as the corresponding envelopes of the three receiver-sampler pulse-channel outputs, which may be applied to the three-color display apparatus. If the pulses used are very narrow and if double-sideband transmission is used, there will be no cross talk between channels and no distortion of the information. The error caused by single-sideband transmission will be considered in the following.

Color Multiplexing by Orthogonal-Cisoidal Functions

In the preceding section, the method of sampling and separation described is accomplished by means of narrow pulses filtered at the transmitter so that only the dc plus the fundamental terms are actually used. The use of such narrow pulses at the receiver would present rather stringent requirements as to circuitry and components, which would result in costly receivers. This is evident when one considers the requirements for a pulse width of only 0.0353 microsecond and rise times less than 0.018 microsecond.

In the following, it will be shown that color multiplexing may be accomplished, to a degree equivalent to that obtained by the use of pulses, by means of a simplified arrangement wherein each sampling function consists of a dc term and a fundamental-frequency term. A single cosine wave of the sampling frequency is generated, and then phase shifted twice in 120-degree increments. Appropriate amounts of dc are added to the cosine signals, giving three separate orthogonal functions. Each of these functions is modulated by a color signal, and the resulting modulated signals are then combined and transmitted. This method can be proportioned to give results which are exactly equivalent to those obtained by pulse sampling and filtering.

If the three color signals are $V_r(t)$, $V_g(t)$, and $V_b(t)$, representing the filtered outputs of the red, green, and blue cameras, respectively, the output of the final adder shown in Figs. 1 and 6 (disregarding the mixed highs) would be the video signal,

$$\begin{aligned} V_v(t) = {} & V_r(t)[1 + 2\cos\beta t] \\ & + V_g(t)[1 + 2\cos(\beta t + 2\pi/3)] \\ & + V_b(t)[1 + 2\cos(\beta t + 4\pi/3)]. \end{aligned} \quad (6)$$

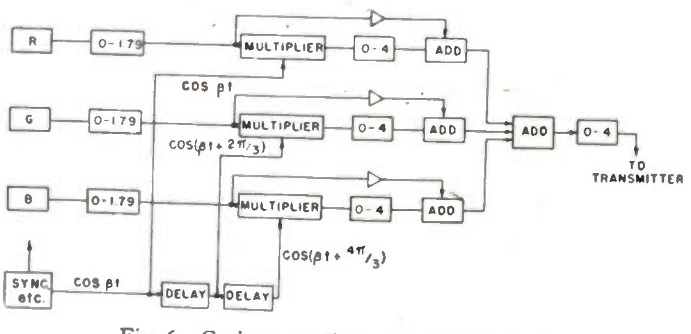

Fig. 6—Cosine sampling color camera chain.

One means of employing the cisoidal sampling method is shown in Fig. 6. The three primary-color camera outputs are passed to three multipliers, where the multiplying signals are cosine waves whose frequencies are all $\beta/2\pi$, except that each is shifted 120 degrees from the other two. After modulation, some of the original signal of the proper proportion is added to the modulated wave, which gives the effect of modulating a carrier with a dc term. The three results are then added together and are used as a video signal for transmission. The three inputs to the final adder and its output (again disregarding the mixed highs) are shown in Fig.

7. Expression (6) and the representation of Fig. 7 are identical with the results obtained when narrow pulse sampling and filtering are employed. It should be noted, that the use of mixed highs is in no way obviated or modified by the use of simple cosine sampling. The transmitted signal is compatible with the signal produced by the RCA dot-sequential apparatus, and, inasmuch as the RCA system is compatible with existing black-and-white television, this signal will also be compatible with black and white.

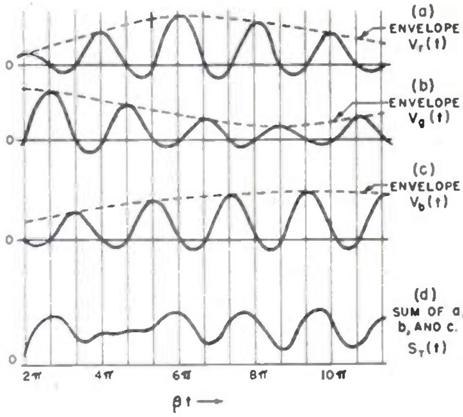

Fig. 7—Camera chain output components.

For separation of these color signals at the receiver, one can use the correlation orthogonality relationships between the three signals presented to the final adder at the transmitter.[5] Thus to separate $V_r(t)$ from $V_v(t)$, the product of $V_r(t)$ by the function $(1+2\cos\beta t)$, when passed through a low-pass filter to remove all but the color signal, yields $V_r(t)$ modified by a constant. Similar treatment by the same separation function shifted 120 and 240 degrees yields the other two color signals. The three channel outputs are,

$$9V_r(t) \text{ at } \beta t' = n2\pi; \text{ and zero at } \beta t' = n2\pi \pm 2\pi/3;$$

$$9V_g(t) \text{ at } \beta t' = n2\pi + 2\pi/3; \text{ and zero at } \beta t' = n2\pi,\ n2\pi + 4\pi/3;$$

$$9V_b(t) \text{ at } \beta t' = n2\pi + 4\pi/3; \text{ and zero at } \beta t' = n2\pi,\ n2\pi + 2\pi/3,$$

which is exactly the result desired, namely, separation of the video signals into their respective channels. This is identical with the result described in the preceding section, except for multiplying constants.

Referring to the block diagram of Fig. 8, practically the same circuit may be used for the receiver as for the transmitter. The incoming video signal is presented to three modulators, each of which is being modulated with the same separation function as the corresponding modulator in the transmitter. Again the proper proportion of the original signal is added and the resultant output from each of the channels (after being passed through a low-pass filter) is one of the primary-color signals. The error caused by single-sideband transmission and color cross talk is identical with those errors inherent in pulse separation, which is discussed in the next section.

Some question might arise as to the necessity for passing the video signals in the receiver through low-pass filters, having cutoff frequencies just above the highest modulation frequency. In the absence of the filter, the high-frequency terms serve to define the very sharp sorting pulses which would appear on the screen as a dot pattern. It is believed that use of the filters and consequent elimination of the dot structure may offer a more acceptable picture than would be had by leaving the dot pattern in the picture.

It should be noted that this type of sampling and separation may be used for a three-gun picture tube, which makes the use of mixed highs possible with its attendant advantages; the transmitted signal would then be the same as the RCA transmitted signal. This type of separation need not be used, however, if single-gun color-tube separation is used where the separation takes place by rotation of the electron beam inside the tube.

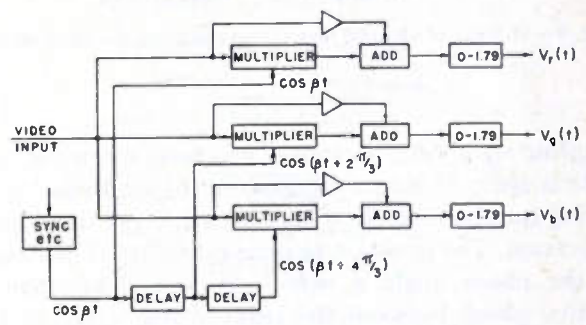

Fig. 8—Cosine sampling receiver.

The principle of employing simple orthogonal functions, like sine and cosine waves, to accomplish the sampling and sorting processes has, besides the attendant simplicity of circuits and waveforms, the further property of permitting the process of separation to be coincident with or prior to detection in the receiver.

Consider a received signal consisting of an rf carrier that is modulated by video intelligence and in which the video signal (assuming double-sideband transmission and omitting mixed highs from the discussion) is described by (6). If this signal is heterodyned with a local oscillator signal, the resulting intermediate frequency signal will be, except for a constant multiplier,

$$V_v(t)\cdot\cos\Omega t, \tag{7}$$

where Ω is the IF angular frequency. With reference

[5] M. Leifer and N. Marchand, "The design of periodic radio systems," *Sylvania Technologist*, vol. 3, pp. 18–21; October, 1950.

to Fig. 9, the IF signal is sent to three mixers, where it is multiplied by a local signal of frequency $\Omega/2\pi$ that has been modulated by the separation function

$$[1 + 2\cos(\beta t + \alpha)]\cos\Omega t; \tag{8}$$

α is zero, 120, or 240 degrees, according to the channel to be separated. The output of the mixer is the product of (7) and (8), which is

$$V_v(t)\cdot[1 + 2\cos(\beta t + \alpha)]\cdot[\cos\phi + \cos(2\Omega t + \phi)], \tag{9}$$

where ϕ is the relative phase angle between the IF and local oscillator signals. The high-frequency components will be eliminated by the filter which removes the

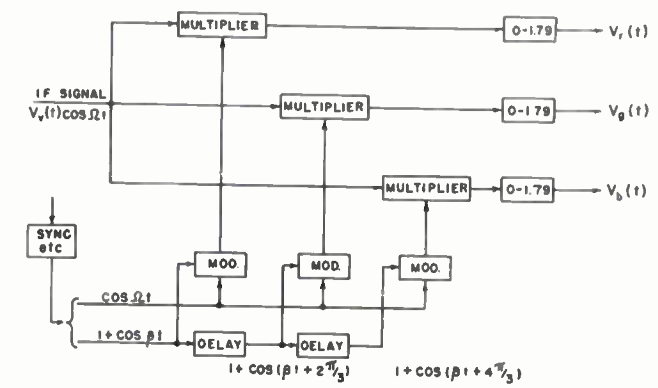

Fig. 9—Method of channel separation coincident with detection.

sampling signal dot pattern. Therefore, when the phase angle is zero, (9) is seen to result in (6) multiplied by the sorting function which, it was shown, gives the required separation. The question of phase stability is introduced by the phase angle ϕ, which is dependent upon the relative phase between the transmitted signal and the local-oscillator signal of the receiver. This should present no serious problem since adeqate phasing pulses or bursts from the transmitter could be incorporated into the system.

When a two-color system is considered, or a three-color system in which only two of the primary colors need be multiplexed, similar orthogonal functions may be used to accomplish the time sharing. For example, let $V_1(t)$ and $V_2(t)$ be the original video information functions, having terms of frequency less than $\beta/4\pi$. Making use of the fact that similar sine and cosine functions are orthogonal over their common period, let $V_1(t)$ modulate a cosine function and $V_2(t)$ modulate a sine function. The sum of the two modulated functions would be the video-signal output of the sampler at the transmitter,

$$V_T(t) = V_1(t)\cdot\cos\beta t + V_2(t)\cdot\sin\beta t. \tag{10}$$

At the receiver, either before or after detection, $V_T(t)$ is modulated at separate points by $\cos\beta t$ and $\sin\beta t$ by means of mixers. Referring to Fig. 10, the output of the first mixer is

$$V_T(t)\cdot\cos\beta t = V_1(t)(1/2 + 1/2\cos 2\beta t) + V_2(t)\cdot(1/2\sin 2\beta t). \tag{11}$$

After filtering to remove the high-order terms which would give rise to a dot pattern, the result is $V_{FT_1} = V_1(t)/2$. Similarly, the output of the other channel is $V_{FT_2} = V_2(t)/2$. It is noted that when double-sideband transmission is employed, there is no distortion and no cross talk between channels.

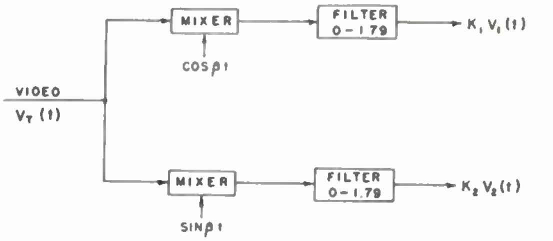

Fig. 10—Two-channel separation at receiver by cisoidal separation functions

This procedure, even with cisoidal functions of forms other than that given above, may be employed to give separation, prior to or coincident with, detection. It is particularly applicable in a color-television system in which only two of the three primary-color video signals need be multiplexed, these two multiplexed signals being interlaced in frequency[6] with the other intelligence.

Color Cross Talk and Distortion Introduced by Sideband Clipping

It was shown in the preceding sections that if the transmission-channel bandwidth is three times the highest modulation frequency, three channels of information may be transmitted, received, and perfectly presented by sampling methods. Obviously, no saving in bandwidth is realized by this time-division multiplexing as compared with frequency multiplexing techniques. The question naturally occurs, then, as to what distortion and cross-talk difficulties would arise if the transmission bandwidth were reduced.

For simplicity in calculation, let a single-frequency modulation function as in (2) be assumed and let the low-pass filter at the output of the camera chain possess the ideal admittance characteristic of Fig. 5, with the cutoff frequency X being bounded as $\beta < X < (\beta+\omega)$ so that the transmitted signal from the filter for one channel (for example, channel 1), is

$$K[(1 + m\cos\omega t)(1 + 2a_1\cos\beta t) - ma_1\cos(\beta + \omega)t], \tag{12}$$

[6] P. Mertz and F. Gray, "A theory of scanning and its relation to the characteristics of the transmitted signal in telephotography and television," *Bell Sys. Tech. Jour.*, vol. 13, pp. 464–515; July, 1934.

which is the same as (4), (the single-sideband case), except for the multiplying constant. The product of the first two terms within the bracket is actually (3), (the double-sideband case), which was shown to produce a distortionless signal in the receiver. Hence any distortion and cross talk is contributed by the missing upper sideband term, $-Kma_1 \cos(\beta+\omega)t$.

If the signal expressed by (12) is sampled at the receiver by a pulse of the same form as $G(t)$ in (1), the distortion and cross talk at the sampler output in the receiver are given by the product

$$- Kma_1B'd/T\left[1 + 2\sum_{n=1}^{\infty} a_n' \cos n(\beta t + \Delta)\right] \cdot \cos(\beta + \omega)t$$

$$= - Kma_1B'd/T\left\{\cos(\beta + \omega)t + \sum_{n=1}^{\infty} a_n'\left[\cos([n+1]\beta t + \omega t + n\Delta) + \cos([1-n]\beta t + \omega t - n\Delta)\right]\right\}, \qquad (13)$$

where Δ is an arbitrary phase angle.

As before, if the signal expressed by (13) is passed through a low-pass filter, which cuts off just above the highest modulation frequency, the distortion of the original modulation on channel 1 and the cross talk on the other channels from channel 1 may be found. Letting $K' = Kma_1a_1'B'd/T$ and letting Δ take on the three values of the relative phases of the three receiver sorter pulse sets, the result is

$-K' \cos \omega t,$ (distortion on channel 1);

$-K' \cos(\omega t + 60°), \Delta = 120°$ (cross talk on channel 2 from channel 1);

$-K' \cos(\omega t - 60°), \Delta = 240°$ (cross talk on channel 3 from channel 1).

Hence the color cross talk between channels may be as high as $33\frac{1}{3}$ per cent. The distortion in channel 1 may be eliminated by preemphasis of those video frequencies whose upper sidebands, after sampling, are removed.[7] However, this increases the color cross talk to a maximum of 50 per cent. The question as to which alternative is less objectionable must be resolved by experiment.

If the transmitted signal is that given by (12) and separation at the receiver is by means of the cosine-separation function instead of by pulse sampling, the distortion and cross talk at the receiver is similarly found to give the same result.

[7] A fundamental article (which arrives at a similar distortion figure) has been published since this paper was originally written. For this reason, certain parts of the fundamental discussion of dot-sequential color television have been omitted here. RCA Laboratories Division, "An analysis of the sampling principles of the dot-sequential color television system," *RCA Rev.*, vol. 11, no. 2, pp. 255–286; June, 1950.

Mixed Highs

The use of mixed highs, previously mentioned in connection with Figs. 1 and 2, was proposed in order to achieve for three-color television the full 4-mc resolution of present monochrome television, without having to provide a full 4-mc bandwidth for each of the three primary-color channels.[8] Briefly, the method presents a black-and-white monochrome relief picture (forming the edges and details of the televised scene), and then tints this black-and-white picture with color to make a most presentable color picture. Referring to Figs. 1 and 2, the three groups of color information occupy the low-frequency range from 0 to 1.79 mc, while the black-and-white details are in the higher frequency region from 1.79 to 4 mc. These mixed highs, consisting of the higher frequency portions of each primary-color camera video outputs, furnish the white, black, and gradations of grey for edges and other fine details.

To better understand the operation of the dot-sequential system with mixed highs, it would help, at this point, to set down the different signals that are present in terms of frequency, and to make a few descriptive remarks concerning each group of signals.

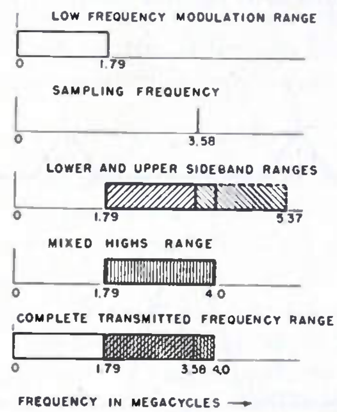

Fig. 11—Transmitted frequency ranges of RCA dot-sequential system.

The transmitted signal is made up of the sampled low-frequency modulations, with their lower sidebands intact and with part of the upper sidebands, plus the mixed highs (Fig. 11), included. This may be expressed as

$$S_T = \sum_{c=0}^{2} S_L(t) \cdot [1 + 2\cos(\beta t + 2c\pi/3)] - \sum_{c=0}^{2} [\text{Upper sidebands}]_{4.00 \text{ mc}}^{5.37 \text{ mc}} + [\text{Mixed Highs}]_{1.79 \text{ mc}}^{4.0 \text{ mc}}$$

where $c = 0, 1, 2$ and refers to the three colors. At the receiver, this whole signal is sampled by the receiver sorter; the frequencies from about 1.79 to 4 mc are by-passed and added to the sampler outputs again. Considering one color output channel only (for example, the red), the signals present in that output channel are:

[8] A. V. Bedford, "Mixed highs in color television," Proc. I.R.E., vol. 38, pp. 1003–1009; September, 1950.

$$\left[1 + 2\sum_{n=1}^{\infty} a_n \cos \beta t\right]$$

(Sorting Pulse)

$V_r(t) \cdot [1 + 2 \cos \beta t]$	Sorting accomplished correctly; only distortion and cross talk caused by finite pulse width.
− [Upper sidebands, 4.0 to 5.37 mc]	The missing upper sidebands, which give cross talk and distortion.
+ [Mixed Highs, 1.79 to 4.0 mc]	The sampled mixed highs which fold back into the low-frequency modulations.
+ [Total 1.79 to 4.0 mc]	The mixed-highs' signals plus both sidebands of low-frequency modulations from 0 to 0.42 mc, plus the lower sidebands of modulations from 0.42 to 1.79 mc.

If we neglect the distortions here due to the finite pulse widths, the greatest amount of distortion and cross talk will be caused by the missing upper sidebands. The mixed-highs signal from the transmitter are also multiplied by the receiver sorter; the upper sideband from the product is of too high a frequency to concern us here, but the lower sideband is a low-frequency signal which falls into the low-frequency color-modulation range.

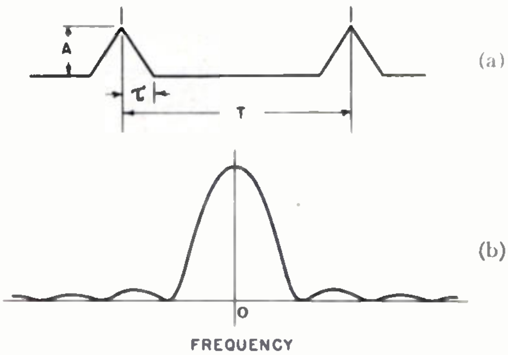

Fig. 12—Triangular pulse and its spectrum.

Consider a repeated band-limited triangular pulse corresponding to the light intensity of one of the primary colors (Fig. 12(a)). This pulse contains frequencies from 0 to 4 mc, and may be expressed by the Fourier series

$$P(t) = \sum_{h=1}^{H} C_h \cos h\alpha t,$$

where

α = radian line-repetition frequency;

αH = 4 mc;

$$C_h = 2A/T\left[\frac{\sin h\pi/T}{h\pi/T}\right]^2. \quad (14)$$

The spectrum of this pulse is shown in Fig. 12(b). The higher frequencies between 1.79 and 4 mc would be

$$\sum_{h=H_1}^{H} C_h \cos h\alpha t, \quad (15)$$

where

$$\alpha H_1 = 1.79 \text{ mc},$$

and are those components of the pulse which are passed undisturbed through the transmitter as mixed highs. At the receiver, however, (15) is multiplied by the sorting pulses, and hence, will be a coefficient of the receiver-sorting function, giving the product

$$\sum_{h=H_1}^{H} C_h \cos h\alpha t[1 + 2 \cos 2H_1\alpha(t + \theta)]. \quad (16)$$

This product gives the original mixed-highs signal, plus upper and lower sidebands (five terms in all). The two frequency regions of immediate concern are those which now appear in the low-frequency color-modulation region as frequencies within the ranges of 0 to 1.79 mc and 0 to 0.42 mc. These are derived from the two portions of the mixed highs from 1.79 to 3.58 mc and 3.58 to 4.0 mc. Rewriting (16) to account for this, we have

$$\left[\sum_{h=1.79 \text{ mc}}^{3.58 \text{ mc}} C_h \cos h\alpha t + \sum_{h=3.58 \text{ mc}}^{4.0 \text{ mc}} C_h \cos h\alpha t\right] \cdot [1 + 2 \cos 2H_1\alpha(t + \theta)]. \quad (17)$$

Expansion of (17) gives the expression for the two sideband regions:

$$\sum_{(2H_1-h)=0 \text{ mc}}^{1.79 \text{ mc}} C_h \cos [(2H_1 - h)\alpha t + 2H_1\alpha\theta] + \sum_{(h-2H_1)=0 \text{ mc}}^{0.42 \text{ mc}} C_h \cos [(h - 2H_1)\alpha t - 2H_1\alpha\theta]. \quad (18)$$

Note that the frequencies $(2H_1 - h)\alpha$ give rise to low frequencies in the color range, and the angle $2H_1\alpha\theta$ is a constant phase angle, which is determined by the relative phase of the sorting in the receiver.

At first glance, it appears that the function (18) would seriously distort the color signal (to which it adds vectorially). In addition, the shape of the pulse itself would be distorted since correct cancellation outside the pulse region does not occur. This distortion of the pulse is evident when it is noted that each part of (18) may be expanded to the form, for example,

$$\sum_{(2H_1-h)=0\text{ mc}}^{1.79\text{ mc}} C_h[K_1\cos(2H_1-h)\alpha t+K_2\sin(2H_1-h)\alpha t], \quad (19)$$

the K term arising from the constant phase angle. The cosine term will give a pulse since each cosine term in the summation will start with its maximum value at $t=0$ and cancellation will occur outside the desired pulse range. The summation of the sine terms gives a fairly uniform, but low-amplitude, voltage level as a result of interference of the frequency components, which are not in phase except when all are zero.

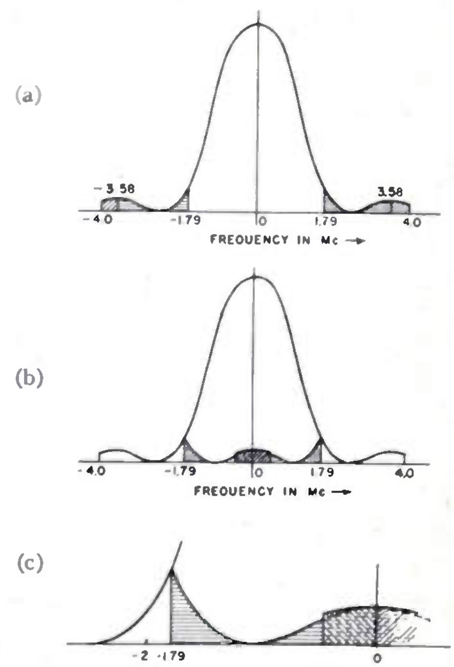

Fig. 13—Spectrum of band-limited triangular pulse with ranges of frequency foldback. (a) Complete spectrum. (b) Complete spectrum showing frequencies which are folded back. (c) Enlarged view of folded-back portions.

Relative to the distortion introduced by the folded-back frequencies expressed by (18), it should be noted from Fig. 13 that the coefficients

$$C_h\ [\text{in the summation from } (2H_1-h)\alpha = 0 \text{ to } 1.79 \text{ mc}]$$
$$= C_h\ [\text{in the summation from } h\alpha = 1.79 \text{ to } 3.58 \text{ mc}],$$

and

$$C_h\ [\text{in the summation from } (h-2H_1)\alpha = 0 \text{ to } 0.42 \text{ mc}]$$
$$= C_h\ [\text{in the summation from } h\alpha = 3.58 \text{ mc to } 4.0 \text{ mc}].$$

The magnitudes of each of the coefficients of the folded-back frequencies are less than the coefficient of the desired low-frequency color signals, C_h [in the summation from 0 to 1.79 mc], with which they would interfere.

To arrive at a picture of the amplitude of the folded mixed highs, assume a horizontal resolution of 300 lines[9] for the color picture. The triangular pulse probably could not be distinguished as a triangle if the ratio τ/T were smaller than 1/150. Referring to (15) for the definition of C_h, if $T=1/\alpha=1/15{,}750$, then $h_{max}=4{,}000{,}000/15{,}750=254$. The amplitude of the 254th harmonic is then $C_{254}=0.048\ A\tau/T$, and the spectrum is shown in Fig. 13. In this rather extreme case, the folded-back mixed highs would do very little damage to the pulse and would have practically no effect on the low-frequency color signals. As the pulse width 2τ is increased, less and less damage is done to the pulse shape and to the low-frequency color signals since the amount of energy in the high-frequency components that are reflected and changed in amplitude and phase decreases very rapidly.

In summary, the distortion produced by the sorting process upon the mixed highs will be small although the exact amount must also await experiment. The color cross talk, on the other hand, may be 100 per cent. It is found that this presents no particular problem inasmuch as the seeing process emphasizes the black-and-white features of the edges and other high-frequency portions of objects. The value of the mixed highs in determining the resolution of the color picture has been further emphasized by the Hazeltine Electronics Corporation in their constant luminance system.

VI. Conclusions

The requirement that a color transmission utilize no more than the frequency bandwidth of a conventional monochrome television system with no appreciable deterioration in the picture resolution, at first appeared self-contradictory. However, it was then realized that the eye-brain component of the viewing system, although still imperfectly understood, is capable of a high degree of flexibility in the interpretation of what is displayed on the screen; consequently a certain amount of picture distortion and color cross talk is tolerable. The preceding analysis of a typical dot-sequential color system brings out the price which must be paid in picture distortion and color cross talk, with some scanty evidence as to the effect upon picture acceptability. The use of mixed highs has been found to be a most efficient means of saving bandwidth in those frequency regions where the transmission of color information is negligible. A sampling and sorting process not using pulses is described, which appears to offer a simpler and more economical type of circuitry for the high-speed operations of the dot-sequential system.

Acknowledgments

The authors wish to express their deep appreciation to R. M. Bowie for his many helpful suggestions during the course of this study, and to D. W. Cawood for his generous mathematical assistance.

[9] R. M. Bowie, "Color television," *Sylvania Technologist*, vol. 3, pp. 2–11; July, 1950.

Color Television—U.S.A. Standard*

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Summary—With the advent of commercial color television, the invitation of The Institute of Radio Engineers to present an up-to-date picture of the officially adopted system seemed most timely.

This paper is divided into four sections. The first deals with the actual standards as established by the Federal Communications Commission and discusses their colorimetric significance. Section II discusses the design and performance of typical commercial color-television receivers. Section III will be of special interest to the broadcaster as it describes the conversion of existing black-and-white studio equipment for color-television use. Some data on studio installation and lighting are also furnished. Section IV deals with nonbroadcast uses of color television and describes industrial color-television equipment known under the name "Vericolor."

Other advances such as a method of increasing picture sharpness are presented in an accompanying paper (pp. 1314–1322) under the heading of "A new technique for improving the sharpness of television pictures."

I. Color-Television Standards

Most of the fundamental data and early developmental stages of the field-sequential color-television system are known to the engineering profession, partly from publications[1–4] and partly from material presented at the FCC hearing. Now that color television has attained the status of commercial operation, it seems advisable to fashion this paper in such a way that it is most useful to the studio and receiving-equipment engineer.

It is appropriate to begin with a recital of the official FCC color-television standards as they appeared in the Federal Register, and to follow this with a brief discussion of their significance from a colorimetric point of view.

"It is ordered, that effective the 20th day of November, 1950, the Commission's "Standards of Good Engineering Practice Concerning Television Broadcast Stations" are amended in the following respects:

(I) Paragraphs 5, 6, 7, and 8 of Section 1B entitled "Visual Transmitter" are revised to read as follows:

5. *Color transmission.* The term "color transmission" means the transmission of color television signals which can be reproduced with different values of hue, saturation, and luminance.

6. *Field.* The term "field" means scanning through the picture area once in the chosen scanning pattern and in a single color. In the line-interlaced scanning pattern of two to one, it means the scanning of the alternate lines of the picture area once in a single color.

7. *Frame.* The term "frame" means scanning all of the picture area once in a single color. In the line-interlaced scanning pattern of two to one, a frame consists of two fields.

8(a). *Color field.* The term "color field" means scanning through the picture area once in the chosen scanning pattern and in each of the primary colors. In the line-interlaced scanning pattern of two to one, it means the scanning of the alternate lines of the picture area once in each of the primary colors.

(b). *Color frame.* The term "color frame" means scanning all of the picture area once in each of the primary colors. In the line interlaced scanning pattern of two to one, a color frame consists of two color fields.

(II) Paragraphs 5, 6 and 13 of Section 2A entitled "Transmission Standards and Changes or Modifications Thereof" are revised to read as follows:

5. For monochrome transmission the number of scanning lines per frame shall be 525, interlaced two to one in successive fields. The frame frequency shall be 30, the field frequency 60, and the line frequency 15,750 per second.

6. For color transmission the number of scanning lines per frame shall be 405, interlaced two to one in successive fields of the same color. The frame frequency shall be 72, the field frequency 144, the color frame frequency 24, the color field frequency 48, and the line frequency 29,160 per second.

13. The level at maximum luminance shall be 15 per cent or less of the peak carrier level.

(III) The following new paragraphs 19 and 20 are added to Section 2A:

19. The color sequence for color transmission shall be repeated in the order red, blue, green in successive fields.

20. The transmitter color characteristics for color transmission shall be such as to reproduce the transmitted colors as correctly as the state of the art will permit on a receiver having the following trichromatic coefficients, based on the standardized color triangle of the International Commission on Illumination:

Red	Blue	Green
$x=0.674$	$x=0.122$	$x=0.227$
$y=0.326$	$y=0.142$	$y=0.694$

* Decimal classification: R583. Original manuscript received by the Institute, August 22, 1951.

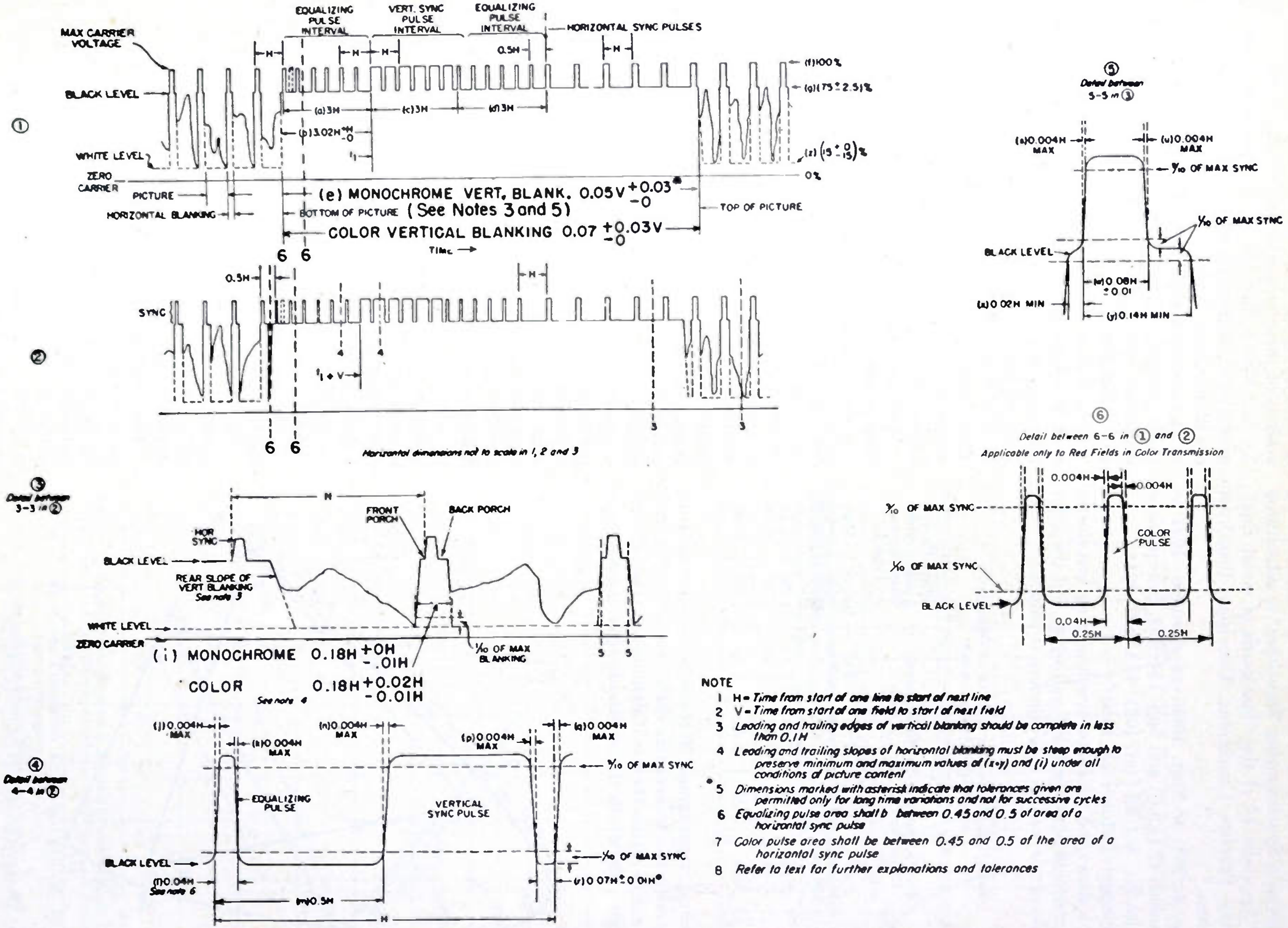
† Laboratories Division, Columbia Broadcasting System, Inc., New York, N. Y.

[1] P. C. Goldmark, J. N. Dyer, E. R. Piore, and J. M. Hollywood, "Color television—Part I," Proc. I.R.E., vol. 30, pp. 162–182; April, 1942.

[2] P. C. Goldmark, E. R. Piore, J. M. Hollywood, T. H. Chambers, and J. J. Reeves, "Color television—Part II," Proc. I.R.E., vol. 31, pp. 465–478; September, 1943.

[3] P. C. Goldmark, "Brightness and color in television," *Elec. Eng.*, vol. 68, pp. 237–242; March, 1949.

[4] P. C. Goldmark and J. M. Hollywood, "A new technique for improving the sharpness of television pictures," Proc. I.R.E., pp. 1314–1322; this issue.



NOTE

1. H = Time from start of one line to start of next line
2. V = Time from start of one field to start of next field
3. Leading and trailing edges of vertical blanking should be complete in less than 0.1H
4. Leading and trailing slopes of horizontal blanking must be steep enough to preserve minimum and maximum values of (x+y) and (i) under all conditions of picture content
5. Dimensions marked with asterisk indicate that tolerances given are permitted only for long time variations and not for successive cycles
6. Equalizing pulse area shall be between 0.45 and 0.5 of area of a horizontal sync pulse
7. Color pulse area shall be between 0.45 and 0.5 of the area of a horizontal sync pulse
8. Refer to text for further explanations and tolerances

Fig. 1—Television synchronizing waveforms.

(IV) New "Appendix I" attached hereto entitled "Television Synchronizing Waveform" is substituted for "Appendix I" of the "Standards of Good Engineering Practice Concerning Television Broadcast Stations."

(Secs. 4, 303, 48 Stat. 1066, as amended, 1082 as amended; 47 U.S.C. and Sup. 154, 303, Interprets or applies Sec. 301, 48 Stat. 1081; 47 U.S.C. 301)

Released: October 11, 1950."

Fig. 1 shows the television synchronizing waveforms which combine both the black-and-white and the color wave shapes as well as their numerical values.

TABLE I

RELATIVE LUMINOSITY VALUES OF ORIGINAL AND REPRODUCED COLORS

Wratten Filter No.	Filters through Illuminant C		Reproduced with		Filters Photographed with Kodachrome Type 5	
	Published Values	Actual Values	Primaries C	Primaries A	Before (with 3200°K)	After (with 3200°K)
13	2.57	2.06	2.97	2.42	1.56	0.46
22	2.54	2.10	2.25	1.81	2.30	1.74
32	1.—	1.—	1.—	1.—	1.—	1.—
38	3.12	2.39	1.61	1.43	1.78	0.96

Referring to paragraph 20 of the preceding standards, dealing with the transmitter color characteristics, it is important to realize their real significance. The receiver primaries E to which the standards refer are shown in

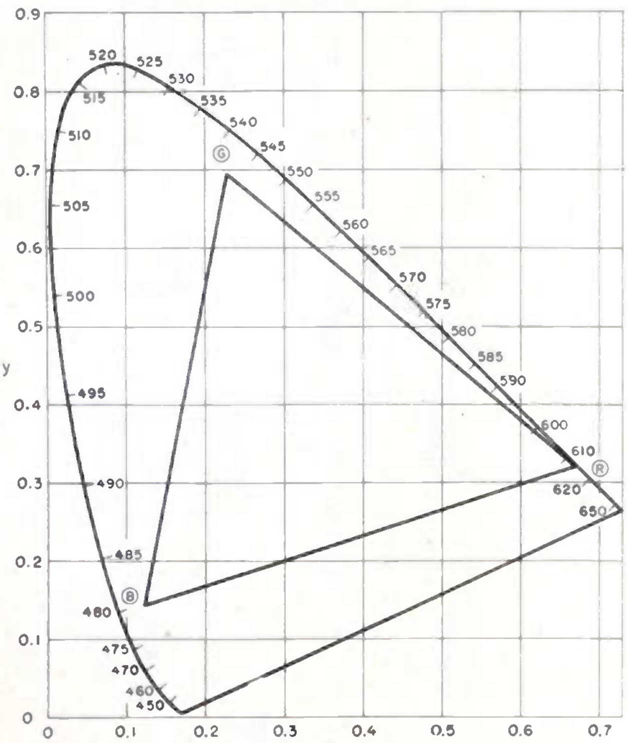


Fig. 2—Color triangle for receiver primaries E.

Fig. 2. The co-ordinates on the ICI color diagram correspond to those listed in paragraph 20. These primaries E satisfy certain performance conditions for specific types of color receivers. The ratios of the luminosities of these primaries are green to red to blue as 2.9 to 1.8 to 1. Because of the favorable ratios, these primaries at the receiver will permit a high flicker threshold illumination. Thus, if receiver illumination as high as 24 foot-lamberts is required and a color disk is used, these primaries E are recommended. The theoretical maximum color gamut possible with these primaries is more than adequate.

Calculations and experiments, comparing the maximum possible color fidelity with primaries E using only the major positive lobes of the transmitter color curves (Fig. 3), have shown that the color fidelity obtainable is at least as good as, if not better than, Kodachrome. This is particularly true if the distortion in luminosity values is also taken into consideration. Fig. 4 and Table I show the tabulated results.

With the field-sequential system, when using a single pickup tube in the camera, it is not practical to employ masking, that is, utilization of the negative lobes. In view of the results of the fidelity experiments just referred to, masking can be dispensed with. It will be shown that the standard transmitter primaries as used in practice, namely, without the negative and minor positive lobes as shown in Fig. 5, can satisfy not only primaries E, but also a wide variety of other receiver primaries. This gives the receiver manufacturer the necessary flexibility in the choice of color fidelity, resistance to flicker, light efficiency, etc. In Fig. 4 the color fidelity of another set of primaries has been plotted against primaries A as well as Kodachrome. They are receiver primaries C and are represented in Fig. 6. These color primaries were theoretically derived by an early industrial color committee, using Wratten filters Nos. 47, 58, and 25 combined with Illuminant C (one of the ICI illuminants). The resultant white when using equal amplitudes of red, blue and green is again Illuminant C. Another set of receiver primaries is plotted in Fig. 6, namely, primaries D using a specific phosphor mixture with Wratten filters Nos. 47, 58 and 26. Both primaries C and D show better blues than primaries A or primaries E, as illustrated in Fig. 2. However, the greens of primaries A and primaries E are superior while the reds of all four primaries, namely, A, C, D, and E, are almost identical.

The more recent primaries E differ only slightly from primaries A. They were derived from primaries A in such a way as to provide a more suitable white, using available phosphor-filter combinations.

The luminosity ratios of primaries A, C, and D are given in Fig. 6 and it can be seen that primaries A (similar to primaries E) belong to the low luminosity-ratio primaries (high flicker threshold illumination). Transmitter primaries for primaries A, C, and D have been calculated and plotted with the condition that equal amplitudes will correspond to the desired white at the receiver. These transmitter primaries are shown in Fig. 7. Actually, only two families of curves are shown because primaries C and primaries D result in almost

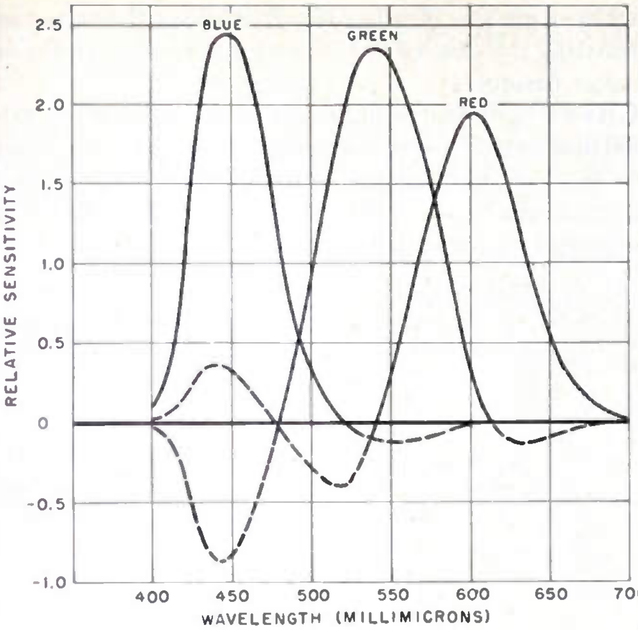


Fig. 3—Theoretical (ideal) spectral sensitivities of the transmitter based upon receiver primaries *E*. Note—White to be reproduced by equal voltages of the three primaries.

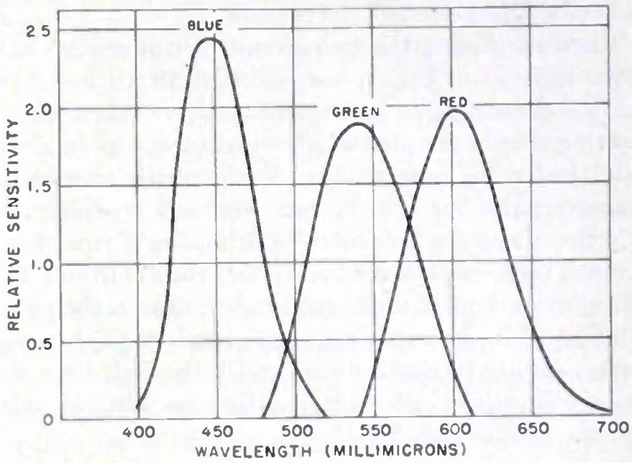


Fig. 5—Standard transmitter color primaries, neglecting minor lobes and adjusted to produce equal signal amplitudes for red, blue, and green (based upon receiver primaries *E*).

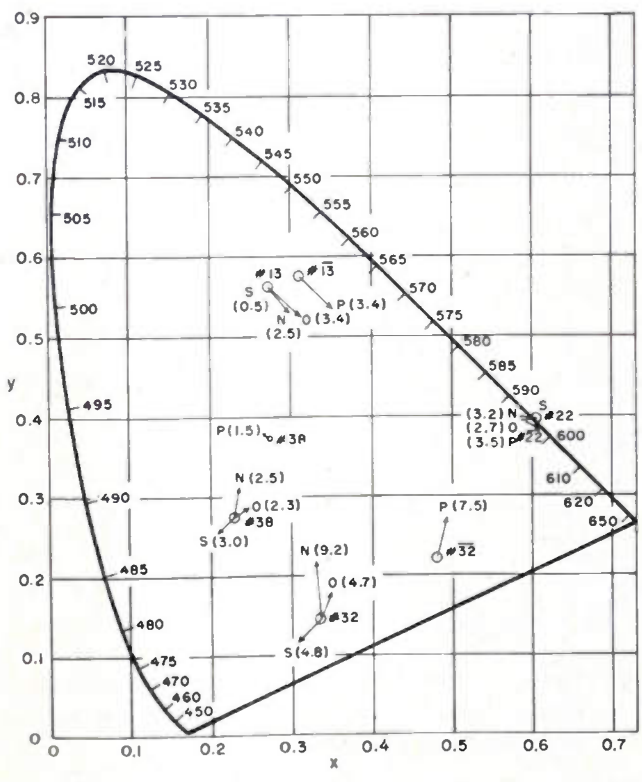


Fig. 4—Comparative fidelity of reproduction of colors by means of transmitter primaries of Fig. 3 (using only positive lobes) together with receiver primaries *C* and *A*, and type *B* Kodachrome. Note—Primaries *A* similar to primaries *E*.
Legend: *S* = Published filter values
O = Reproduced with primaries *C*
N = Reproduced with primaries *A*
Numbers in brackets indicate approximate discernible color differences.
Numbers—$\overline{13}$, $\overline{22}$, $\overline{32}$, $\overline{38}$
Filters at 3,200° K
P—Reproduced with Kodachrome type *B* and 3,200° K

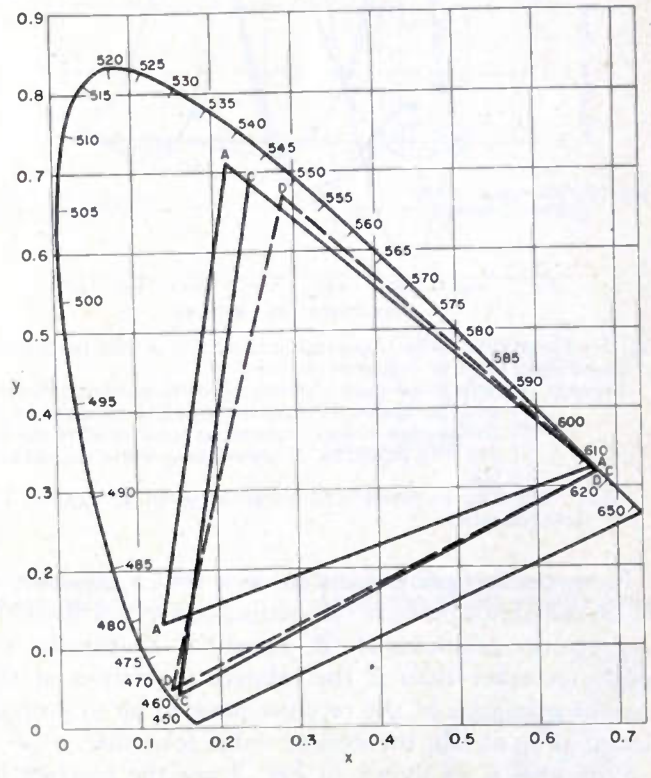


Fig. 6—Comparative color gamuts of receiver primaries *A*, *C* and *D*.
Legend: *A*—Low flicker synthetic primaries, White = Illuminant *C*
C—Color Committee Primaries: #47, 58, 25 Kodak filters + Illuminant *C*
White = Illuminant *C*
D—(dotted line) CBS 2-phosphor with #47, 58, 26 Kodak filters
Triangle $A = Y_b : Y_r : Y_g = 1 : 1.5 : 2.4$
Triangle $C = Y_b : Y_r : Y_g = 1 : 4.3 : 12.3$
Triangle $D = Y_b : Y_r : Y_g = 1 : 4.9 : 13.4$

identical transmitter characteristics as represented by the broken curves. Transmitter color sensitivities for primaries A are shown with solid lines. It should be understood that these sensitivities combine the color response of the light source, camera tube photo-surface, and color filters used at the camera.

When examining the two groups of transmitter color characteristics in Fig. 7, one will note that when disregarding the negative and minor positive lobes, the remaining shapes are almost identical except as to amplitude. Referring now to Fig. 5, the three transmitter characteristics for blue, green, and red represent not only the major positive lobes of primaries E from Fig. 3 but also those of primaries A, C, and thus D from Fig. 7. The electrical amplitudes required to obtain the proper value of white at a receiver using receiver primaries E, corresponding to equal areas under the red, blue, and green transmitter color sensitivities, are already taken into account in Fig. 5.

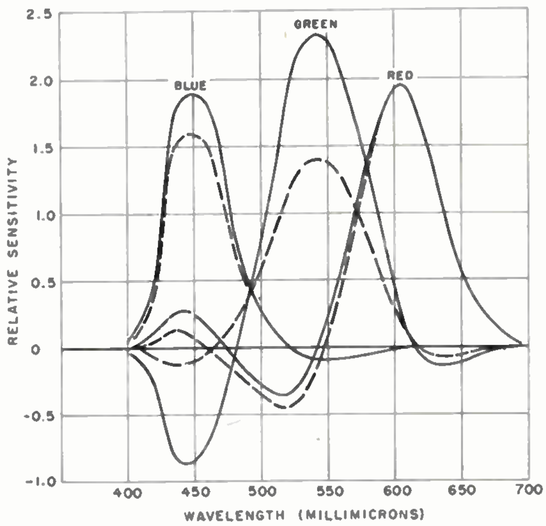


Fig. 7—Theoretical (ideal) spectral sensitivities of the transmitter based upon receiver primaries A and C.
Legend: I. Solid line = ideal transmitter color sensitivities for use with primaries A, reproducing white (Illuminant C)
II. Broken line = ideal transmitter color sensitivities for use with primaries C, reproducing white (Illuminant C)
Note—White to be reproduced by equal-signal voltages of the three primaries.

From the foregoing it can be seen that a transmitter which radiates signals corresponding to Fig. 5 will satisfy the receiver primaries A, B, C, and E. Naturally, for primaries other than E the relative intensities of the various primaries at the receiver have to be so proportioned as to obtain the desired value for white.

Primaries E as shown in Fig. 2 are the product of the phosphor characteristic and specific filters. Such filters have been manufactured by Monsanto and Eastman Kodak in large acetate sheets. The typical transmittance curves are shown in Fig. 8.

The universal transmittance curves as shown in Fig. 5 require certain tolerances if they are to be used as standard. The following is an attempt to interpret the color standards in such a fashion that the transmitter characteristics are specifically defined, while at the same time permitting the utmost flexibility for the color-television-receiver designer.

Given a light source illuminating the scene to be televised and having a spectral energy distribution E, where E is the radiant flux per unit wavelength throughout the visible spectrum (400 to 700 millimicrons), the over-all spectral response comprises:

(a) Spectral sensitivity S of the camera tube, defined as its response to unit radiant flux of spectrally homogenous energy as a function of wavelength,

(b) Spectral transmittances, R, B, G, of the red, blue and green color filters; spectral transmittances being the ratio of transmitted to incident radiant flux of spectrally homogenous energy as a function of wavelength,

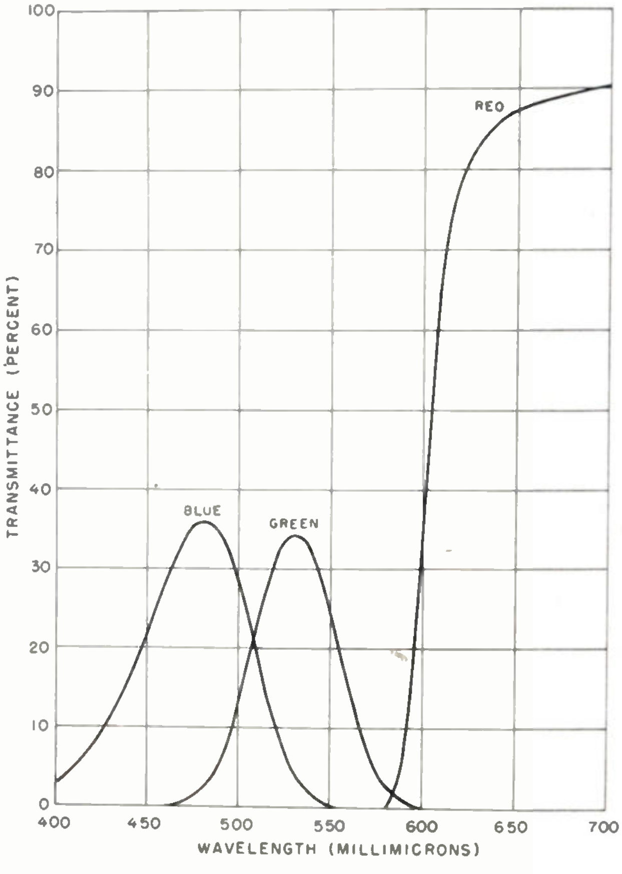


Fig. 8—Spectral transmittance curves of primary E filters.

(c) Color amplitude factors r, b, g, of the color mixer, defined as the respective ratios of the outgoing and incoming individual color signals.

The camera sensitivity, the color filters, and the color amplitude factors shall satisfy the following four conditions:

1. $\int_{550}^{660} ESRd\lambda \Big/ \int_{400}^{700} ESRd\lambda$ be not less than 0.90,

2. $\int_{410}^{500} ESBd\lambda \Big/ \int_{400}^{700} ESBd\lambda$ be not less than 0.90

3. $\int_{490}^{600} ESGd\lambda \Big/ \int_{400}^{700} ESGd\lambda$ be not less than 0.90,

4. The color amplitude factors r, b, g, shall be adjusted so that the color signals, corresponding to a white test area[5] illuminated by the light source E, are equal within ± 5 per cent.

II. Commercial Color-Television Receivers

It is common knowledge that methods used by any color-television system for presentation of a color picture at the receiver may be used with the field-sequential system, while the reverse is not true. Several of these methods are illustrated in Fig. 9. The majority are unsatisfactory for home use because of one or more of the following undesirable features: (1) difficulty of maintaining optical registration; (2) difficulty of maintaining electrical registration; (3) narrow viewing angle; (4) high cost; (5) insufficient high-light brightness. Table II shows the undesirable features associated with each method.

[5] The white area of the test chart shall have a spectral reflectance substantially constant, independent of wavelength.

TABLE II

Method	*Undesirable Features*				
(From Fig. 9)	1	2	3	4	5
a	X	X	X	X	
b	X	X		X	X
c	X	X		X	X
d	X	X			X
e					X
f					X
g					
h					
i		?		?	

The direct-view color tube will likely offer a convenient method, when developed to a commercial product at a reasonable price. Of the remaining tabulated methods, at present only the last three yield sharp color pictures usable in the home, and only two (g, h) are capable of generating bright and sharp enough pictures suitable for home viewing in a normally lighted room.

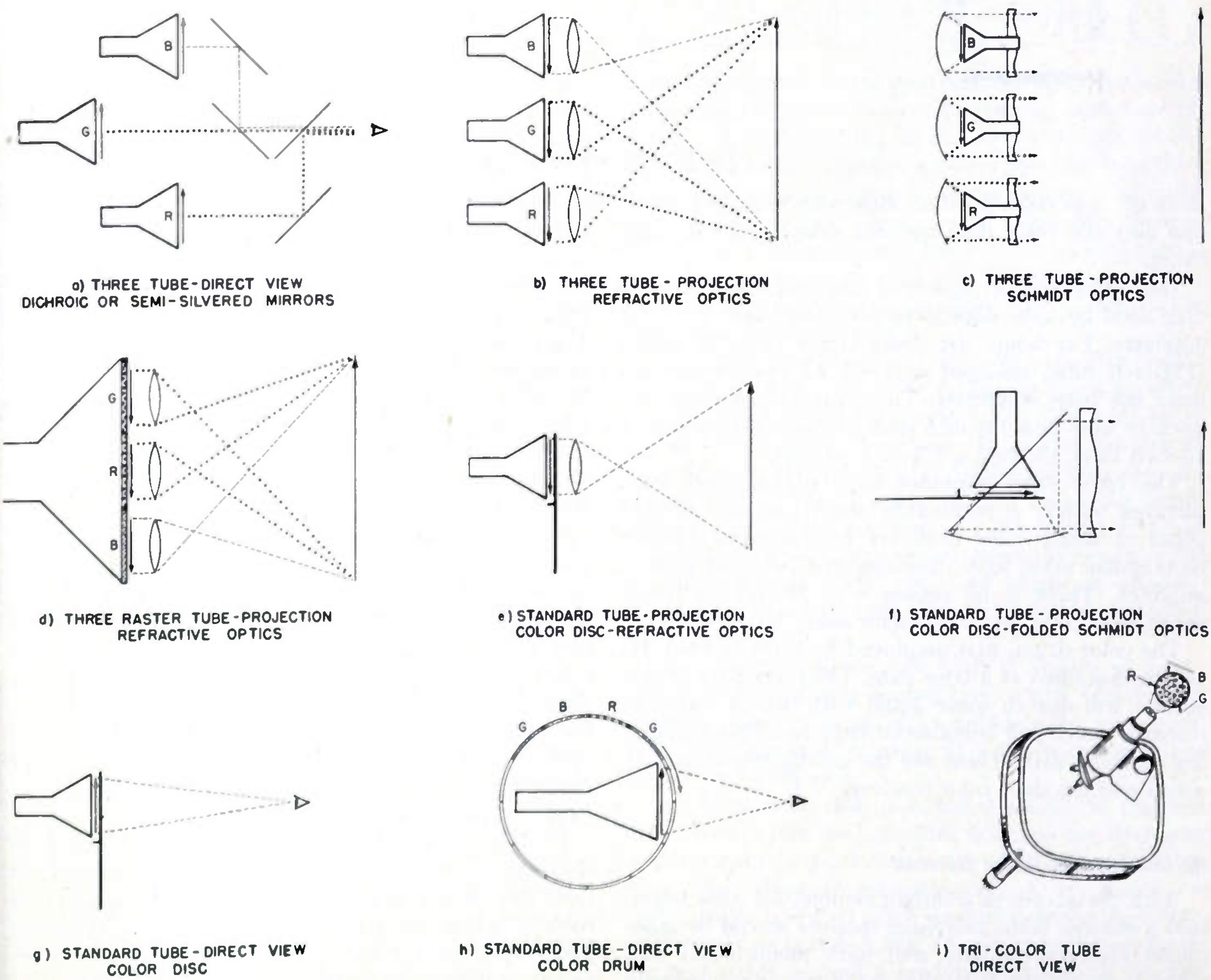


Fig. 9—Color-television picture presentation methods.

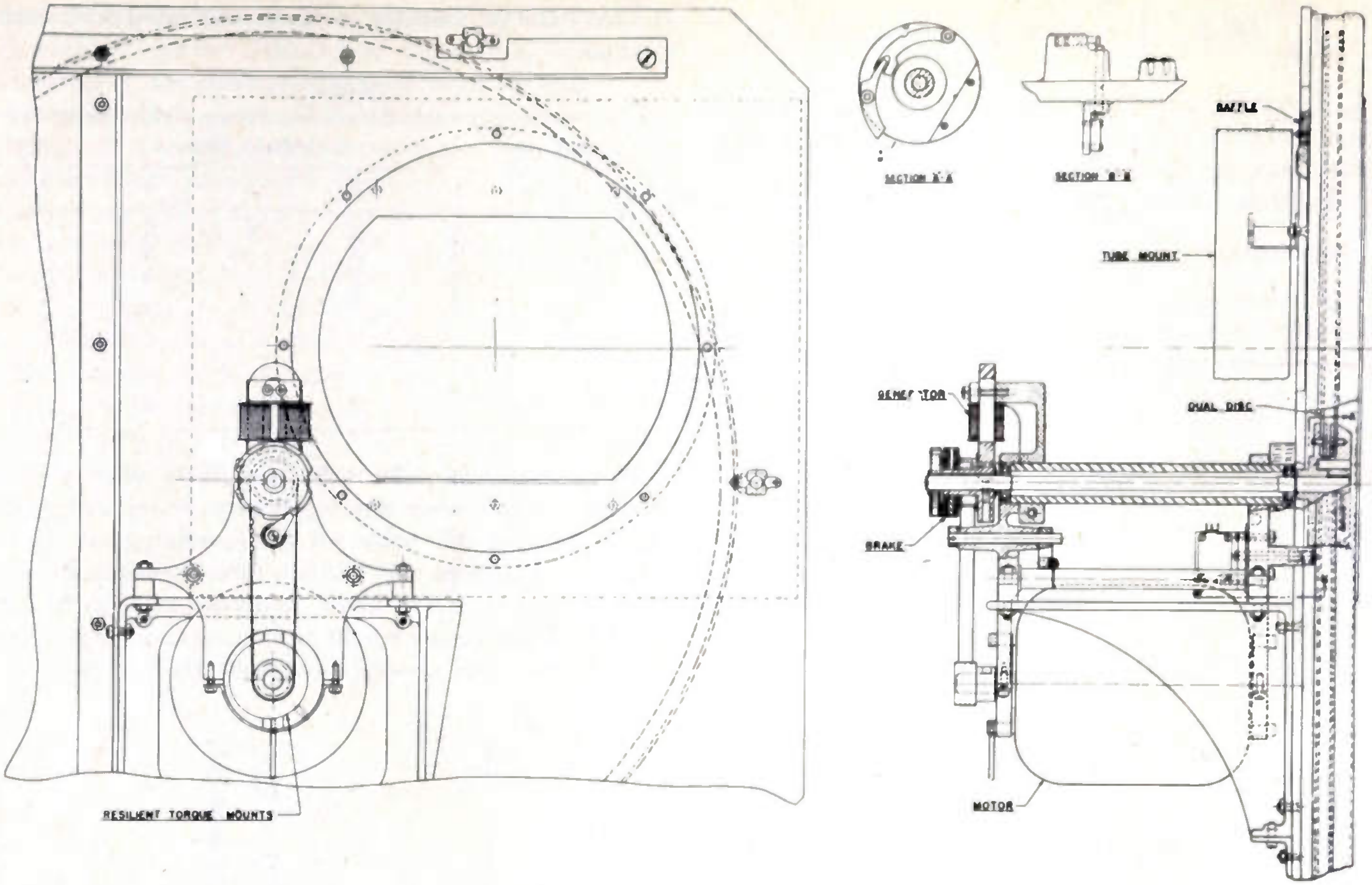


Fig. 10—Dual color-disk drive.

Both of these employ direct view with standard tubes; one uses the color disk and the other uses the color drum.

With proper arrangement of disk and raster, a color disk need be only slightly larger than twice the tube diameter. For home use disks larger than 27 inches ($12\frac{1}{2}$-inch tube, enlarged optically to 16-inch picture) have not been employed. The arrangement most frequently used is a $22\frac{1}{2}$-inch disk in combination with a 10-inch tube, yielding a $12\frac{1}{2}$-inch picture.

The color drum provides large unmagnified color pictures within a reasonably sized cabinet. Several types of drum color receivers built around 17-inch rectangular tubes have demonstrated excellent picture qualities. There is no reason why 20-inch or larger direct-view color pictures cannot easily be obtained.

The color drum, first employed by CBS in 1940–41, will be described at a later date. The remainder of this section will deal in some detail with two of the most recently developed commercial-type receivers employing the color disk. These are the combination color receiver and the slave color receiver.

A. Combination Color Receiver

With the advent of standard commercial color television a modern home television receiver should be capable of receiving equally well both monochrome and color. It should also have the ease of operation presently associated with monochrome receivers. The combination receiver here described satisfies these requirements and is designed to sell at a moderate price.

1. Physical Characteristics. The dual color-disk drive used in the combination receiver is shown in Fig. 10. The main chassis is shown in Figs. 11 and 12 and a detailed schematic is given in Fig. 13. Including rectifiers, 23 tubes are used. Except for the dual frequency scanning and the disk drive mechanism, the receiver is essentially the same as a standard monochrome receiver; discussion will therefore be confined largely to these differences.

A 10FP4 picture tube is used for both monochrome and color. In both cases a $12\frac{1}{2}$-inch picture is obtained by means of an oil filled lens fastened integrally with the front of the cabinet. In the dual-disk arrangement only one half of each disk is covered with filters, the other half being transparent. This permits the disks to be relatively phased so as to provide between the tube and the observer continuous filters for color operation or, when stopped, only clear sections for monochrome operation. The disk assembly rotates between the tube face and the back of the lens.

In this set, for the sake of economy, the color-pulse separator is omitted and the color disk is synchronized from the vertical pulses. Since these pulses contain no color information, a color phasing button on the front panel is provided (which has to be pressed no more than twice) to obtain the correct colors. In other units, con-

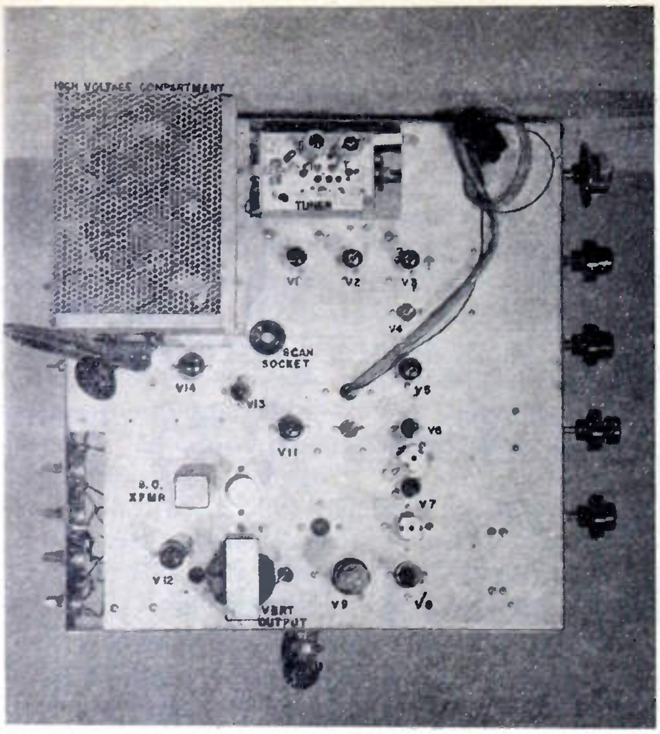


Fig. 11—Combination receiver chassis, top.

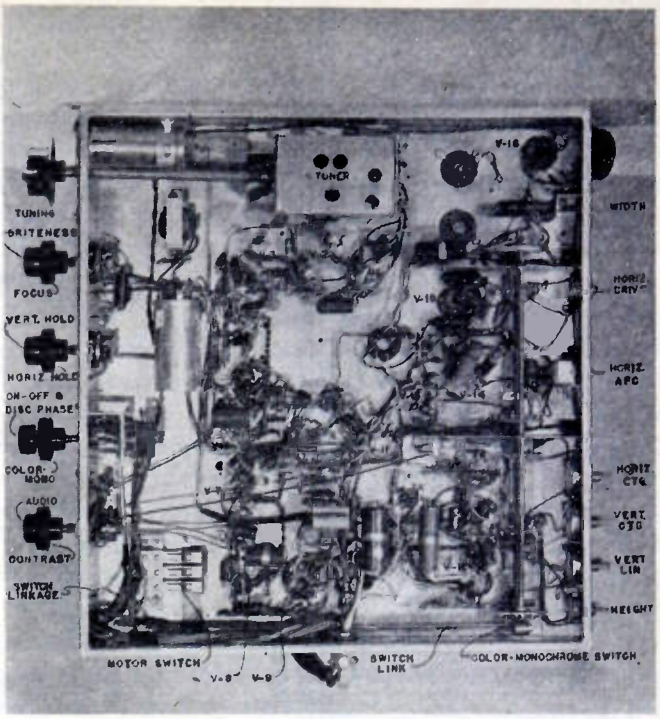


Fig. 12—Combination receiver chassis, bottom.

taining the color-pulse separator, this color phase button, of course, is not required.

A front panel color-monochrome switch permits manual selection of either of the two standards. When this switch is thrown to monochrome, the following takes place automatically; the scanning is changed to the monochrome rates, the dual disk is stopped with the clear sections superimposed, and the clear sections are rotated to a position over the tube face where no filters are visible.

2. Color-Disk Drive Mechanism. An important requirement for a color-disk drive mechanism and associated circuits is to maintain accurate disk phasing even when operating under changing temperatures, adverse conditions of varying line voltages and frequencies, and variable signal inputs. Further requirements are rapid acceleration of the disk to synchronism upon the application of power, and short disk pull-in time, i.e., the time required to synchronize a disk after selecting a particular station. Moreover, electrical interference should be absent and weight, size, cost, and mechanical noise should be a minimum.

The combination receiver disk drive mechanism shown in Fig. 10 satisfies these requirements. Proper phase within ± 2 degrees over the normal range of operating temperatures is maintained with line voltages between 105 and 125 volts and with line frequencies between 59.5 and 60.5 cps. The unit generates no electrical interference, has no rubbing contacts, and operates with a minimum of mechanical noise and vibration. It is designed to operate with a standard motor, a toothed rubber-fabric belt drive, and other components relatively easy to obtain.

As shown in Fig. 10 the dual disk assembly, generator, brake, and resiliently mounted induction motor are all fastened to a supporting baffle. Also mounted on the back of the baffle is the kinescope supporting structure. The disk housing is fastened to the front of the baffle by twist-lock screws. This housing completely encloses the disk in a fairly air tight space. Such an enclosure is important in order to keep disk driving power to a minimum and to retard the accumulation of dust on the disk and picture tube face.

The motor is a standard four-pole capacitor induction type with the following operating characteristics: It delivers 23 in.-oz. torque at 1,748 rpm with 80 to 85 volts rms input at 60 cps. It is also capable of delivering the above torque at 1,764 rpm with approximately 90 to 95 volts input at 60 cps. This latter condition corresponds to operation at 1,748 rpm at 59.5 cps. A centrifugal switch is provided internally which opens at approximately 1,700 rpm and closes at approximately 1,600–1,650 rpm. Its purpose is described later.

The motor drives the disk shaft by means of a rubberized-fabric toothed timing belt, which maintains a constant speed ratio of 17/14 between the motor and disk. With the disk rotating at 1,440 rpm the motor rotates at $1{,}748\frac{4}{7}$ rpm.

The front color disk is fastened solidly to the disk drive shaft, while the back disk floats on the shaft and is free to rotate back and forth with respect to the front disk through approximately $\frac{1}{3}$ revolution. A centrifugally operated catch mounted on the back disk, as shown in section A-A Fig. 10, prevents it from rotating backwards beyond a predetermined point. At this

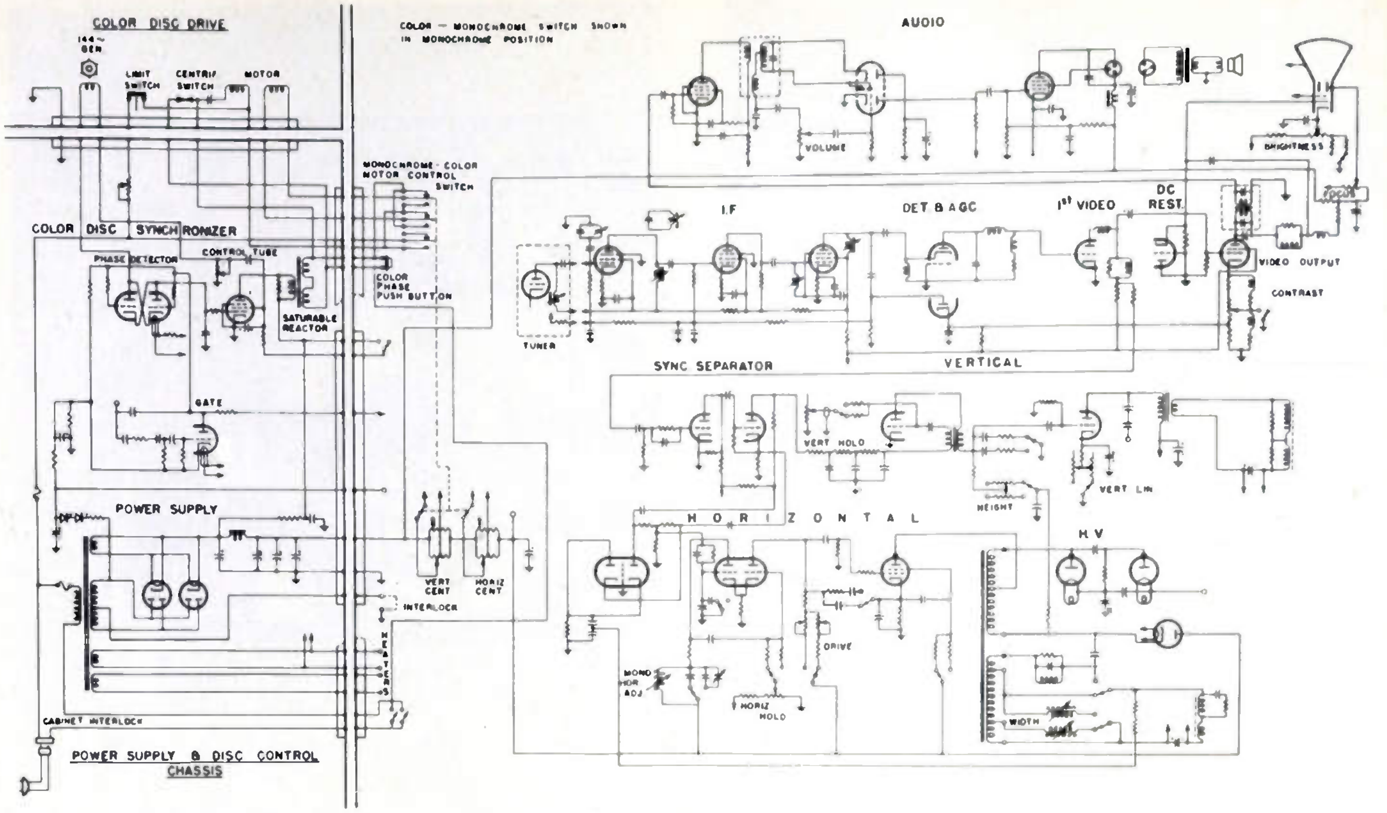


Fig. 13—Combination receiver schematic.

point the catch actuates a microswitch whose function will be described later.

When the disks are rotating rapidly forward, the centrifugal catch withdraws and is inoperative, and the air drag on the back disk causes it to lag the maximum amount. Under this condition the filters on one disk are adjacent to the clear area on the other disk, thereby providing in front of the picture tube a succession of six color filters, as required for color operation.

When the receiver is switched to monochrome, the brake is engaged and the motor is reversed. The disk assembly is rapidly brought to a stop and is then slowly rotated in a backward direction by the motor. The centrifugal catch stops the back disk, while the front disk continues to rotate until the back disk leads the front disk by the maximum amount, at which time the centrifugal catch actuates the microswitch, turning off the motor. This leaves the two clear areas of the disks adjacent to each other and over the tube face, as is required for monochrome reception.

The brake mechanism consists of a simple friction plate notched on its periphery and mounted under tension between two felt plates keyed to the disk drive shaft. During operation, a stationary latch engages the brake plate at its periphery.

The reluctance-type generator consists of a magnetically-hard U-shaped stator with a coil around each leg and a magnetically-soft rotor. It is magnetized by discharging a heavy electrolytic condenser through the coils while the generator is running.

The stator and rotor pole pieces are shaped to provide a saw-tooth wave output of approximately 200 volts peak-to-peak. This saw tooth has a very steep downward slope of approximately 10 volts per degree disk rotation, which limits the variation of disk phase to approximately ± 2 degrees over the wide range of operating conditions described previously.

Precision ball bearings with sealed-in lifetime lubrication are used to float the color disk drive shaft. These require no care, retain low and constant friction over a wide range of operating conditions, and eliminate any oil seepage onto the color disks.

3. Chassis Component Placement. In the combination color-monochrome receiver it is necessary to switch components of normally isolated circuits, such as vertical deflection, horizontal oscillator, horizontal output, etc. This results in a somewhat different placement of chassis components than that normally used on monochrome receivers. As evident in Fig. 13 most color-monochrome switch contacts are connected to the so-called "screw-driver" controls located on the rear chassis skirt. A practical location of the switch is, therefore, adjacent to, and parallel with these controls. To maintain short leads, the components of the various horizontal and vertical deflection circuits obviously should also be located near their respective switches.

The chassis layout of the combination receiver is shown in Figs. 11 and 12. Arranged in line along the rear of the chassis are the vertical scanning circuits, the horizontal oscillator circuits, and under a perforated metal shield, the horizontal output circuits. Beneath the chassis, parallel to the rear "screw-driver" controls and under the corresponding circuits, is the ganged wafer switch. The switch is actuated by a connecting rod and rocking arm mechanically linked to a knob on the front panel.

The close placement of adjacent electrical components is evident from a cross-comparison of the schematic with the chassis arrangement. From the RF tuner, the signal travels a short path through the IF strip to the second detector and first and second video amplifiers. At the second video amplifier the signal branches to the audio and the sync separator circuits; from here it travels over short paths to the vertical and horizontal scanning sections.

The power supply and color disk synchronizing circuits are mounted on a separate small chassis. Components sensitive to a 60-cps magnetic field, such as the picture tube and vertical oscillator, are thereby separated from the power transformer, the filter choke, and the saturable reactor (Fig. 13).

It is very important that the 60-cps component be kept to 50 db below the peak-to-peak color signal in both video and sync circuits. Larger amounts may be characterized by horizontal jitter, vertical jitter, picture flutter, poor interlace, etc. The 60-cps component may be injected by the magnetic fields mentioned above, by filaments, or by power supply ripple. One of the most sensitive areas with respect to magnetic fields is the neck of the picture tube. In earlier receivers this tube was shielded with a mu-metal funnel. In the combination set, however, the over-all hum is reduced to the desired low level by properly orienting components radiating 60 cps, by using a well-filtered power supply, and by observing the usual practices of twisting filament leads, etc.

4. RF, IF and Video Circuits. Since the horizontal scanning rate of color pictures is approximately twice that of monochrome, it is important to preserve the higher video frequencies. In addition, it is necessary that the video output be as linear as possible over the entire video band in order to avoid contrast distortion in the color picture. Such distortion is less noticeable in monochrome, since in color television it manifests itself as poor color rendition.

It has also been found desirable to switch both contrast and brightness when switching from monochrome to color, since an optimum color picture as seen through the color disk has excessive brightness and contrast when seen in black and white without the disk.

The RF-IF section is composed of a standard Sarkes-Tarzian tuner, two tuned IF pairs in cascade, and a second detector. Its response is essentially flat to 3.7 mc and is down 3 db at 4 mc.

The video amplifier consists of one-half of a 12AU7 triode first video stage and a 6AQ5 output video stage. The second half of the 12AU7 is used as a dc restorer. With three volts peak-to-peak input 120 volts peak-to-peak are realized at the kinescope grid. The 6AQ5 stage is capable of 130 volts peak-to-peak without appreciable amplitude distortion.

A degenerative type contrast control in the 6AQ5 cathode circuit is frequency compensated to provide essentially uniform frequency response throughout the control range. For monochrome the maximum video level is lowered by switching a 560-ohm resistor into the contrast control circuit.

5. Audio Circuits. These circuits are identical to those used in monochrome receivers. The IF trap attenuates the sound carrier approximately 10 db. The 4.5 mc intercarrier signal is removed from the plate circuit of the video output stage. A 6AU6 amplifier drives a 6T8 stage, which is a combination ratio detector and first audio amplifier. Additional audio amplification is provided by the 6V6GT audio output stage, which also acts as a dropping resistor and regulator for the 150-volt supply.

6. Synchronizing Circuits. Synchronizing signals are derived from the 12VH7 first video amplifier. This provides signals of essentially constant amplitude independent of contrast adjustment.

The noise immunity of the synchronizing signal separator is improved through the use of a combination long- and short-time-constant coupling circuit. The usual phase-inverter-type second triode delivers the separated signals to the vertical oscillator and the horizontal phase detector diode.

7. Vertical Oscillator and Output Amplifier. A 12BH7 is used as a vertical blocking oscillator and output stage. Necessary circuit changes between color and monochrome are provided by five SPDT switches which act at the following points: (a) vertical oscillator grid return resistor (vertical hold); (b) *RC* charging network in the plate circuit of the vertical oscillator; (c) height controls, (d) linearity controls; (e) centering controls.

8. Horizontal Oscillator and Output Amplifier. A 6AL5 phase detector controls the 12BH7 horizontal multivibrator in the usual manner. A 6BG6G horizontal output tube, a 6U4GT damper, and a pair of 1X2 voltage-doubling rectifiers provide adequate 55-degree scan and a hv potential of approximately 15 kv.

Nine monochrome-color SPDT switches provide circuit changes at the following points:

(a) AFC time-constant capacitor in the grid circuit of the horizontal oscillator;
(b) flywheel *LC* tuning capacitor in the plate circuit of the horizontal oscillator;
(c) fixed resistor in series with the horizontal hold control;
(d) horizontal drive control potentiometers;
(e) *RC* charging network in the output of the horizontal oscillator;
(f) 6BG6G screen voltage;
(g) yoke tap on the horizontal output transformer;
(h) width controls;
(i) centering controls.

A horizontal output transformer developed specifically for use on both color and monochrome frequencies is employed. The construction of this transformer is conventional and a ferrite core is used. Pertinent constructional details are shown in Fig. 14.

In this type of dual-frequency transformer the leakage reactance may resonate with the distributed capacitance, resulting in undesirable "ripples" on the left edge of the raster. This effect is eliminated in the combination receiver by connecting, for monochrome, a highly damped tuned circuit in the transformer secondary. As indicated in Fig. 13, this circuit is a parallel combination of a 200-microhenry inductance, a 1,000-$\mu\mu$f capacitance, and a 5,000-ohm resistor.

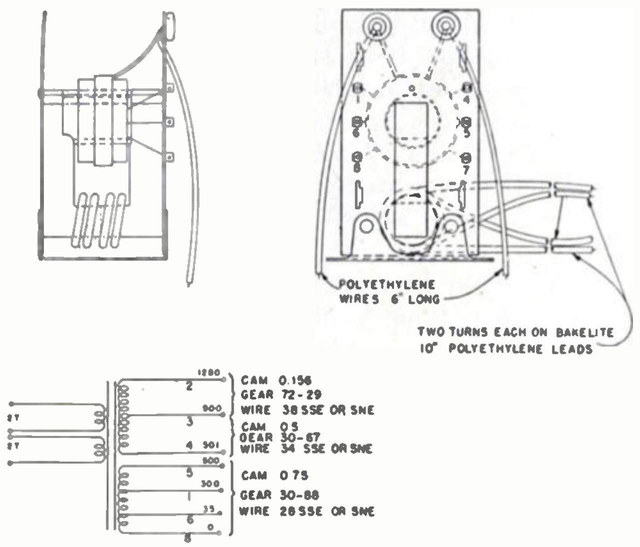


Fig. 14—Dual frequency horizontal output transformer.

A conventional monochrome anastigmatic scanning yoke is used. This again employs a ferrite core. The vertical and horizontal windings are of a type with inductances of 50 mh and 8.3 mh, respectively.

9. Color Disk Synchronizing Circuits. As indicated in Fig. 13 a pulse gate, a phase detector, and a saturable reactor control tube are used for color disk synchronization. The saw-tooth wave produced in the disk shaft generator is applied to both sections of the phase detector tube. This tube conducts momentarily when excited by the vertical pulses. The clamped voltage appearing at the grid of the control tube is therefore dependent upon the relative phase relationship between the vertical pulses and the locally generated saw-tooth wave. A variation of control tube current causes a corresponding change in the degree of saturation of the motor control reactor, thereby varying the speed of the color disk.

If, for example, the disk momentarily slows to slightly below synchronous speed, the point on the locally generated saw-tooth wave at which the vertical pulses clamp moves upward, thereby decreasing the bias on the control tube. The increased control tube current increases the degree of saturation in the motor control reactor, thereby increasing motor and disk speed to synchronism.

The pulse gate provides velocity correction of the color disk. This tube is normally conducting, thereby preventing the vertical pulses from reaching the phase detector. The locally generated saw-tooth wave from the generator is differentiated and applied to the grid of the gate tube in such a manner as to make it nonconducting only during the downward steep portion of the saw-tooth wave. Thus the operation of the phase detector is permitted during this period only. With this arrangement the *average* bias appearing at the control-tube grid is high when the disk is running considerably over speed, and low when running considerably under speed. This provides effective disk velocity correction.

In the color-disk synchronizing circuits, as in most servomechanisms, an anti-hunt network is required to eliminate hunting. Such a network is provided by the 20,000-ohm resistor, 16 μf electrolytic capacitor, and 2 μf paper capacitor at the screen of the control tube and the 250,000-ohm potentiometer between the saw-tooth generator and ground. This network returns from the control tube to the phase detector the necessary amount of phase-shifted anticipating voltage to prevent hunting. Optimum anti-hunt adjustment is provided by the 250,000-ohm potentiometer.

Changes in the type of color disk (as to its inertia), motor, or saturable reactor, usually require corresponding changes in the anti-hunt feedback network.

10. Color Disk Synchronizing Operation. In effect, three separate operations pull the disk into synchronism and keep it there. When power is first applied the centrifugal switch in the motor is closed, shorting the ac windings of the saturable reactor. Full line voltage is thereby applied to the motor, causing rapid acceleration of the color disk to near synchronous speed. The centrifugal switch then opens and the saturable reactor with its associated circuits takes control. The velocity correcting circuits bring the disk to synchronous velocity, at which time the phasing circuits bring the disk into exact phase and maintain it there. Only ten to fifteen seconds is required to bring the 22½-inch disk into synchronism and phase from a standstill. When running, the disk synchronizes in less than one second.

11. Power Supply. The power supply in the combination color-monochrome receiver is similar to that of any good monochrome receiver. As discussed previously, both the 60-cps and 120-cps hum components are kept very small. Decoupling is provided between the terminals supplying the disk synchronizing circuits and those supplying the remainder of the receiver. This eliminates any low-frequency variation of picture size, brightness, etc., induced by the action of the color disk synchronizing circuits. These circuits require a relatively constant current of 10 to 30 ma while the disk is in synchronism, but during the time the disk is being pulled into synchronism the current may vary at a slow rate between approximately 0 and 60 ma, with a corresponding induced variation in power supply voltages.

Two 5V4G cathode-type rectifiers prevent high voltage surges when the receiver is first energized. After filtering, 390 volts at 240 ma are available.

A selenium half-wave rectifier is connected to one side of the high-voltage winding of the power transformer to provide the negative voltages for the electrostatic picture tube focus and the disk control circuits.

B. Slave Color Receiver

Of universal interest to present television set owners is how to use present monochrome sets to receive color. While adaptors may be used to permit reception of color

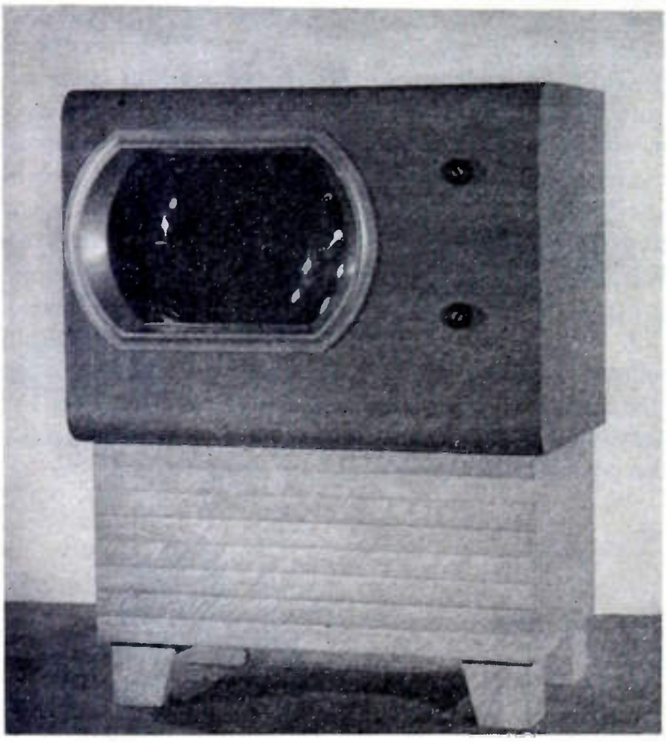


Fig. 15—Slave color receiver, front.

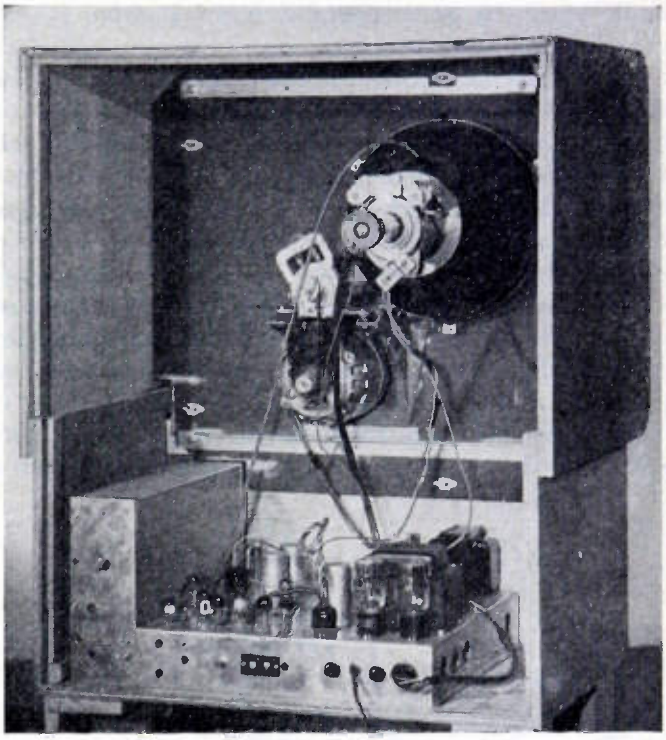


Fig. 16—Slave color receiver, back.

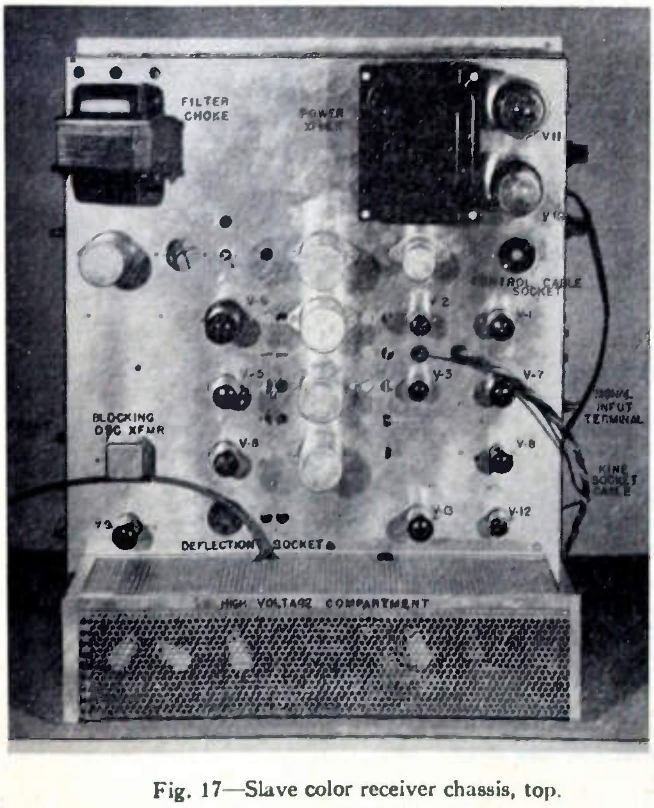


Fig. 17—Slave color receiver chassis, top.

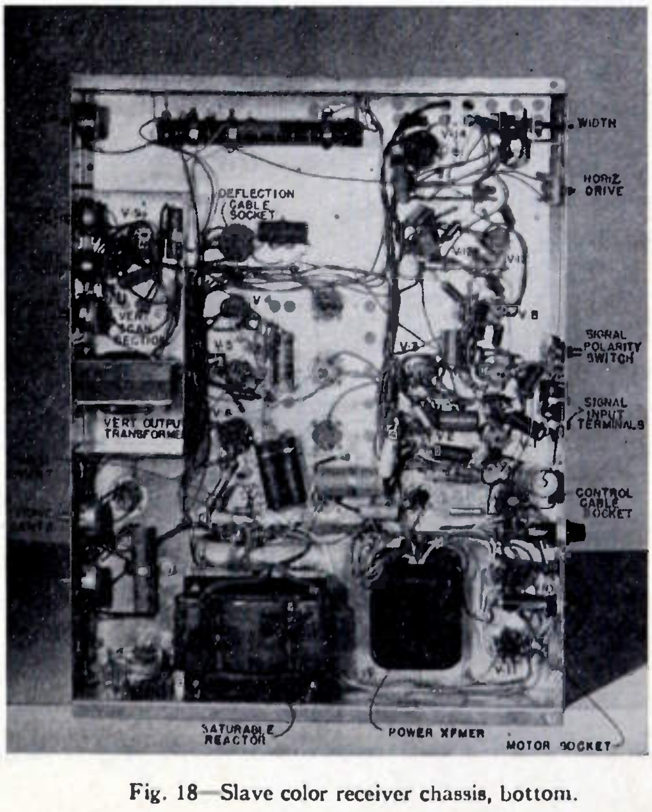


Fig. 18—Slave color receiver chassis, bottom.

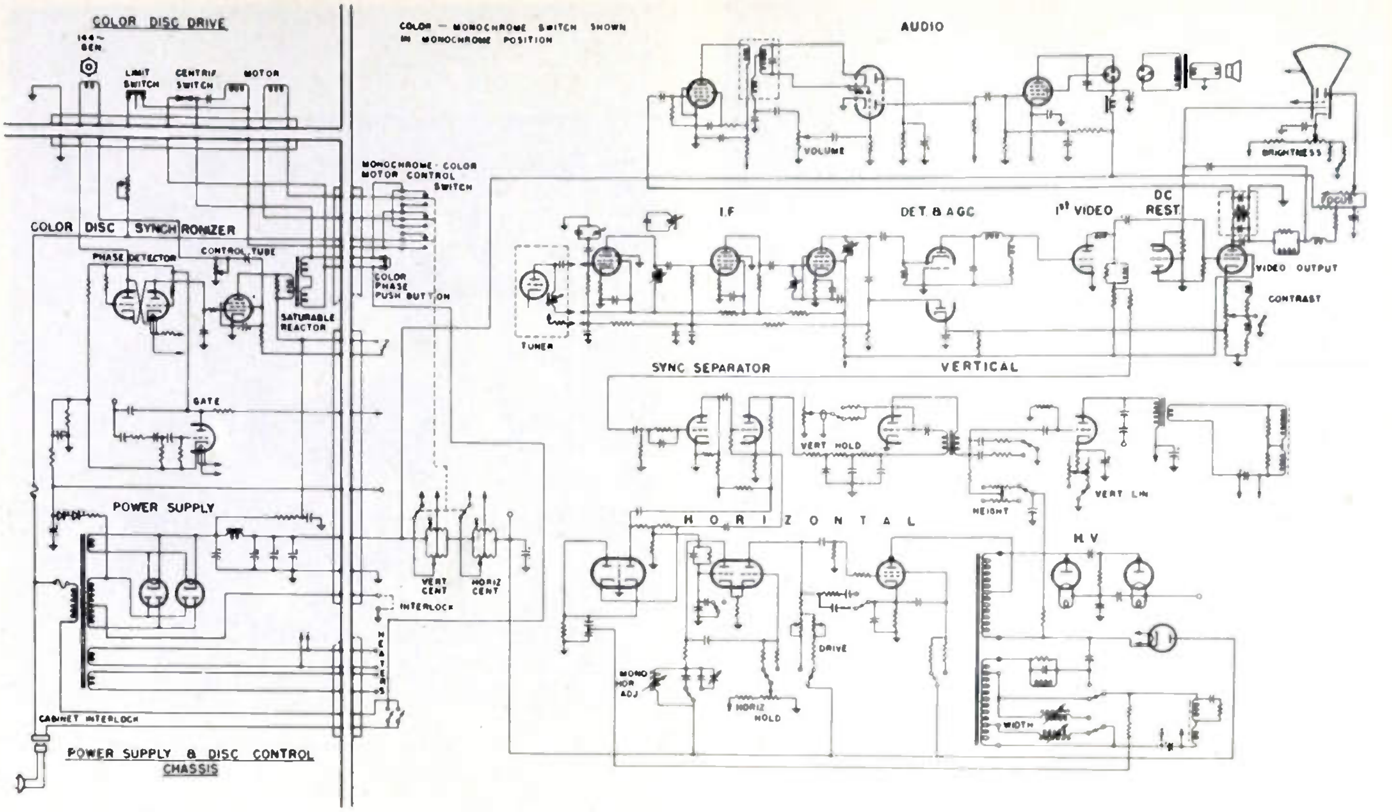


Fig. 13—Combination receiver schematic.

point the catch actuates a microswitch whose function will be described later.

When the disks are rotating rapidly forward, the centrifugal catch withdraws and is inoperative, and the air drag on the back disk causes it to lag the maximum amount. Under this condition the filters on one disk are adjacent to the clear area on the other disk, thereby providing in front of the picture tube a succession of six color filters, as required for color operation.

When the receiver is switched to monochrome, the brake is engaged and the motor is reversed. The disk assembly is rapidly brought to a stop and is then slowly rotated in a backward direction by the motor. The centrifugal catch stops the back disk, while the front disk continues to rotate until the back disk leads the front disk by the maximum amount, at which time the centrifugal catch actuates the microswitch, turning off the motor. This leaves the two clear areas of the disks adjacent to each other and over the tube face, as is required for monochrome reception.

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A horizontal output transformer developed specifically for use on both color and monochrome frequencies is employed. The construction of this transformer is conventional and a ferrite core is used. Pertinent constructional details are shown in Fig. 14.

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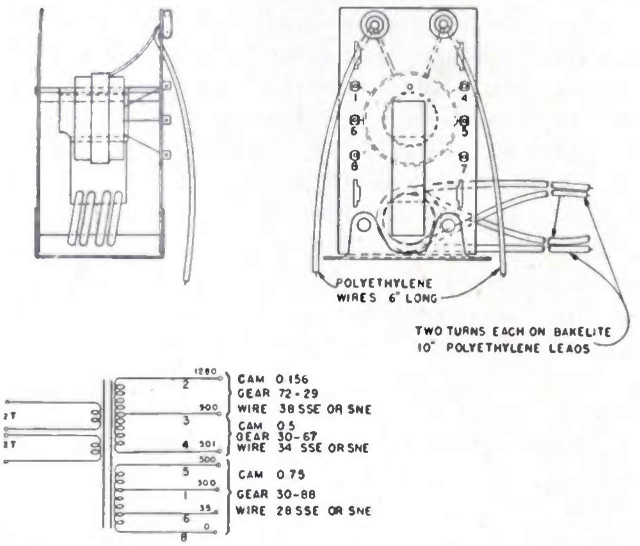

Fig. 14—Dual frequency horizontal output transformer.

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A selenium half-wave rectifier is connected to one side of the high-voltage winding of the power transformer to provide the negative voltages for the electrostatic picture tube focus and the disk control circuits.

B. Slave Color Receiver

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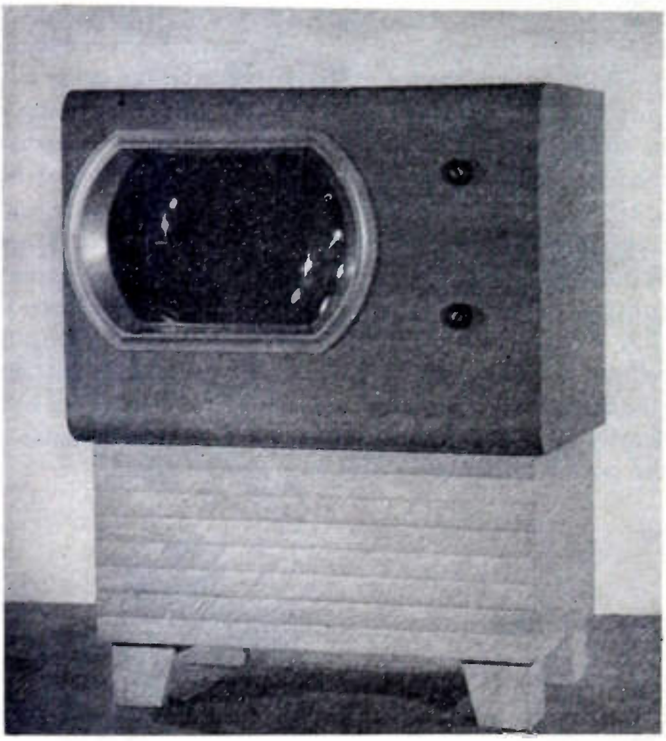

Fig. 15—Slave color receiver, front.

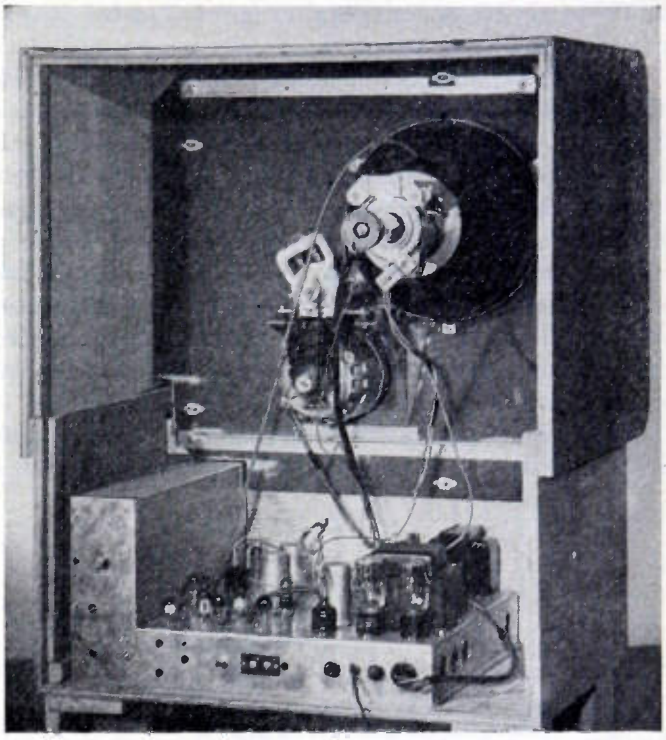

Fig. 16—Slave color receiver, back.

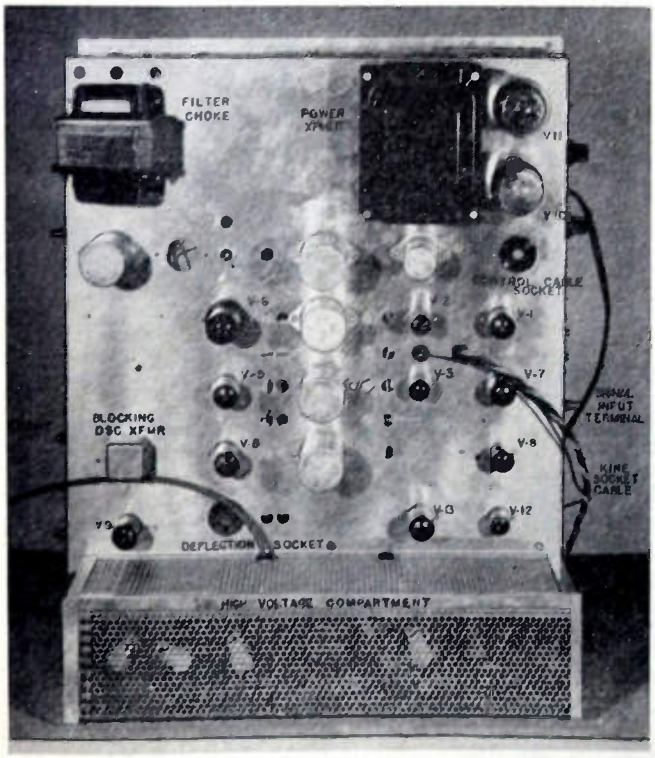

Fig. 17—Slave color receiver chassis, top.

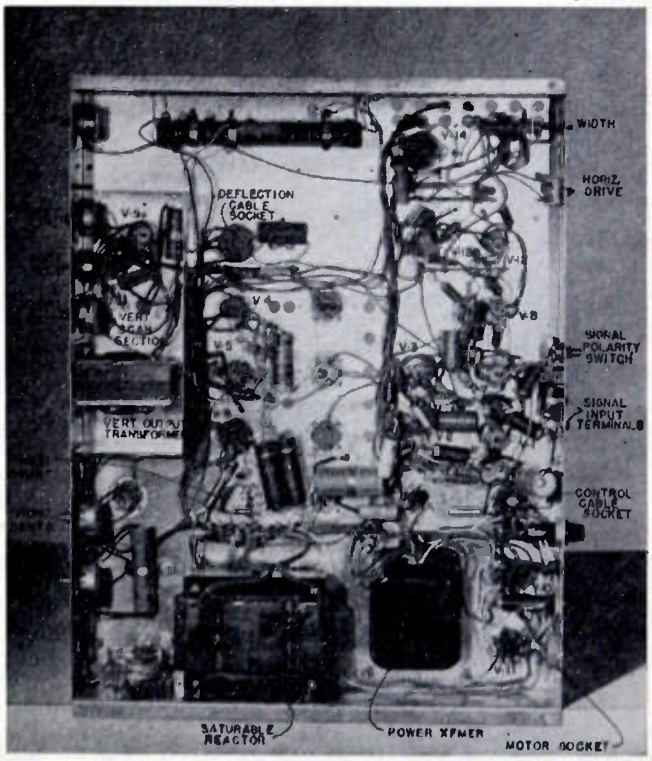

Fig. 18—Slave color receiver chassis, bottom.

broadcasts in black-and-white, and converters may be used to change these to color, a preferred method is that of using a slave color receiver. This unit scans at color frequencies only and presents a color picture by means of its own separate tube and color disk. It requires from the monochrome receiver only composite video. Sound is derived from the monochrome receiver in the usual manner. Since the slave receiver requires no RF, IF, nor audio stages, it is considerably less expensive than a complete color receiver.

The slave color receiver is shown in Figs. 15 and 16; the chassis is shown in Figs. 17 and 18; and its schematic is given in Fig. 19. Requirements for the various sections of this receiver are essentially the same as those described for the combination receiver. A few departures, however, are described in the following paragraphs.

1. Physical Characteristics. The over-all dimensions of the slave color receiver are somewhat less than those of the combination receiver, being $27\frac{1}{2}$ inches wide by 33 inches high by 20 inches deep. Sixteen tubes are employed, including rectifiers.

Only a single chassis is used; the power supply and color disk drive components being arranged in such a manner as to produce no undesirable effects from their magnetic fields.

The lower of the two front panel knobs controls the off-on switch and the contrast. The upper knob is rotated to control the brightness and depressed to bring the color disk to the proper phase.

2. Video Circuits. Two stages of conventional design are employed. Video response is flat within 2 db from 30 cycles to 4 mc with a voltage gain of approximately 115. A 4.5-mc sound trap in the 6AQ5 screen circuit provides 35 db rejection. A polarity-reversal stage with unity gain provides operation with either polarity of incoming composite video. Since the contrast control is mounted at a distance from the chassis, a somewhat unconventional circuit is used in which a variable positive bias is applied to the cathode of the first video stage. With the constants used, this circuit gives adequate contrast range with negligible frequency discrimination.

3. Vertical Oscillator and Amplifier Circuits. To insure reliable interlace these circuits are placed in a shielded compartment. This eliminates interference from both nearby electrical fields and from the magnetic fields of the power transformer and saturable reactor.

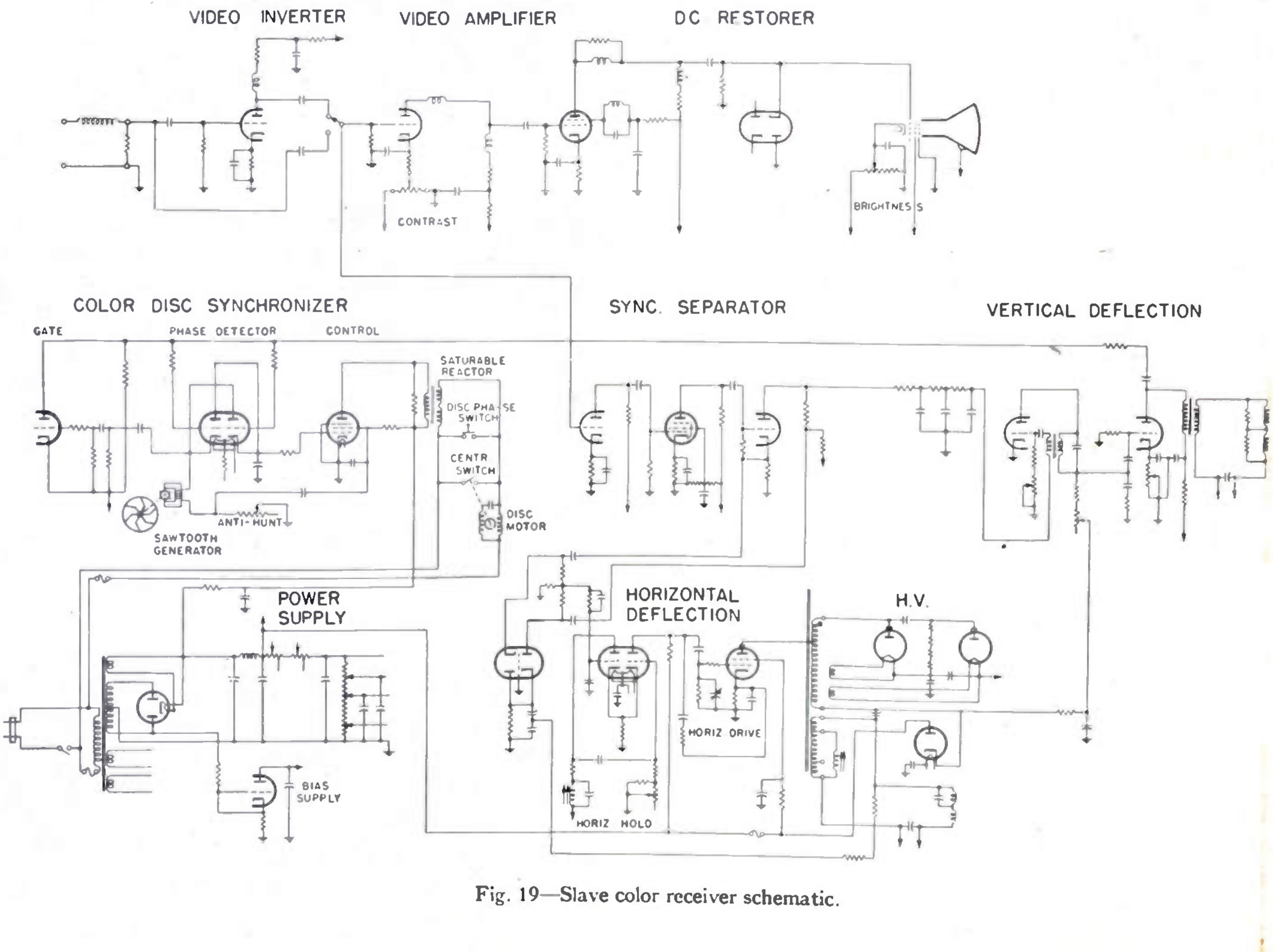

Fig. 19—Slave color receiver schematic.

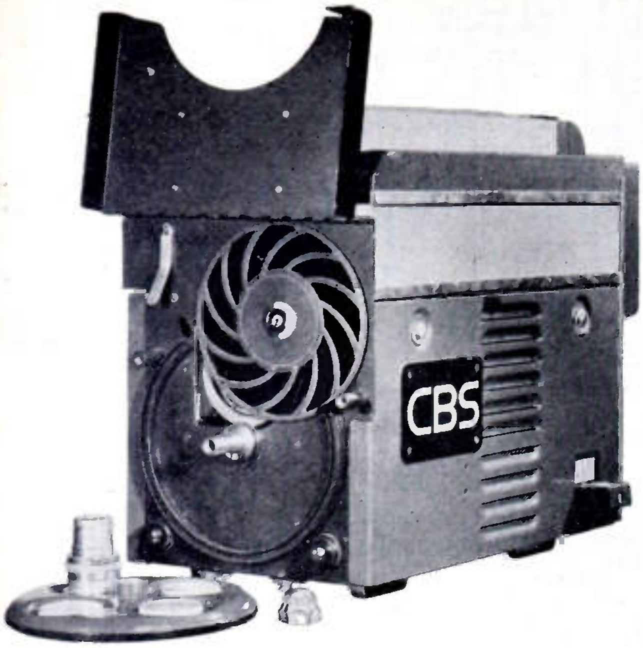

Fig. 20—RCA monochrome camera converted for color, front view; lens turret removed and added color disk in place.

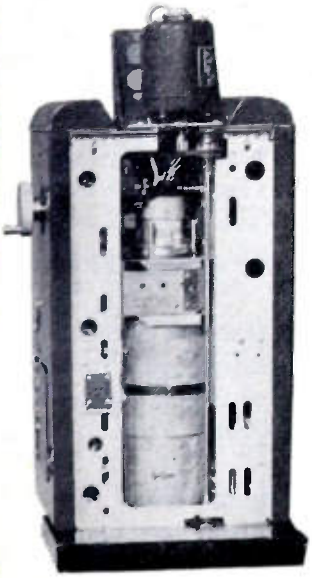

Fig. 21—RCA monochrome camera converted for color; top view, showing color drive assembly with added color-disk drive motor.

III. CBS Color-Television Broadcast Facilities

A. *Conversion of the RCA Monochrome Field Camera for Color Television*

The first prototype conversion of the RCA field television camera chain was undertaken by the RCA Terminal Facilities Engineering Group in Camden, New Jersey, between May and July of 1950. Circuit changes and additions, which CBS had used satisfactorily in earlier color-television equipment, were incorporated into several sections of the converted equipment. During late 1950 a second and third camera chain were converted in the CBS Engineering Department incorporating improvements resulting from experience gained through use of the first equipment. These, and a few additional improvements are now being incorporated in a new series of color camera chains again using standard monochrome equipment as a basis.

In the first three conversions type TK-30A field camera chains with studio type RCA M126000 cameras were used. Figs. 20 and 21 show how the color disk housing on these cameras is incorporated in a new front cover. Since the studio and field type cameras are identical as to circuit and chassis construction, the field camera with similar mechanical changes to the cover can also be successfully modified.

A block diagram showing the signal connections of a single camera chain, complete with synchronizing signal generator, is shown in Fig. 22. It will be noted that the connections are identical to those used for monochrome except for the addition of cables to the color mixer amplifier. The modifications necessary to each of the units shown in Fig. 22 will be described in some detail in the following sections.

1. Synchronizing Signal Generator Pulse Former. The principal changes to this unit are:

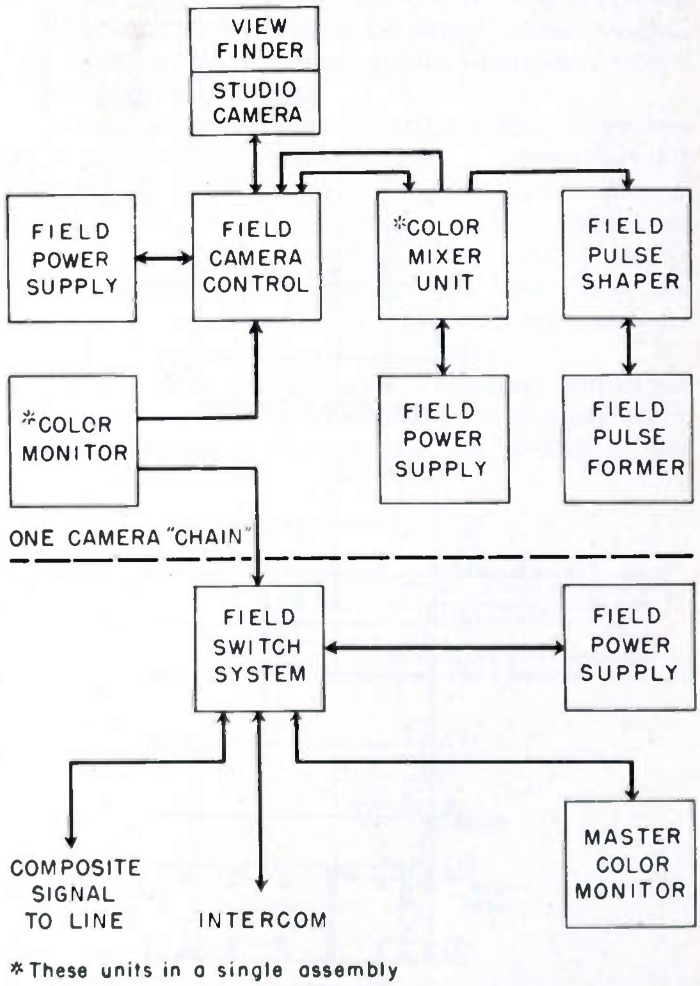

Fig. 22—RCA single camera chain converted for color, block diagram.

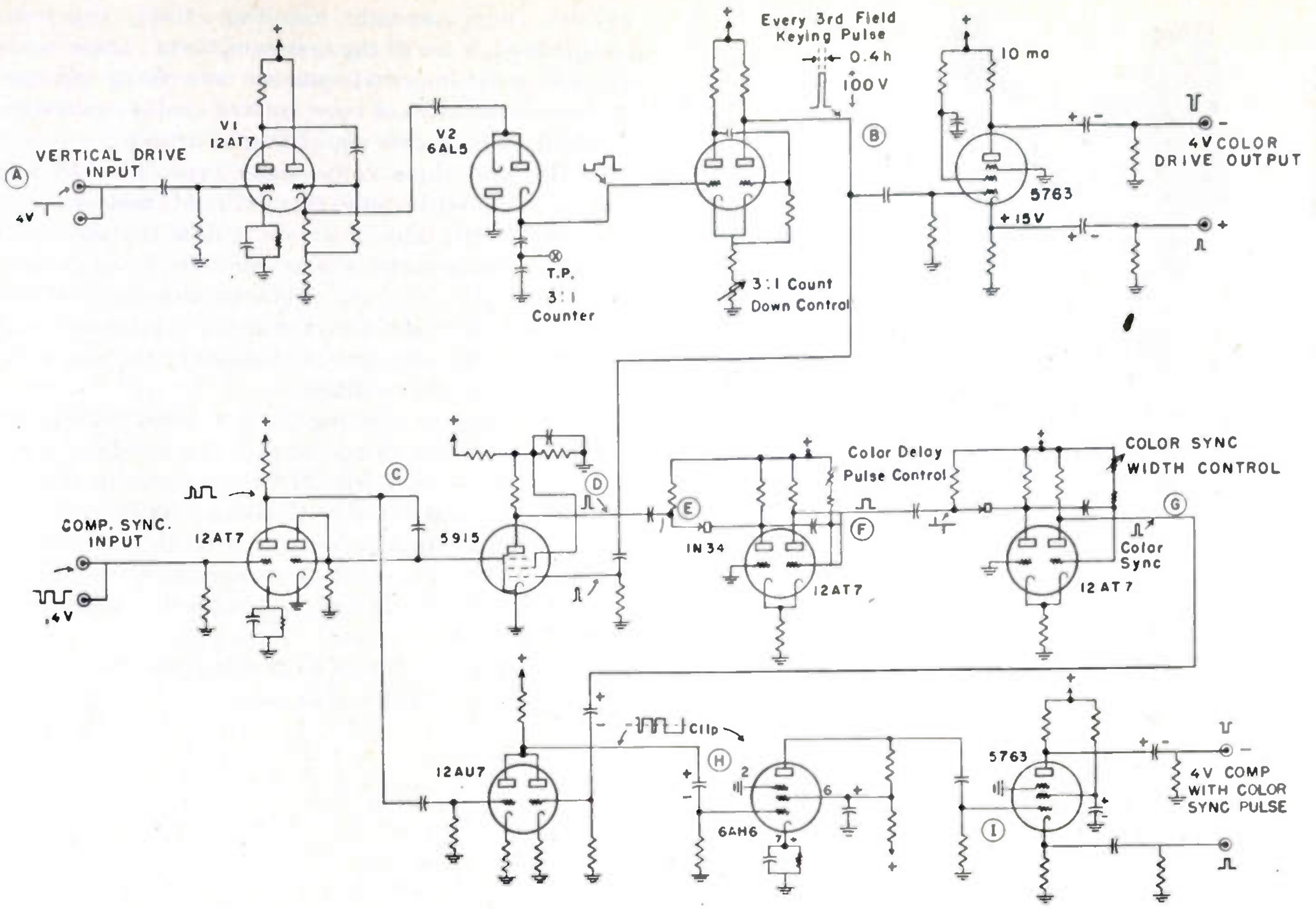

Fig. 23(a)

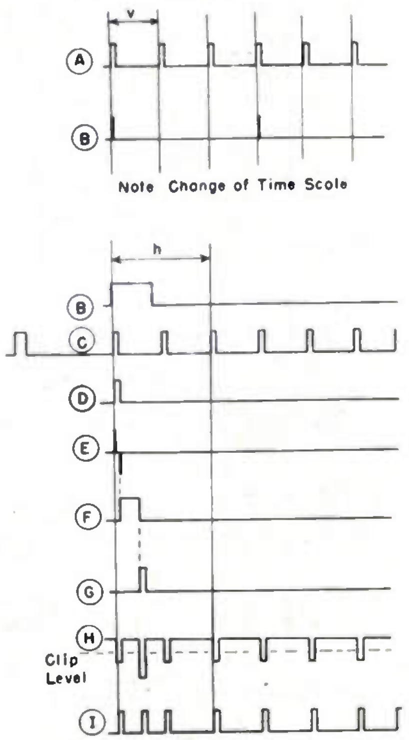

Fig. 23(b)

Fig. 23—A method of adding color sync pulse to composite sync signals.

(a) Shift the master oscillator horizontal scanning frequency to 58,320 cps.
(b) Change the cathode bias resistors of the counters so that the first three counters count down 9-9-5 to give the 144-cps vertical triggering pulse, and the fourth counter counts down 3 to 1 to give the color triggering pulse.
(c) Install three double triode miniature tubes on a small shelf mounted between terminal boards. These generate a color drive pulse and a color synchronizing pulse, both at a 48-cps rate. The color drive pulse is used for two purposes: first, to provide a trigger pulse for the color mixer red-gating circuit so that the red video channel is always properly identified (to be further described later); second, to provide a variable time delay to center exactly the timing of the color synchronizing pulse between the first and second equalizing pulses.

The color synchronizing pulse is introduced over an unused terminal and cable connection into the pulse shaper unit, where it is mixed with the composite synchronizing signal.

The above describes an earlier method of generating a color synchronizing pulse, and while convenient, it is not satisfactory when using step counters since there is excessive time delay between the front edge of the original 58,320-cps trigger pulse and that of the 48-cps pulse from the fourth counter.

A more recent method is indicated in Fig. 23. A sufficiently wide color drive pulse *b* is generated to gate in only the first equalizing pulse of every third field. This single equalizing pulse, which does not shift in time phase, is used to trigger the color delay multivibrator. The resulting pulse is in turn differentiated and its trailing edge is used to trigger the color synchronizing pulse multivibrator. The width of the delay pulse thus controls the start of the color pulse generator, and the width of the color synchronizing pulse can then be adjusted to the required value of 0.04 *H*. The color synchronizing pulse should be properly centered between the first and second equalizing pulses through the use of a trigger-time-base oscilloscope.

It is preferable to supply power for the filaments and the master oscillator lock-in from a small 144-cps generator driven by a synchronous motor. This avoids 60-cps phase modulation in the generated pulses due to poor filament grounds or common cathode-filament ground returns. Three miniature tubes on a small subchassis are used to generate a 60-cps comparison pulse for afc locking. This unit counts down 12 to 1 from the 720 pulse per second output of the second counter. In some conversions a 4-to-1 and a 3-to-1 counter were used to obtain the 12-to-1 ratio with better stability. No problems were encountered in operating synchronizing signal generators expressly designed for color standards on a 60-cps power source.

2. *Synchronizing Signal Pulse Shaper.* In order to produce the pulse width required for the higher scanning speeds, *RC* changes are necessary in all the multivibrator pulse generating circuits. Pulse slopes with fast enough time-of-rise to meet FCC standards as shown in Fig. 1 can be obtained without difficulty. To inject the color synchronizing pulse directly into the synchronizing pulse mixing and clipping circuits, a miniature tube is mounted on the chassis with its plate circuit connected in parallel with the composite synchronizing pulse mixing tubes.

3. *Camera.* Two major changes are required in the camera:

(a) A new horizontal scanning circuit to supply the higher scanning power necessary for camera tube deflection.
(b) The addition of the color disk to the front end of the camera with accompanying mechanical modifications of the focusing mechanism.

The horizontal scanning circuit used in the second and third conversions has proved entirely reliable in extensive use in industrial color camera equipment. This circuit is shown in Fig. 24. The normal output transformer is replaced with a specially designed transformer using grooved textolite and formex forms placed over dual three-mil laminated hypersil cores.

Instead of the +360-volt unregulated source normally used, the damping tube is used to provide a rectified boost voltage. This avoids any 120-cps ripple component that might cause a 24-cps phase jitter in the horizontal scanning. As in black-and-white service, a scanning current of 1 ampere peak-to-peak is normally required. This circuit, however, is capable of supplying a linear scanning current of 1.3 amperes peak-to-peak, which allows sufficient overscanning to prevent burn-in of the mask on the target.

Installation of the color disk drive assembly requires that the lens turret and light trap be moved forward and that the front face plate of the camera be replaced. To permit lenses to be focused to infinity, the back edge of the camera tube bakelite mask retainer ring is undercut by approximately ⅛ inch. This allows the tube to be pushed sufficiently forward into the focus coil assembly.

The color disk, which rotates at 720 rpm, is mounted directly on the end of a one-quarter inch shaft which extends lengthwise through the top portion of the

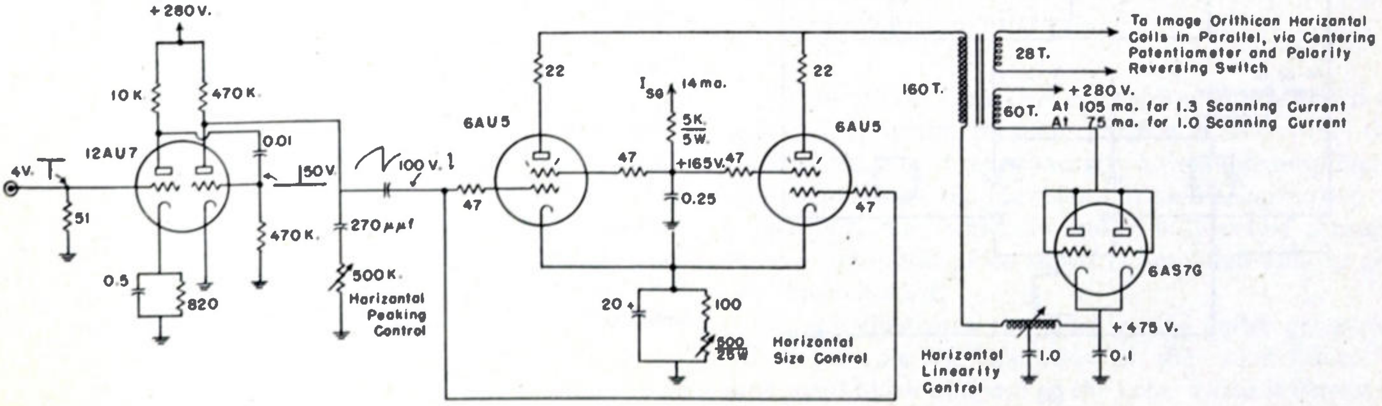

Fig. 24—Horizontal scanning circuit for image orthicon tube used in RCA camera converted for color and in industrial color-television camera.

camera and runs in oilite sleeve bearings mounted on the new front face plate and the rear of the camera chassis. At one end of the shaft is mounted a twelve-tooth sprocket which is coupled to a six-tooth sprocket on the motor by means of a Gilmer timing belt (mold No. 9164). The motor is a one-hundredth horsepower salient pole synchronous type (Cyclohm model No. SWC2914-10). It operates from a 48-cps, 115 volt, 25 watt amplifier located in the color mixer chassis. This arrangement permits continuous electrical phase adjustment. Proper phase adjustment occurs when the spokes of the disk, separating adjacent color filters, coincide with the locus of the scanning beam in the camera tube. This condition is necessary in order to avoid color carry-over from one field to the next. Since the optical image is inverted on the photocathode and the raster is therefore scanned from bottom to top, it follows that the disk, as viewed in Fig. 20 must turn clockwise. To meet the colorimetric requirements discussed previously in this paper, No. 25 red, No. 47 half-density blue, and No. 58 three-quarters density green color filters are used.[6]

[6] These numbers refer to the published transmittance characteristics for Wratten filters.

4. Camera Viewfinder. The circuit modifications in the viewfinder are of a minor nature, mostly involving *RC* changes. The original deflection yoke and transformer may be retained if the horizontal coils of the yoke are reconnected in parallel in order to obtain a sufficiently fast retrace. This is required since the narrow image orthicon target blanking derived from the vertical and horizontal driving pulses is used for blanking of the picture tube in the viewfinder.

5. Camera Control Unit. In this unit it is necessary to:

(a) Substitute a 7RP4 picture tube for the 7CP4. This provides a brighter picture as is desirable for monitoring in color.
(b) Add a high voltage supply of at least 10,000 volts (for the 7RP4 picture tube).
(c) Modify the horizontal scanning circuit.
(d) Provide mechanical modifications necessary to mount the new tube in place.
(e) Move the front panel controls to provide space for a color disk and its enclosure in front of the picture tube.

Not all of these changes are necessary if the original 7CP4 picture tube is used as a monitor in black-and-white (color standards without color disk). In this case it is advisable to include a picture monitor in color in the color mixer.

With this latter arrangement, i.e., black-and-white monitoring of the color picture, the camera control unit need be modified only as follows:

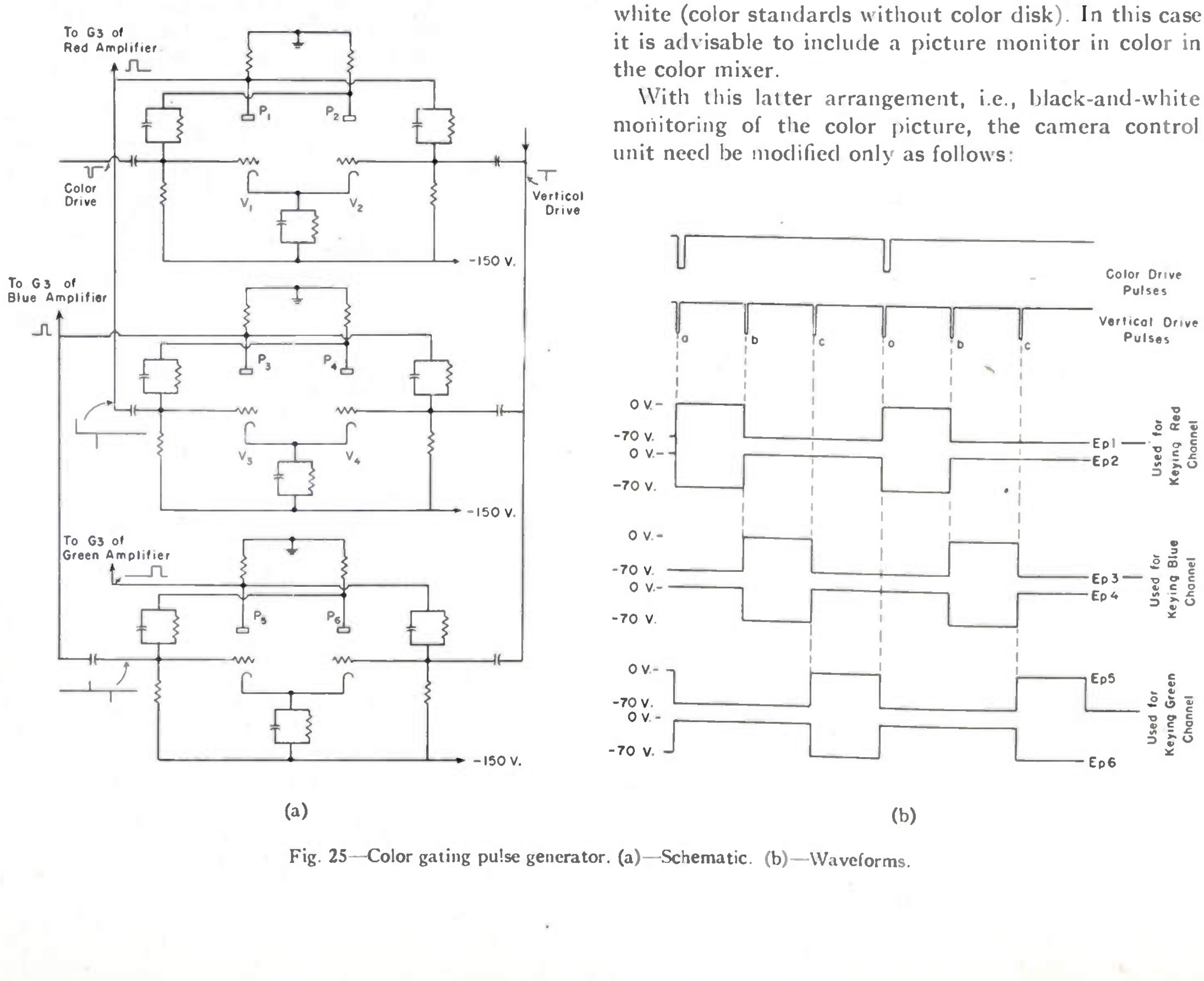

Fig. 25—Color gating pulse generator. (a)—Schematic. (b)—Waveforms.

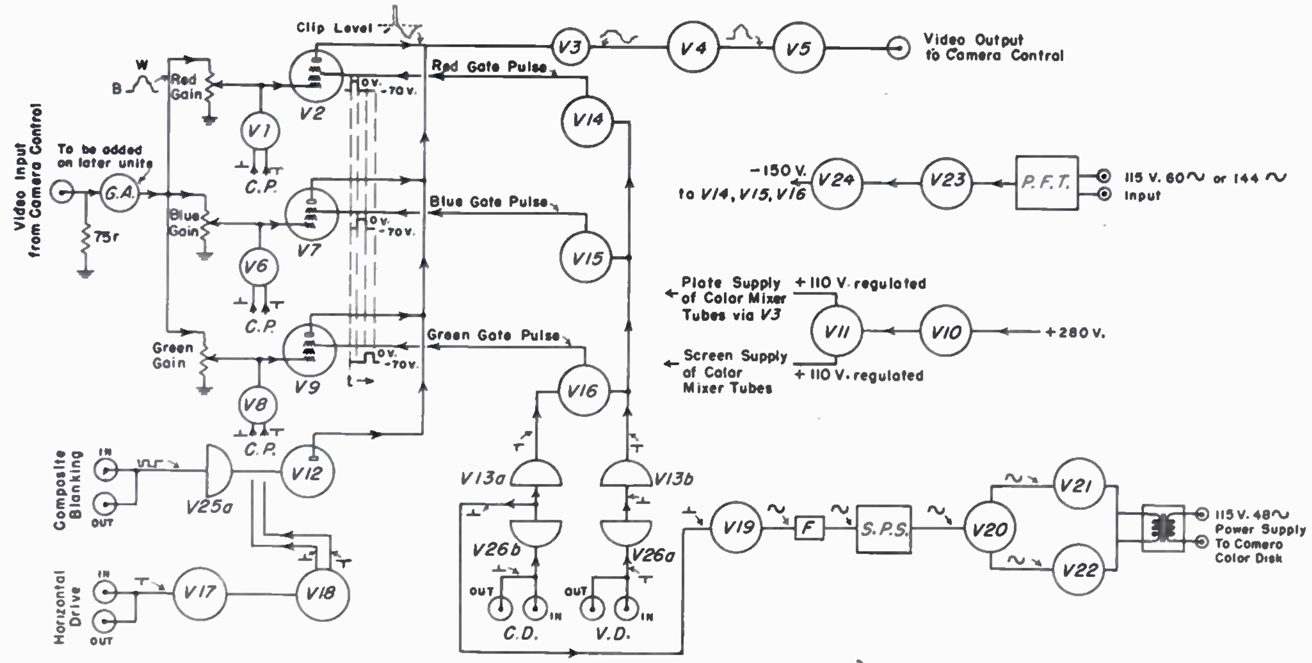

Fig. 26—Color mixer added to RCA camera chain converted for color.

Legend

C.D. = color drive
C.P. = clamp pulses
F. = filter
G.A. = gamma amplifier
P.F.T. = power and filament transformer
S.P.S. = selsyn phase shifter (continuous rotation)
V.D. = vertical drive
V1 = 6AL5 diode clamper
V2 = 6AU6 red amplifier
V3 = 6AL5 clipper
V4 = 6AC7 amplifier
V5 = 6AG7 output
V6 = 6AL5 diode clamper
V7 = 6AU6 blue amplifier
V8 = 6AL5 diode clamper
V9 = 6AU6 green amplifier
V10 = OB2 regulator
V11 = 12AT7 voltage regulator
V12 = 12AT7 clipper amplifier
V13a = 6J6 amplifier
V13b = 6J6 amplifier
V14 = 6J6 flip-flop
V15 = 6J6 flip-flop
V16 = 6J6 flip-flop
V17 = 12AT7 amplifier
V18 = 6AQ5 output
V19 = 12AU7 square wave generator
V20 = 12AT7 amplifier
V21 = 6L6 push-pull
V22 = 6L6 push-pull amplifier AB₁
V23 = 6X5GT rectifier
V24 = VR150 regulator
V25a = 12AT7 amplifier
V26a = 12AT7 amplifier
V26b = 12AT7 cathode follower

(a) Connect the output of the fourth video stage to an output jack by means of a 6AG7 tube with a low impedance plate coupling circuit. The signal from this point may be passed through an external connection to a color mixer, for color mixing and injection of blanking. The signal is then returned to an input jack on the control unit, where the signal is further amplified in the normal manner. Since blanking is not used in this camera control unit, tube V8 can be removed and the additional 6AG7 tube can be installed in its place.

(b) Parallel the horizontal yoke coils and install a new horizontal output transformer of the type used in color receivers. These circuits should be powered from the regulated dc supply. The boost winding should be used to provide the additional plate voltage required

(c) Provide a definite color sequence presentation on the waveform monitor so that both the amount of red, blue, and green video signals and the blanking constants can be observed and individually adjusted. The 48-cps color drive pulse can be applied to the synchronizing circuit of the vertical sweep, preferably through tube V6, connected as a cathode follower. This provides the necessary isolation to prevent kick-back into the color drive circuits.

6. *Color Mixer Unit.* One color mixer unit is added to each camera chain. Its main purpose is to channel the video signal into three separately adjustable amplifiers, each amplifying only one color and each being turned on sequentially, i.e., when the image is televised through the red filter, the video signal is amplified only in the red video channel.

Fig. 25 illustrates the color gating pulse generator which controls the operation of the color mixer. A functional block diagram of the color mixer is shown in Fig. 26. The color mixer, front view and rear view, is shown in Fig. 27. A view of this unit with cover removed is shown in Fig. 28. In this unit composite receiver blanking is injected in the normal manner, clipped, amplified, and, if so desired, returned to the camera control unit for further addition to synchronizing signals.

For the accurate rendition of delicate color shades a gamma correction amplifier is incorporated to compensate for the compressed black output of the typical kinescope (light output versus signal input).

The 48-cps, 115-volt power required by the camera disk motor is derived as follows: The color drive pulse actuates a multivibrator to generate a 48-cycle square wave, which is converted to a sine wave by filtering out all harmonics above 48 cycles. The resultant signal is coupled through a selsyn motor to a push-pull output amplifier. A standard 5,000-ohm output transformer is used to couple the amplifier to the camera disk motor. The selsyn mentioned above permits convenient and accurate adjustment of the color disk phase with respect to camera scanning. The circuit arrangement for the camera disk motor power supply is also shown in Fig. 26.

Fig. 29—Studio 57 stage with two color cameras.

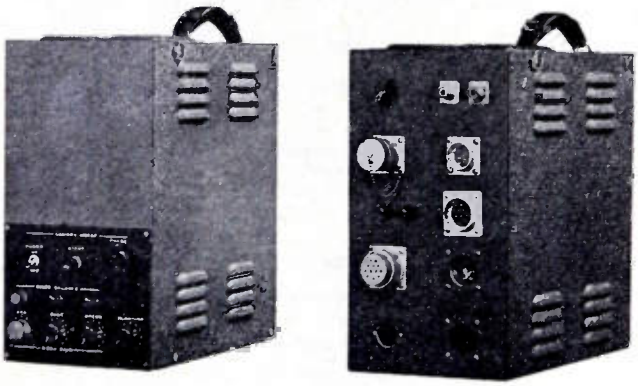

Fig. 27—Color mixer for RCA camera chain converted for color, front view and rear view.

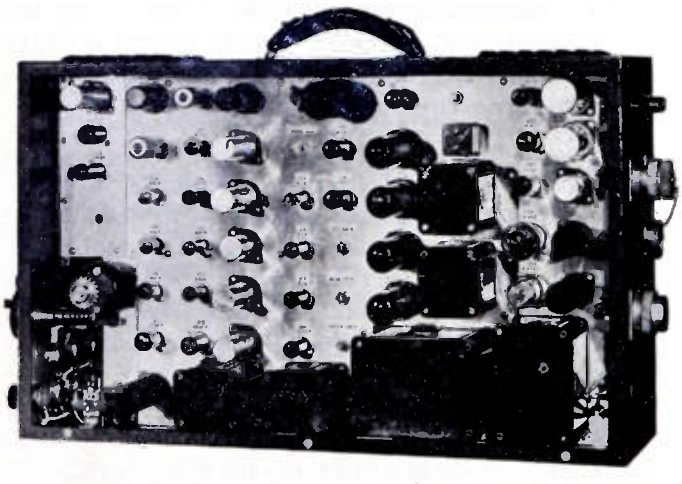

Fig. 28—Interior of unit of Fig. 27.

7. Regulated Power Supplies. Originally, additional filtering was required on the +360-volt unregulated terminal since power from this terminal was used for horizontal camera scanning. In later conversions, however, only the horizontal scanning circuit of the viewfinder is operated from this terminal and the horizontal camera scanning is connected to the regulated source. If a slight amount of 120-cps ripple in the 360-volt terminal causes interference in the horizontal scan of the viewfinder, a small 4 h, 80 ma, choke in conjunction with a 10 μf, 600 W. V. condenser will prove helpful.

8. General Considerations. No difficulty should be experienced in operating the entire camera chain from a 60-cps source if a synchronizing signal generator originally designed for color television is used and if common cathode-filament leads and all inadequate ground leads are eliminated. As an alternative, a synchronized 144-cps motor generator can be used to power all filaments and the synchronizing generator shaping units. A 1,500 watt unit is adequate for a two-camera chain.

The interlock circuits should be so connected that the regulated supplies of the two chains can be turned on only if the separate power input for the filament transformer is energized (with either a 60-cps or 144-cps, 115-volt source).

Identical procedures to those used in monochrome may be employed in operating and adjusting the camera control and tube voltages of the color chains.

B. Film and Slide Scanning Equipment

One method of color film scanning has been described in detail in the *Journal of the Society of Motion Picture and Television Engineers*.[7] Another method makes use of an intermittent type motion picture projector to project the color film through a shutter directly onto the image orthicon photocathode through filters.

The projector is a monochrome type used for 16 mm film at 24 frames per second. The projector is driven by a synchronous motor and is thereby locked to the 144 cps field rate of the color system. Between the projector lens and the color camera rotates a light shutter[8] which has a multiple of three slots. If the shutter rotates at 48 rps, three slots are required, and the width of each slot is such that the duration of exposure is less than the vertical blanking time. This shutter is also driven by a phaseable synchronous motor. The proper red, blue, and green color filters cover the shutter openings, and the projector and shutter disk are so phased with respect to the camera scanning that successive red, blue, and green color images are flashed onto the camera tube photocathode only during vertical retrace times. The pull-down time of the projector is of short enough duration so that the film moves 24 times per second only during portions of the active scanning period. During the latter, however, the light from the projector is cut off by the opaque sections of the slotted disk.

Two methods have been used to scan color slides. One, using an image-dissector tube, has been described[7] together with the film scanning method. In this arrangement, the slide projector and its color disk replace the film scanner; the images are projected directly onto the photocathode of the dissector tube. The second method consists simply of projecting the color slides at a predetermined low light intensity[9] directly into a conventional image-orthicon-equipped color television camera.

C. Studio Lighting for Color Television

In general, flat lighting over the entire stage area gives best results for color television. A certain amount

[7] Bernard Erde, "Color television scanner," *Jour. Soc. Mot. Pic. & Telev. Eng.*, vol. 51, p. 351; October, 1948. This scanner uses an image dissector tube and continuously moving film.

[8] It may have only 1 slot if the filters are in the camera.

[9] The light intensity is low relative to that required for the dissector.

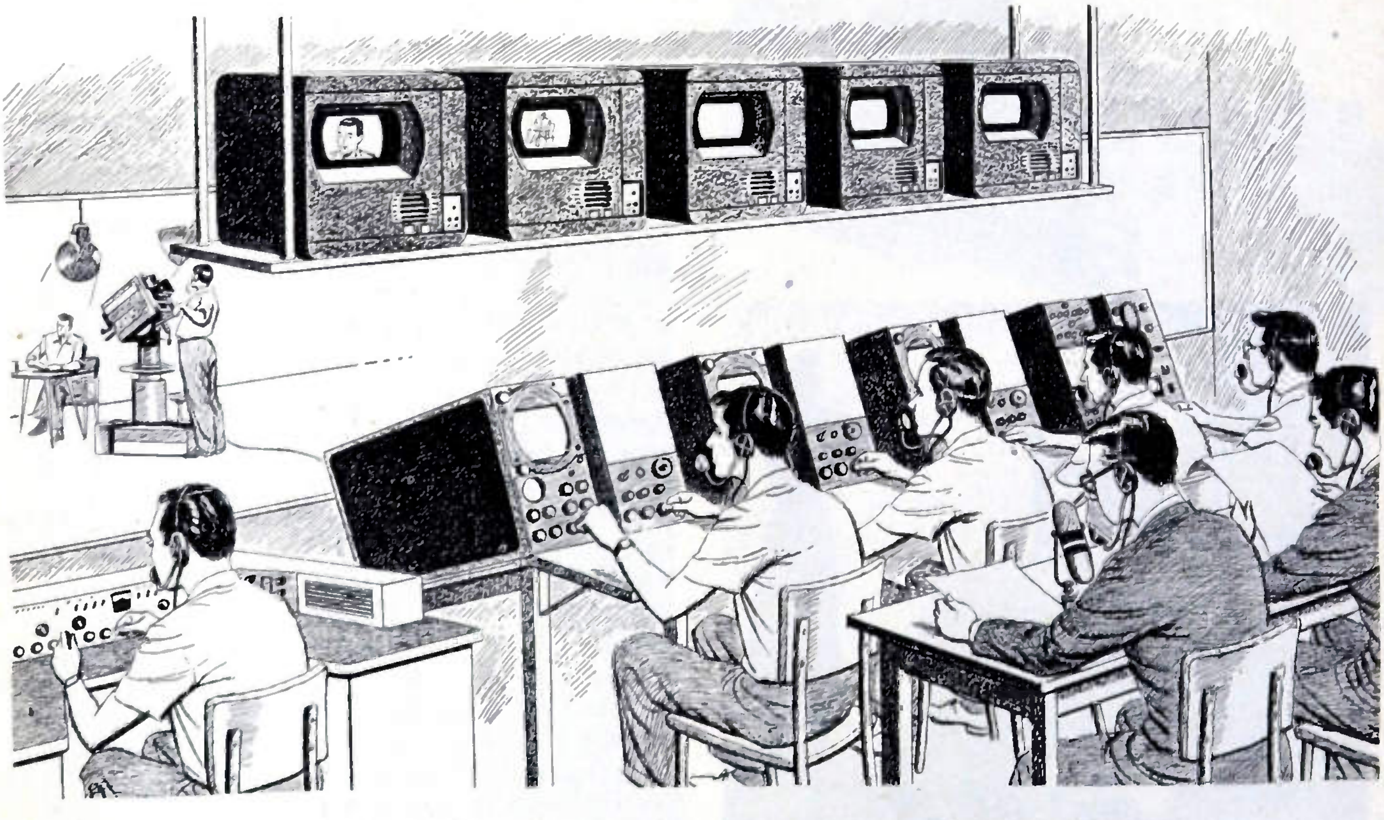

Fig. 30—Sketch of Studio 57 control room showing the director, assistant director, technical supervisor monitoring operators, and monitoring equipment.

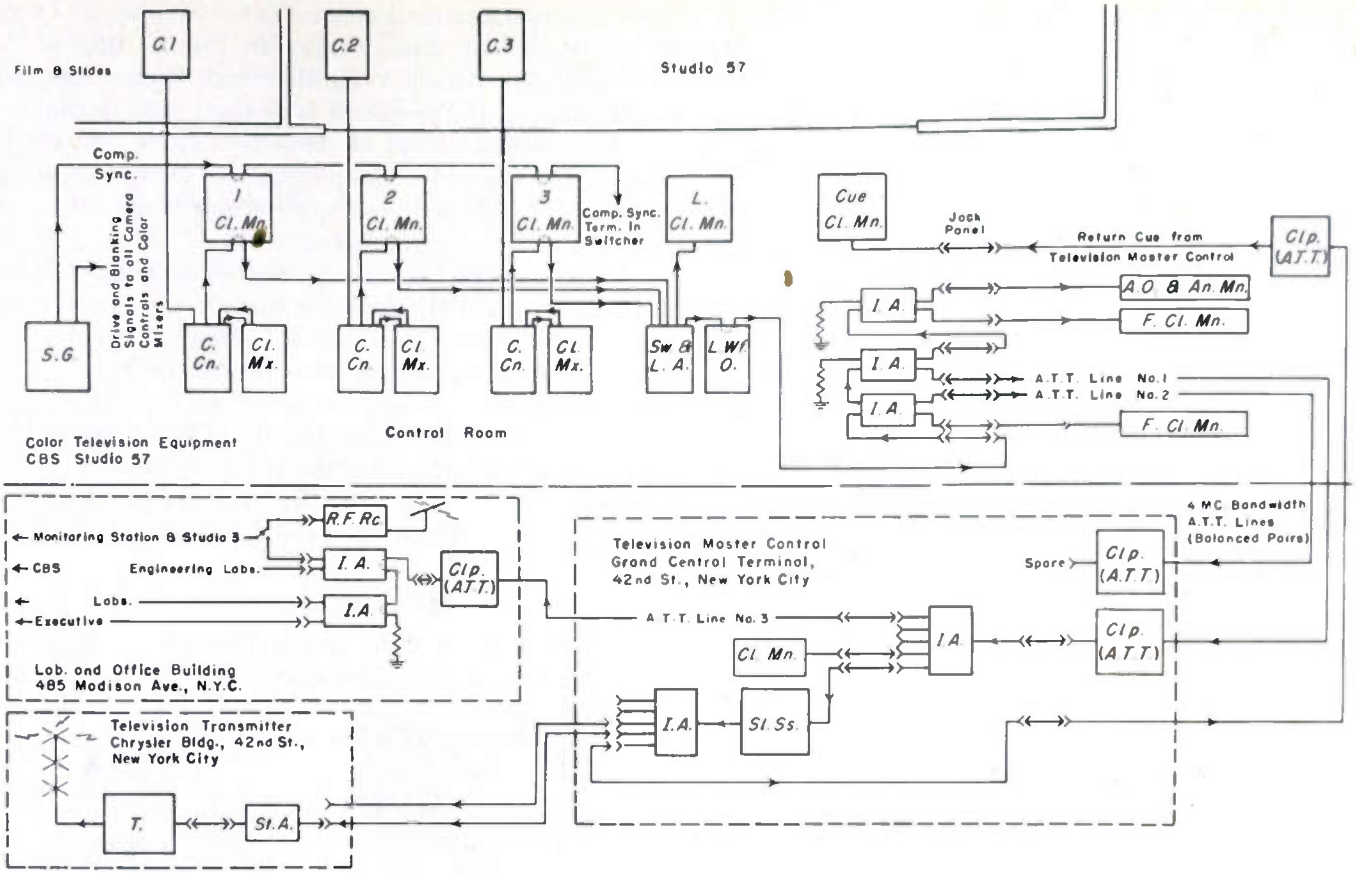

Fig. 31—Color-television signal distribution system, block diagram.

A. O. & An. Mn. = audio operator, announcer and monitor
C. = camera
C.CN. = camera control
CL.MN. = color monitor
CL.MX. = color mixer
CLP. = clamper
COMP. = composite
F.CL.MN. = floor color monitor
I.A. = isolation amplifier
L.WF.O. = line waveform oscilloscope
L.CL.MN. = line color monitor
RC. = receiver
S.G. = sync generator
SL.SS. = selector system
SW. & L.A. = switcher and line amplifier
ST.A. = stabilizer amplifier
T. = transmitter

Fig. 32—Industrial color-television equipment; camera and control console.

of modeling may be desirable, in which case ordinary spotlights are satisfactory.

For over-all flat key lighting 3,500° K (white) fluorescent lighting is excellent. The advantages of this type of key lighting are that it contains no infrared, is relatively shadowless, generates little heat, and is relatively efficient. The fluorescent lamps for key lighting can be operated from a standard three-phase 60-cycle supply but must be connected in such a manner that all three phases are represented in any three adjacent bulbs.

Spotlights for modeling should be infrared corrected. This can be accomplished by means of one-inch strips of Aklo No. 3962 glass (or equivalent) placed in front of the spotlight. The strips prevent the Aklo filter from cracking with absorption of radiated heat.

If incandescent lighting with a color temperature of approximately 2,900° K is used, it is advisable to provide infrared filtering by using a No. 3962 Aklo polished

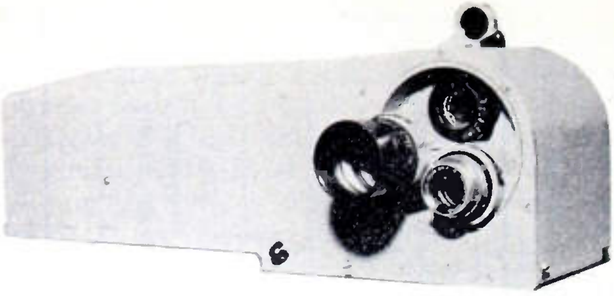

Fig. 33—Industrial color-television camera, front view. Tripod not shown.

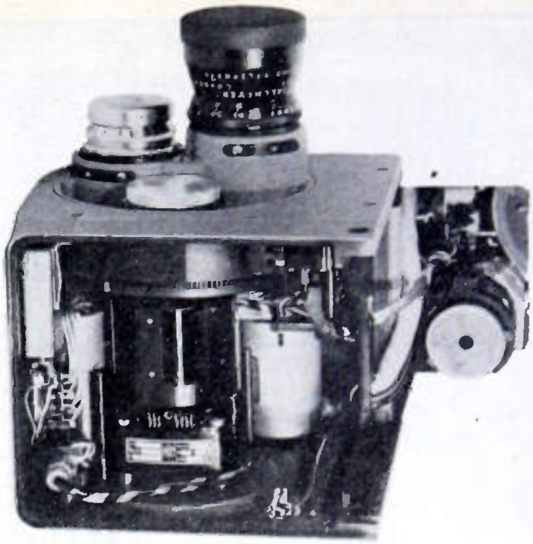

Fig. 35—Industrial color-television camera with color-disk drive.

glass filter between the camera lens and image orthicon tube. Since each Aklo filter attenuates the visual spectrum by approximately 50 per cent, it is preferable, when possible, to employ the newly developed interference heat filters. One type already tested, known as type EK-227, passes the visual range with an efficiency of almost 90 per cent, while the infrared energy is attenuated by 91 per cent.[10]

Standard photofloods furnish satisfactory lighting for color studio use, but naturally are short-lived. In most cases infrared filtering is not required with this type of lighting. Lamps used in clusters and floor strips provide an excellent source of light. These have color temperatures of approximately 3,200° K and require only mild infrared correction.

As to light-level requirements, experience has shown that 200 foot-candles infrared-corrected incident light will permit sufficient stopping down of the camera lenses to provide an adequate depth of focus. On the other hand, an $f/2$ lens and 20 foot-candles of corrected incident light will produce an acceptable color picture.

[10] If the infrared sensitivity of image orthicon tubes were sufficiently low, it would be possible to dispense with infrared filters.

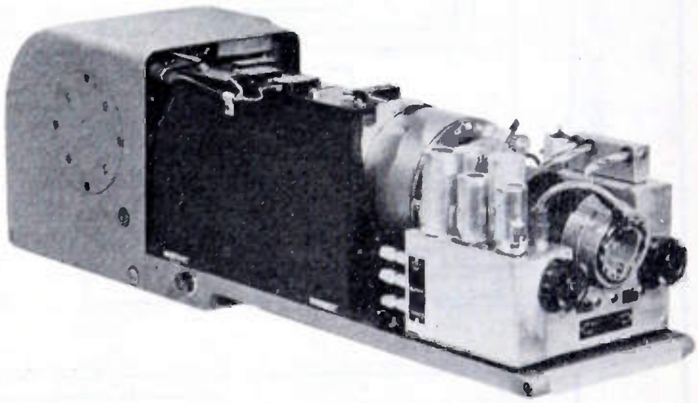

Fig. 36—Industrial color-television camera with preamplifier, dynode power supply, and image orthicon focus and alignment coils.

Fig. 34—Monochrome and industrial color-television cameras.

Fig. 29 (see page 1306) shows two color cameras in operation in CBS Studio 57. The left camera takes long shots while the camera on the right is used for closeups.

Fig. 30 (see page 1307) is a sketch of the control room. In the upper portion are shown the color monitors, one each for the live cameras, slide projectors, film cameras, and one for monitoring the outgoing picture. The operator at the extreme left controls the audio console; the next three operators control the video. Each of these also operates a color mixer in order to assure optimum color fidelity. The remaining indicated personnel are the director, the assistant director, and the technical supervisor.

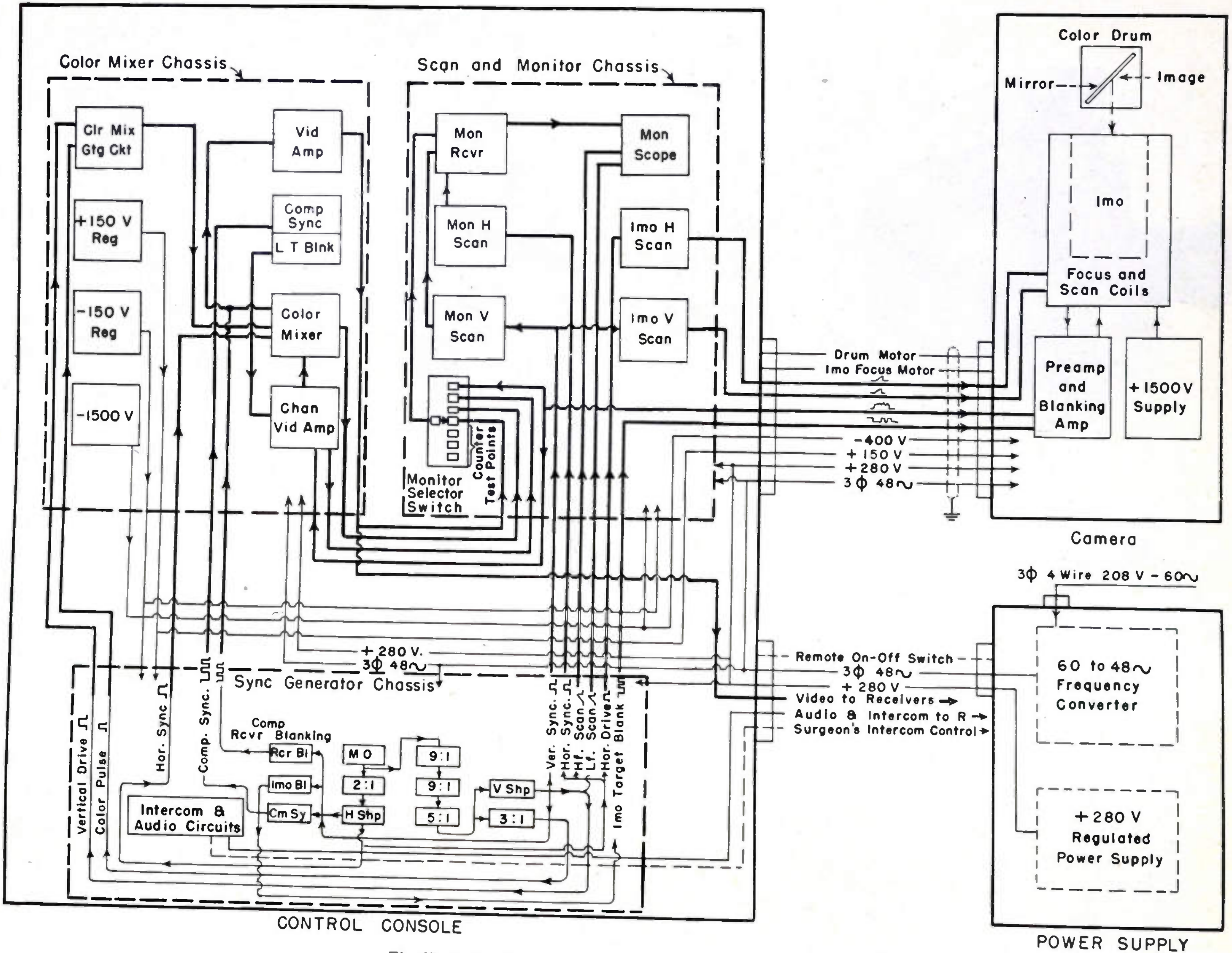

Fig. 37—Industrial color-television equipment, block diagram.

Fig. 31 (see page 1308) is a block diagram of the video signal distribution system. Each camera has an associated camera control, a color mixer, and a color monitor. Several color monitors are used to permit program cueing, timing, and over-all checking.

The outgoing signal is transmitted over video lines of the telephone company from Studio 57 at 108th Street and Fifth Avenue to TV Master Control at Grand Central Terminal in New York City. From there the signals are distributed to network stations and to the WCBS-TV television transmitter in the Chrysler Building.

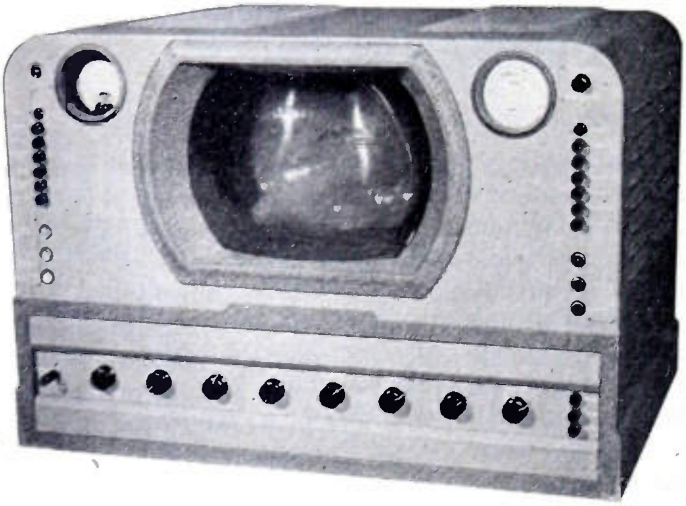

Fig. 38—Industrial color-television monitor console (cover closed). Note—The oscilloscope in the upper right corner shows red, blue, and green signal amplitude levels.

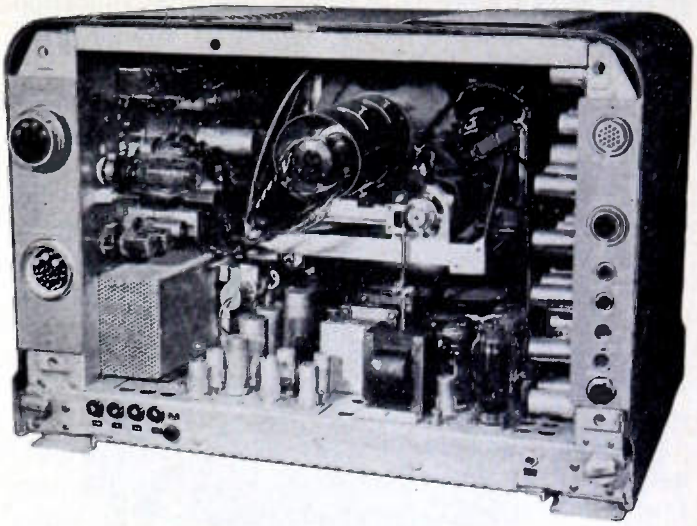

Fig. 39—Rear view of Fig. 38 showing 3-chassis construction.

D. *Motion Picture Color Photography of Color Television*

Motion picture color photography of color-television images has been accomplished and is described in the literature.[11]

IV. Industrial Color Television

Since the advent of industrial television, its uses have expanded enormously, and with the addition of color there seems to be no limit to the number of ap-

[11] W. R. Fraser and G. J. Badgley, "Motion picture color photography of color television images," *Jour. Soc. Mot. Pic. & Telev. Eng.*, vol. 54, p. 735; June, 1950.

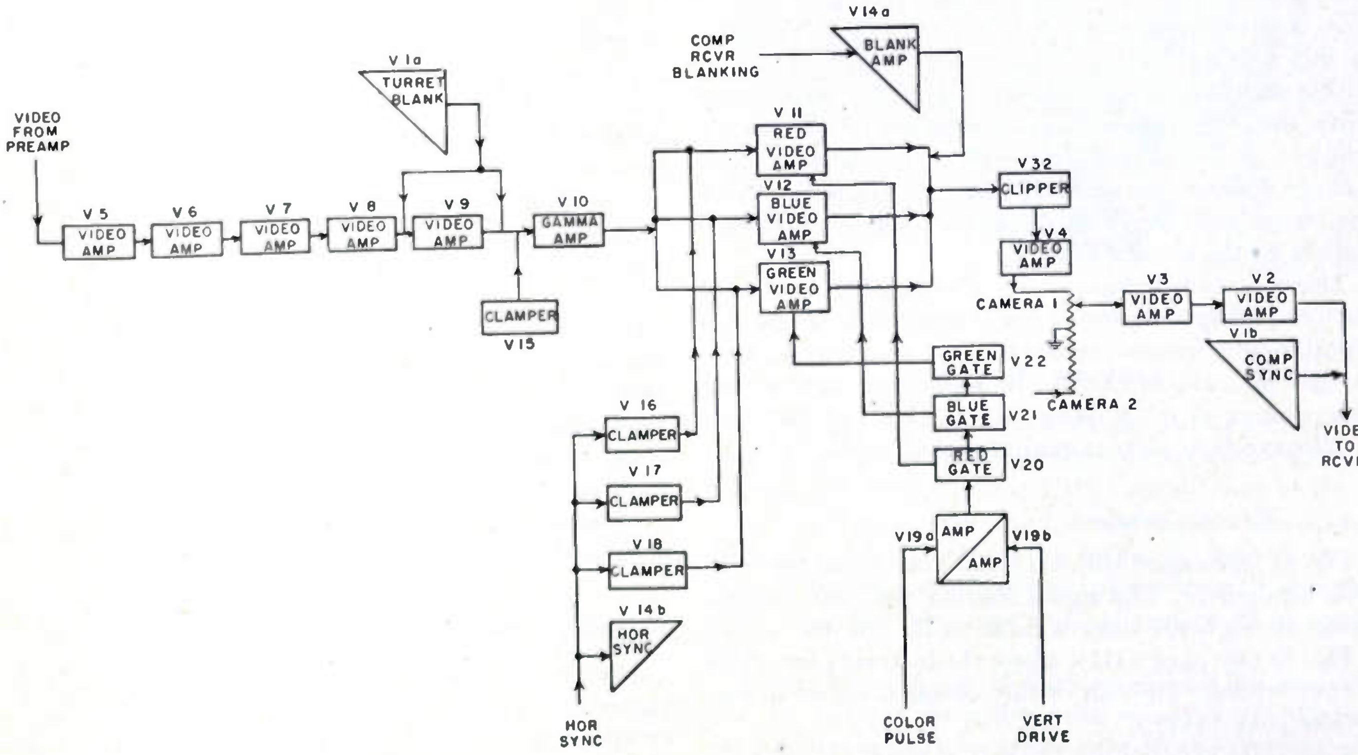

Fig. 40—Color mixer and related circuits, block diagram.

plications it will satisfy in science, medicine, education, industry, and government. Industrial equipment is essentially closed-link equipment designed with emphasis on ruggedness and reliability. Such equipment, designed by CBS, is now available and is marketed by Remington Rand under the trade name "Vericolor."

Fig. 32 (see page 1308) shows the industrial color camera with its control console. Since it is desirable to reduce camera weight and size to a minimum, the camera control equipment, synchronizing signal generator, waveform monitoring, etc., are all located in the control console. The color monitor in the console and the optical view-finder at the camera take the place of a color viewer at the camera.

The industrial color camera (exclusive of the tripod) weighs only 43 lbs. As illustrated in Fig. 33 (see page 1309), it is unusually compact, being only 23 inches long by $7\frac{1}{2}$ inches by $7\frac{1}{2}$ inches. Fig. 34 (see page 1309) is a comparison photograph of a monochrome television camera and the CBS industrial color-television camera. Figs. 35 and 36 (see page 1309) are interior views of the industrial color-television camera.

Camera focusing and lens selection are remotely controllable from the control console. Any one of three lenses in the turret may be selected by pressing the corresponding button. Full focusing range control is provided for the 83-mm and the 135-mm lenses; for the 9-inch lens two lens-shifting steps of 1 inch each are provided on the camera turret in conjunction with a remotely controlled continuous travel range of $1\frac{1}{2}$ inches.

A small synchronous motor operating at 1,440 rpm drives the $2\frac{1}{2}$-inch diameter color filter drum.

The output voltage of the camera in normal use is approximately 0.3 volt peak-to-peak. This is derived from a self-contained preamplifier. The first two tubes in this unit function as normal wide-band amplifiers with a small amount of degeneration in the cathode circuits; the output stage is a conventional triode cathode follower. A compact 3 kc, 1,500 volt supply with its voltage divider furnishes all the voltages required by the image orthicon tube. A 25-foot cable connects the camera to the control console.

This color camera has proved to be extremely valuable for live pickup in color at low illumination levels. Acceptable color images can be obtained with only 45 foot-candles of incident, 3,500° K fluorescent light and a lens opening of $f/3.5$. With incident light of 100 foot-candles excellent picture quality is obtainable.

A. The Control Console

Fig. 37 (see page 1310) is a block diagram of the complete equipment. The signal leaving the color camera passes through the camera cable to the console, shown in Fig. 38 (see page 1311), where the following functions are performed. (The rear of the console is shown in Fig. 39 (see page 1311).)

1. Amplification of the video signal.
2. Reinsertion of the high frequencies lost in the camera, the connecting cable, and the input circuit of the console.
3. Electrical separation of the video signals representative of the three colors in the color mixer so that each may be controlled independently as to brightness and video level (color mixer).
4. Recombining the controlled video signals.
5. Amplification and mixing of the synchronizing pulses with the video signal.
6. Remote control of camera focus.
7. Remote control of camera lens selection; signal automatically blanked during motion of the lens turret.
8. Complete color picture monitoring of the outgoing signal.

B. General Circuits

Fig. 40 (see page 1311) is a block diagram showing the functions of the color mixer and its related circuits. The video amplifier consists of five tubes, *V5* to *V9*. It is of conventional design with a bandwidth of 10 megacycles. A conventional equalizing circuit is located in the plate load of the first stage. Tube *V1* is used to generate a blanking signal which momentarily blanks the video amplifier at *V8* and *V9* whenever the turret selection button is pressed. Tubes *V11* to *V13* inclusive and *V15* to *V18* inclusive operate as conventional clampers in maintaining the desired black level during the blanking signal period.

C. Color Mixer

The signal from *V9* is coupled to a gamma control amplifier, the output of which is branched into three identical amplifiers. A gain control is located at the input of each of these units. Gating is performed by a rectangular wave of 1/144 second duration at the color repetition rate (48 cps) which originates in the ring circuit to be discussed later. In the circuit shown, tube *V11* is the amplifier for red, *V12* for blue, and *V13* for green, each tube controlling only one primary color. Composite blanking, the amplitude of which may be adjusted, is superimposed on the plates of these tubes. The output is amplified and coupled into a voltage divider, which is used as an output gain control. Finally, after passing through two video amplifier stages, the video signal is mixed with the synchronizing pulses to form the final output signal.

Pulse shapes and relative phases from the gating ring circuit are shown in Fig. 25.

D. Sweep Circuits

The sweep circuits for both the image orthicon and the monitor color tube are of orthodox design with the exception of the special horizontal output transformers used.

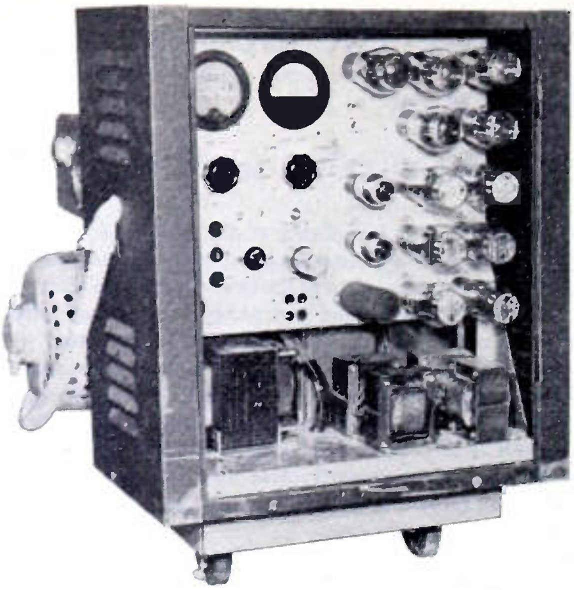

Fig. 41—Frequency converter and power supply regulator.

E. Audio Equipment

The audio circuits are mounted on the synchronizing signal generator chassis. They provide amplified intercommunication between the video operator, camera man, director, and remote locations such as classrooms in other buildings. A control tube *V31B* acts as a remotely controlled switch, allowing extra earphones to be connected across the intercommunication circuit. If, for instance, a medical student watching an operation in a classroom wishes to ask a question of the surgeon in the operating room, he pushes a button located on the intercommunication headset at the color receiver. This connects the surgeon's hearing-aid-type earpiece across the intercommunication circuit. The surgeon answers the question over the regular program channel, using a miniature microphone in his mask.

The audio circuits in the console also provide amplification of the audio program. A two-channel microphone input and +8VU level balanced output are provided. These can accommodate the surgeon's microphone and two additional microphones.

F. Power and Control Circuits

To effect an over-all simplification of the equipment, 48 cps power is obtained from a motor-generator set, shown in Fig. 41, operable from a 60-cps, 3-phase, 4-wire, 208-volt supply. Two hundred eighty volts dc at 1 ampere is obtained from a conventional regulated power supply which is mounted with the motor generator on a portable assembly.

A switch on the console remotely controls power to the entire equipment. Power for field excitation of the motor generator is applied approximately twenty seconds after the main switch closes by means of a time-delay relay.

Maintenance and operational checks are facilitated by both a meter on the regulated supply and test connections at the motor generator.

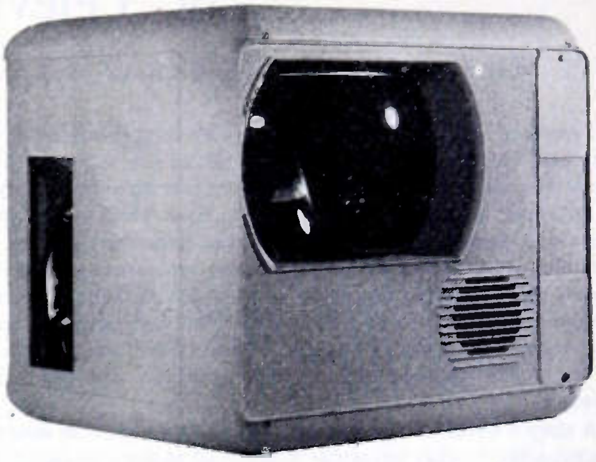

Fig. 42—Industrial color-television monitor.

G. Color Monitor

Fig. 42 is a photograph of an industrial color-television monitor showing an intercommunication handset recessed at the left rear of the console. Fig. 43 shows the chassis construction and arrangement of this unit.

Fig. 43—Industrial color-television monitor chassis.

Acknowledgment

This paper in many ways is intended as a tribute to that handful of tireless and enthusiastic workers, namely, the people of the CBS Laboratories Division, who helped to develop the CBS color-television system from its modest start in the spring of 1940 up to the time it became the national color-television standard after gruelling hearings and exhaustive comparative tests.

To the management of CBS we express our appreciation for their never-failing faith in our work. Without their generous and courageous support this new industry would not have been born.

A New Technique for Improving the Sharpness of Television Pictures*

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Summary—In conjunction with the CBS color-television system a method has been developed for improving the apparent picture definition, called "crispening." It uses nonlinear circuitry to decrease the apparent rise time of an isolated step input which is applied to a bandwidth limited system. This gives the color-television pictures (with the exception of repetitive patterns representing frequencies beyond system cutoff) the appearance of having been transmitted through a system of greater bandwidth. The basic idea is to add to a waveform with a slow transition a second waveform, representing the difference between the desired waveform and the original waveform.

A simple circuit is described which utilizes nonlinear means for reforming the roughly triangular differential of the step signal into a narrower "spike," roughly triangular in shape, which is superimposed on the original waveform to obtain a response corresponding to about half the original rise time. Various crispening circuits have been designed for specific applications and will be discussed in more detail.

These crispening circuits can be applied to standard monochrome pictures. The resultant increase in sharpness, however, would be less apparent because of the law of diminishing returns. The doubling of the bandwidth, that is, halving of the rise time (which is the effect of crispening) will be less apparent in the already high-resolution monochrome pictures than in the lower resolution color pictures.

Various subject matter and test patterns as photographed from the screen of color receivers are shown for 4.5-mc cutoff with and without crispening and for a system flat to 10 mc without crispening. Waveform photographs show the performance of a crispening circuit for step or short-pulse inputs applied through a low-pass filter of approximately 2-mc bandwidth simulating the behavior of the coaxial-cable television network. Also discussed are applications to home television receivers, to coaxial-cable and radio-relay networking, and to other possible uses.

The effect of crispening circuits on signal-to-noise ratio is discussed. Generalized analysis of performance is impractical because circuit designs of different operational characteristics are possible. Nonlinear operation makes "frequency response" meaningless and mathematical evaluation of a specific design difficult.

The Appendix shows an arrangement demonstrating that a gain in steepness greater than 2 to 1 is possible with more elaborate circuits.

I. Introduction

When viewing television pictures, the observer trying to follow the action has little time to delve into any particular area of the picture and focus his attention on any one fine detail, unless the detail is stationary and of some special importance. Nevertheless, an observer will always be able to tell whether a picture is sharp or fuzzy. Experience has shown that pictures appearing sharp do not necessarily contain extremely small objects, objects so small that they require the ultimate bandwidth of the system. It is the sharpness of objects almost always greater than one or two picture elements which matters, and the purpose of this paper is to report on a method rendering outlines of such objects sharper, corresponding to, roughly, double the bandwidth. The over-all impression of such a picture with sharper outlines can be called crisp. The special circuits capable of obtaining such an appearance with a limited bandwidth have been called "crispening circuits."

In the CBS field-sequential color-television system the horizontal resolution is a little over half that of standard monochrome television. In the technique to be described, outlines of objects wider than a single picture element can be made as sharp as the maximum sharpness possible in standard monochrome pictures as far as the horizontal direction is concerned. Naturally, because of the 4-mc video limitation, the smallest object which the color system can now depict accurately in a horizontal direction is equivalent, roughly, to two monochrome picture elements. It is seldom, however, that the over-all sharpness of a picture depends on being able to depict such small objects accurately. As a matter of fact, in such cases, through the choice of proper lens and camera technique, an object, when increased a little over 50 per cent in linear dimension, would have the same definition as in the monochrome system.[1]

At the outset it should be pointed out that crispening has nothing in common with peaking, pre-emphasis, or aperture-correction methods heretofore employed for high-frequency pictorial compensation, as will be shown in the course of this paper.

The relation between bandwidth of a linear system and rise time for a suddenly applied voltage input step is well known. This has probably caused the casual investigator to dismiss the problem of improving rise time as insoluble. However, the well-known relations are confined to linear systems. Improvement of the rise time is possible by means of nonlinear operations performed on waveforms associated with a system of limited bandwidth. Such operations cannot be expected to yield a system output if the system input is a sinusoidal waveform of frequency higher than the limited band-

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[1] The arithmetic mean between the number of alternate bright and dark lines in the horizontal and vertical directions for which total loss of definition occurs is a little over 50 per cent greater for monochrome than for color. (The ratio of the frame frequencies is 2.4 to 1, so that a ratio of linear dimensions of $\sqrt{2.4}$ or 1.55 to 1 would give equal definition.)

width will pass. No new information can be produced at the output, but the original bandwidth-limited information can be changed in its nature.

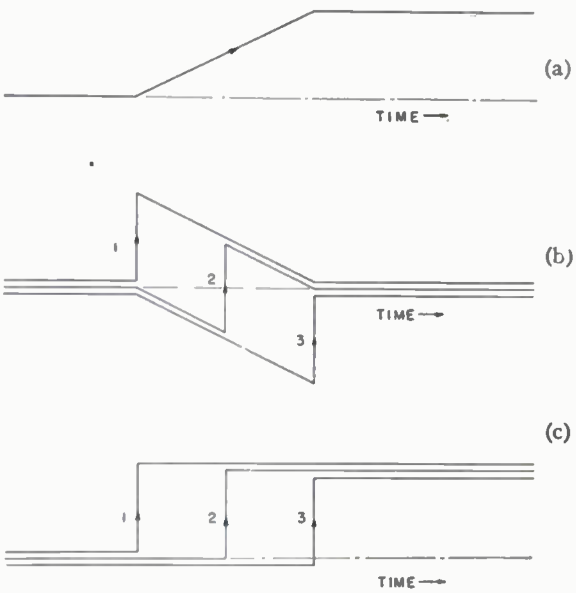

Fig. 1—(a) Waveform of slow transition rate. (b) Added waveform for fast transition rate. (c) Resultant waveform after addition.

In the case of television pictures, high-detail information is, for the most part, of the nature of isolated steps, and only rarely of a repeated nature approximating a steady-state waveform made up of frequency components above the system bandwidth limit. The "crispening" method described in this paper uses nonlinear circuitry to modify the nature of the isolated step response of bandwidth-limited systems. This gives television pictures the appearance of having been transmitted through a system of greater bandwidth than is actually used, except for omission of such high-frequency repetitive patterns, and inability to resolve closely spaced fine lines.

II. Basic Approach

The basic idea is to attempt to add to a waveform having a slow transition a second waveform which represents the difference between the waveform desired and the waveform originally present. Fig. 1(a) shows an idealized waveform of slow transition, and Fig. 1(b) shows a family of curves depicting possible waveforms, any one of which can be added to it to make the resultant have an infinitely fast transition (see corresponding curve in Fig. 1(c)). As a less ambitious illustration, Fig. 2(b) shows a family of curves depicting possible waveforms which can be added to that of Fig. 2(a) to make the resultant have twice the original transition rate (Fig. 2(c)). Any of the three waveforms in Fig. 2(c) can be obtained from that of Fig. 2(a) by the use of the corresponding correction waveform in Fig. 2(b). It will be noticed that the correction waveform of Fig. 2(b) can be of a simple shape, for example, either a negative or positive triangular spike.

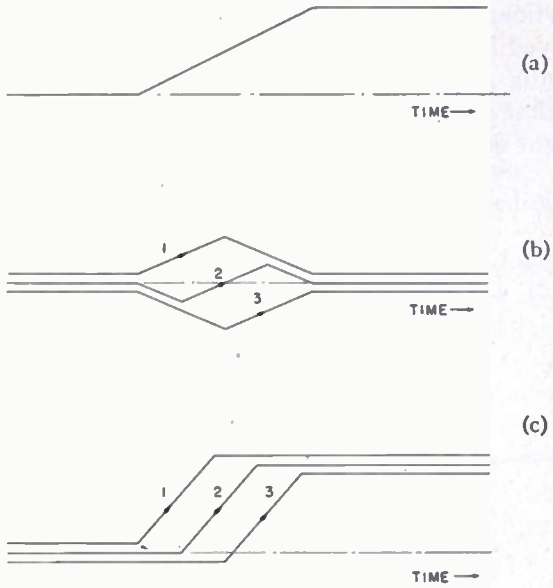

Fig. 2—(a) Waveform of slow transition rate. (b) Added waveform for twice transition rate. (c) Resultant waveform after addition.

In practice, the type of waveform to be corrected would be more like that of Fig. 3(a), the step response of an ideal low-pass filter. Any one of the curves of Fig. 3(b) represents the correcting waveform required to double the transition rate. Thus, the resultant will duplicate the step response of a filter of twice the cutoff frequency. The correcting waveform could be approximated by a negative or positive triangular spike.

The negative or positive differential of the original waveform can serve as a useful approximation. Adding or subtracting the differential increases the transition rate, but it may be accompanied by "over-shoots," which are sometimes undesirable. Looking at it from the corrective waveform standpoint, the added spike is wider than that most desirable.

If the differential of the original waveform is modified, making it less wide by using a nonlinear power-law device (for example, squaring its amplitude for both polarities), a correcting waveform may be obtained, which gives a steepened resultant free from overshoot. But this holds rigorously for only one transition amplitude. If the differential of the original waveform is made less wide by clipping, passing only the peaks of the differential waveform, a correcting waveform may be obtained which also gives a steepened resultant free from overshoot or undershoot. This result also holds true rigorously for only one transition amplitude, unless the clipping action can be made to follow any change in amplitude.

A shortened spike can be obtained from the differential if the latter is made available as the voltage from a low-impedance source which feeds a rectifier having a load consisting of resistance and capacitance in parallel, and the current through the rectifier is used as the output spike. The spike amplitude is then nearly proportional to the transition amplitude. This method is employed in a practical "crispener" to be described. In Appendix A the basic idea will be explored further to show that any degree of steepness correction in isolated transient steps is possible.

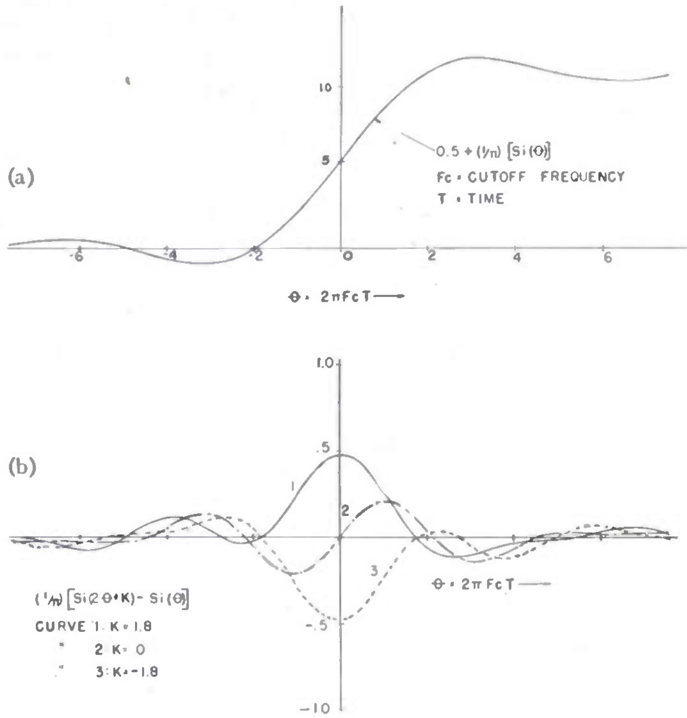

Fig. 3—(a) Transition waveform of ideal low-pass filter. (b) Added waveform for twice transition rate.

III. Applications

Fig. 4 is a block diagram of a simple crispening circuit based on the above method. To insure that a spike can be centered halfway up the slope of the uncorrected waveform, an adjustable delay is included in the main signal path. The frequency response for circuits associated with the main signal path need only be good enough to accommodate all frequencies initially present in the input signal. Preferably, the spike path after the spike has been formed and the circuits handling the combined output should have at least twice the bandwidth of the input signal. Such an arrangement has been used for experimental observations and also has been tested in conjunction with color-television receivers.

In the course of demonstrations of color television originating in New York studios and being shown in cities as far as Chicago, it was desired to apply a similar arrangement to the improvement of pictures transmitted by coaxial cable for which the cutoff frequency was about 2.7 mc. Several units were built for this purpose of a sufficiently versatile nature to warrant giving a detailed description.

Fig. 5 is the schematic diagram of this special crispener. It handles an input of 1.4 volts peak-to-peak including synchronizing pulses, from a 75-ohm line. The output level and polarity into a 75-ohm line are the same as for the input. The circuits for the main signal path and combined output (V_1, V_2, V_3) are flat within 1 db to 6 mc, and 3 db down at 9 mc. The circuits associated with the spike path and combined

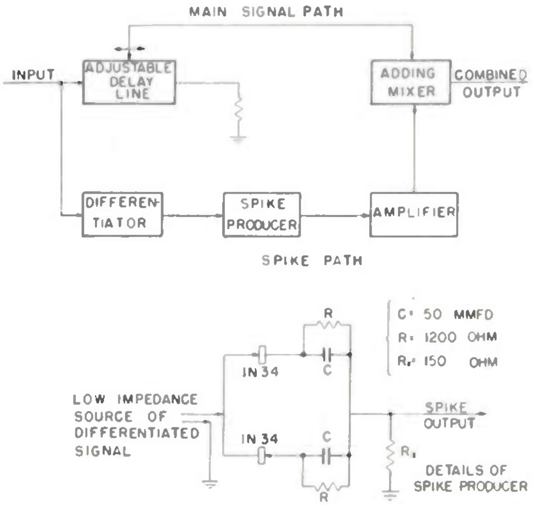

Fig. 4—Block diagram of simple crispening circuit.

output after spike production (V_{11A}, V_{12}, V_{13}, V_3) are flat within 1 db to 8 mc, and 3 db down at 10.5 mc. The main signal path includes a control C_1 to adjust the over-all gain to unity, and a control C_2 to adjust delay in the main signal path, to allow shifting transitions so that the spike falls on the optimum part of the slope. If spikes are not injected, the over-all output is essentially the same as the input, except for delay.

Spikes for either direction of transition are produced by the crystal rectifiers V_9 and V_{10} with their associated RC loads. The input to the spike-producing rectifiers is essentially the differential of the input signal, obtained at low impedance by using a transformer which also serves as the differentiating inductive load for V_{1B}. The spike duration is mainly controlled by the RC values in series with V_9 and V_{10}, although it is also influenced by the frequency responses of circuits both preceding and following the spike formation. The spike path after spike formation includes the tubes V_{11A}, V_{12}, and V_{13}; the plate of the latter is in parallel with the plate of V_2 in the main signal path, at which point the spike is added on to the transition and the combined output fed to the output cathode follower V_3. No control is provided for spike duration. The RC values shown are used for crispening either coaxial-cable television transmissions or transmissions received from a standard television transmitter by a representative television receiver, down 3 db at about 3.4 mc. The capacitors are reduced to 50 $\mu\mu$f when the unit is used to "crispen" pictures transmitted over a circuit that is down 3 db at 4 mc (telephone-company microwave link). Control of spike amplitude is provided by a gain control C_4 associated with the differentiator V_{1B}.

In some applications, these crispeners were used following stabilizing amplifiers, to which a television signal of low bandwidth and long rise time was applied. The stabilizing amplifiers reshaped the synchronizing pulses, causing them to have a much faster rise time, but left the slow rise time of the video signal unchanged. The crispening unit then required a clipper to cut out the synchronizing pulses before producing spikes; otherwise undesirably large spikes were caused by the synchronizing pulses. V_5, V_6, V_7, and V_8 constitute this clipper, the clipping level being adjusted by the control C_3. Naturally, this precaution is necessary only when the signals thus treated are intended for broadcast.

In future applications, a crispening circuit will be built into a suitable stabilizing amplifier, of the type that provides one path for video alone—to which crispening will be applied—and a separate path for reshaped synchronizing pulses alone. It is expected that this will require the addition of six miniature tube envelopes to the stabilizing amplifier, a net economy for applications requiring a stabilizing amplifier in conjunction with a crispening unit.

IV. Results Obtained

In demonstrations of field-sequential color television in cities remote from New York, some of which involved transmissions via standard telephone-company coaxial-cable circuits, use of crispensers gave a definitely more pleasing picture.

Figs. 6, 7, and 8 show, respectively, field-sequential color-television pictures of FCC approved standards transmitted with maximum bandwidth of 4.5 mc (3 db at 3.2 mc) uncrispened, the same crispened, and with a system flat to 10 mc uncrispened, as photographed from the screen of an industrial receiver. Figs. 9, 10, and 11 show the reproduction of a test pattern under the same circumstances. Fig. 12 shows the frequency response of the filter used to limit bandwidth to 4.5 mc.

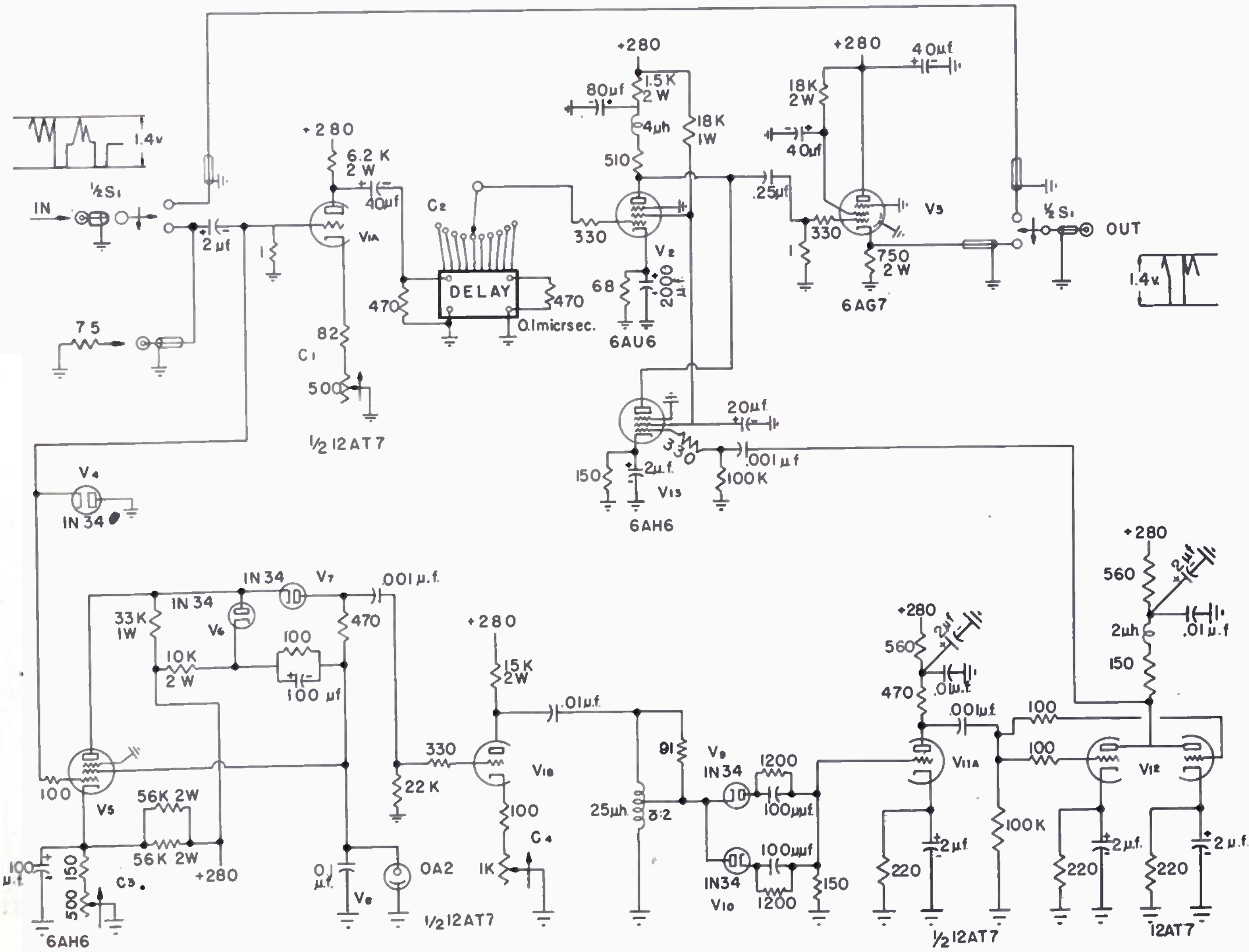

Fig. 5—Schematic of a practical crispening circuit.

Fig. 6—Picture transmitted with 4.5-mc cutoff frequency, uncrispened.

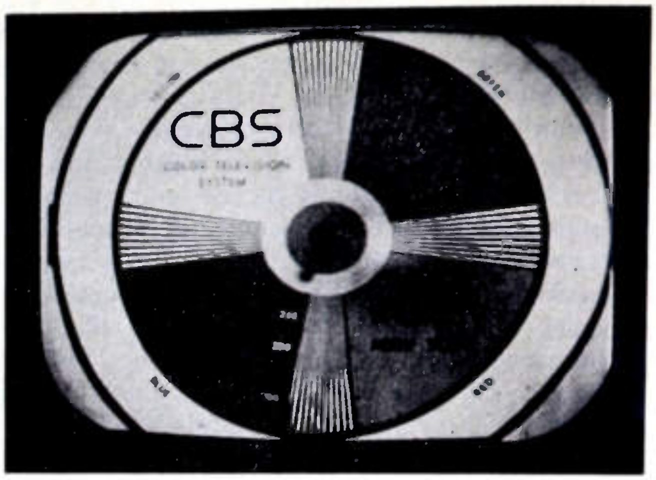

Fig. 9—Test pattern, transmitted with 4.5-mc cutoff frequency, uncrispened.

Fig. 7—Picture transmitted with 4.5-mc cutoff frequency, crispened.

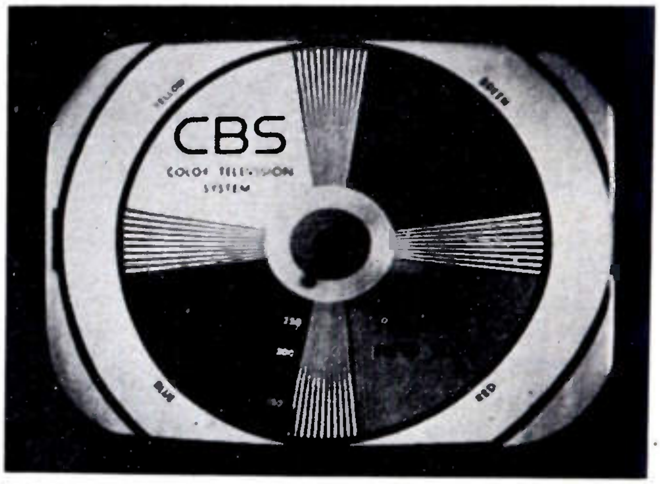

Fig. 10—Test pattern, transmitted with 4.5-mc cutoff frequency, crispened.

Fig. 8—Picture transmitted with system flat to 10 mc, uncrispened.

Fig. 11—Test pattern, transmitted with system flat to 10 mc, uncrispened.

It can be seen that for the narrow bandwidth, even though the fine-detail part of the wedge is not reproduced, the part of the wedge that is reproduced is more clean-cut when crispening is employed; in the photographs of picture material, the edges of objects are delineated in a manner that compares favorably with the 10-mc uncrispened picture.

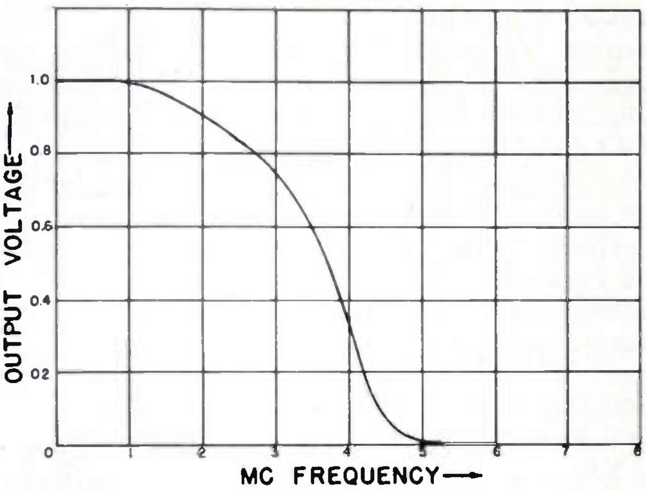

Fig. 12—Response-frequency characteristic of a filter of 4.5-mc cutoff frequency.

Fig. 13 is an oscilloscope picture showing superimposed the normal and crispened waveforms obtained from input steps of different amplitudes where the input steps have been passed through a low-pass filter of 2-mc bandwidth to the 3-db point.[2] The improvement due to crispening is clearly apparent, as well as the extent to which the crispener described achieves a correction independent of transition amplitude.

Fig. 14, taken under the same conditions as those of Fig. 13, shows the normal and crispened waveforms obtained when a square input pulse of $\frac{1}{8}$-microsecond duration is applied. This would give, theoretically, a peak of 48 per cent of the asymptotic response to a long pulse. Doubling the bandwidth would raise the peak amplitude to 87 per cent, an increase of 80 per cent. Fig. 14 shows that the amplitude does not increase appreciably, but that the pulse shape is improved when crispening is applied. Isolated fine-line detail, therefore, is improved in quality by crispening, but is not brought up to the same intensity as with a true increase in bandwidth. Subjectively, however, the improved shape seems to give the impression of somewhat improved fine-line intensity, also.

V. Home Receivers

An interesting application of crispening is in the improvement of color-television picture appearance for home receivers. Considerable simplification is possible as compared to the system of Fig. 5. An experimental arrangement that has been used is shown in Fig. 15. Two double triodes and two crystal rectifiers are added to a conventional receiver. The connections to the added circuit are indicated by dotted lines.

The spikes are produced in a manner similar to that already described for the circuit of Fig. 5. After amplification, the spike is injected into the cathode of the picture tube while the main signal path leads to the grid in the usual manner. If more delay is needed in the main signal path as compared to the spike path, the inductance network that compensates the high-frequency response of the video-output coupling arrangement can be modified, making it into a more extended low-pass filter circuit. The only control shown is for adjustment of spike amplitude.

This particular receiver required only a small voltage range to modulate the picture tube. If more swing were required, a power-output stage might be required for the spike path. To avoid the need for a power stage, an alternative arrangement could utilize a similar chain of stages for crispening, receiving input from the grid of a low-level video stage and feeding spike output to the output of the same stage. Relative delay adjustment could be made by modifying either the input or output coupling network for the low-level stage.

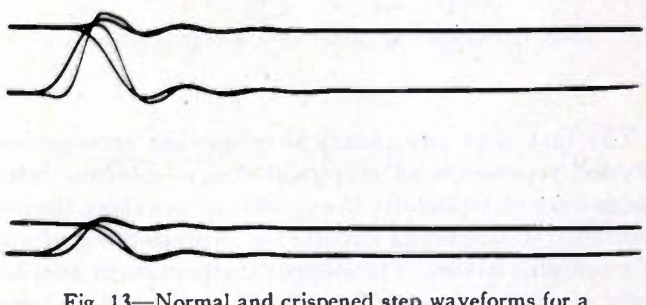

Fig. 13—Normal and crispened step waveforms for a system of 2-mc bandwidth to the 3-db point.

Fig. 14—Normal and crispened $\frac{1}{8}$-microsecond pulse waveforms for a system of 2-mc bandwidth to the 3-db point.

VI. Other Applications

Other applications of the crispening principle may occur to the reader. One application of some interest is in the improvement of the appearance of recorded television transmissions. Crispening can be employed to obtain better over-all sharpness at any point in the system following the film scanner, prior to the transmitter. For this application some control of spike duration would be desirable, in addition to control of spike amplitude.

[2] The choice of a relatively low cutoff frequency (2 mc to the 3-db point) for the input signal makes the waveforms resulting from crispening less subject to modification by bandwidth limitations in the circuits that follow the crispening operation. This choice also represents an approximation to operations with coaxial-cable circuits.

VII. Some Special Considerations

The effect of crispening circuits on the signal-to-noise ratio may be of importance if appreciable noise is present in the picture, either as a result of noise initially present before transmission or additional noise introduced at the receiver. The crispening circuit of Fig. 5 has been found to increase the level of random noise by roughly 50 per cent, which is comparable to the increase in noise that would have resulted from doubling the bandwidth. No exact analysis of the theoretical effect of crispening on signal-to-noise ratio has been carried out; the results would differ depending on the empirical circuitry employed to obtain a practical crispener.

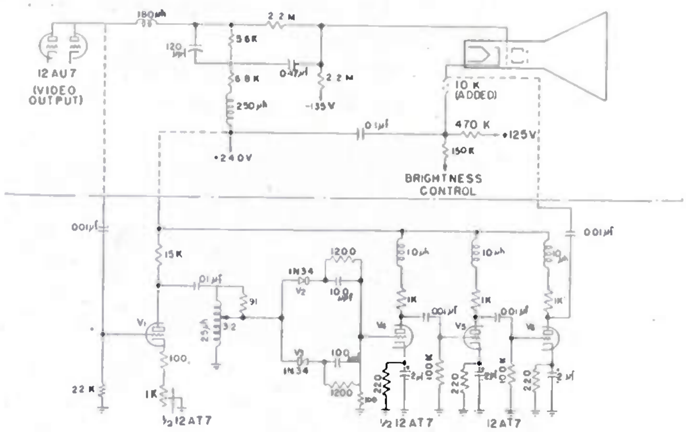

Fig. 15—Crispening circuit for a television receiver.

The fact that any practical crispening arrangement devised represents an empirical-design solution introduces a general difficulty in evaluating, as a class, the performance of crispening circuits for impressed waveforms of a complex nature. The elegant mathematical analyses such as are customary for circuits composed of linear elements cannot be used since there is no unique solution to the circuit-design problem. This is not to say that mathematics cannot be applied to any particular circuit; it can, although the nonlinear behavior introduces difficulty.

"Frequency response" is a meaningless term for nonlinear circuits since, for a given input frequency, the output consists not only of the original frequency but also an infinite series of harmonics, the amplitudes and phases of which vary in different manners with change of the input frequency.

It might be thought that crispening circuits may increase the transition rate to that corresponding to a greater bandwidth than is actually used, not only for sharp brightness transitions in the picture material, corresponding to infinite bandwidth but also for less sharp brightness transitions corresponding to the bandwidth actually used. A system behaving like an ideal low-pass filter with abrupt cutoff at 4 mc would give identical responses for an infinitely steep brightness transition or one having a waveform like the step response of an ideal filter of 4-mc cutoff. The latter response would be the same as that of an infinitely steep transition applied to two ideal low-pass filters in cascade.

Actually, when pictures are scanned, the transition waveforms are not of this shape. They are equivalent to the step response of a circuit having a gradual, rather than an abrupt frequency cutoff. If cascaded with an ideal low-pass filter of 4-mc cutoff, the over-all frequency response falls off gradually up to the 4-mc limit; the amount of rounding that occurs before the abrupt drop at 4 mc depends on the steepness of the original transition. The steepness of the system response, therefore, also varies with the original steepness. When crispening is applied, as with the circuits of Figs. 4 and 5, which add a spike of amplitude and duration dependent upon the steepness of the applied transition, the over-all response slope also varies with that of the original transition. It is true that the degree of sharpness may not be as faithfully reproduced as with a noncrispened system flat to 8 mc. This is due to a crispened 4-mc system having a tendency to introduce a little too much sharpness on transitions having an initial slope corresponding to that of the step response of a low-pass filter of 4-to 8-mc cut-off.

This imperfection is not appreciable in practice since it occurs only on marginal degrees of sharpness in the picture being televised and is outweighed by the advantage of better response sharpness on sharp transitions. Most objects appear either sharp or rounded; in cases where original sharpness is in the marginal region corresponding to step response of a low-pass filter of 4- to 8-mc cutoff, the degree of sharpness is usually of no significance to the observer in identifying the object or appreciating its nature. It is of importance that an initially sharp transition should look sharp. That the imperfection is not apparent is evidenced by the overwhelming preference of observers for pictures with crispening as against pictures without crispening.

VIII. Conclusions

The rise time for the response of a system of limited frequency bandwidth when the excitation consists of isolated steps can be decreased beyond the theoretical limit for a linear system by utilizing nonlinear circuit elements following the point of bandwidth limitation.

Crispening circuits based on this principle can be designed and used to effect a significant improvement in the CBS color-television pictures transmitted through a system with bandwidth limitations.

Such crispening circuits may have other useful applications.

IX. Acknowledgments

Credit is due to members of the Columbia Broadcasting System engineering research department who have

taken part in this development, in particular to Mr. J. J. Reeves who participated in the early experimental work and contributed many valuable suggestions.

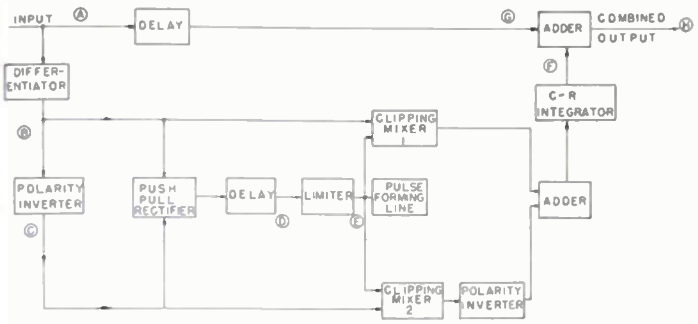

Fig. 16—Block diagram of a method of obtaining more than 2 to 1 increase in transition rate.

Appendix A

More Elaborate Circuits

The relatively simple correction circuit of Fig. 4 is based upon the fact that the waveform to be added to the original to obtain a 2-to-1 increase in slope steepness is roughly of triangular shape and can be approximated by the output of simple circuits. Such circuits were so effective that little need appeared at the moment for pushing the development of circuits giving a higher order of approximation to the ideal performance. It is of interest, however, to see whether an increase of steepness substantially greater than 2 to 1 is possible.

One approach is to use, for the correcting waveform, a nonsymmetrical triangle generated by integration of a short-duration pulse, modulating this pulse in accordance with the amplitude of the differential of the transition and initiating the pulse by the passage of the differential waveform above a small fixed level. Both directions of transition must be accommodated, which introduces further complexity. The block diagram of Fig. 16 shows one method. The waveforms present at various points in this system are given in Fig. 17.

In all waveforms of Fig. 17, the solid lines represent an upward transition at the input and the dotted lines a downward transition. The input signal is shown at A and its differential at B, or after polarity inversion at C. The push-pull rectifier, regardless of transition direction, produces an unidirectional output. This output, shaped like the magnitude of the differential, is used to produce a short pulse, timed to occur near the start of the input transition. For example, feeding the output into a limiter and short pulse-forming line, the waveform of E is produced. The positive pulse can be retained and the negative pulse that follows discarded by clipping in the "clipping mixers." The pulse amplitude and timing is almost independent of the transition amplitude if the level at the limiter is well above the clipping level. In order to center the positive pulse in the middle of the differential waveform B, the input to the limiter is delayed, as shown in D. The time delay shown is $(1/\pi F_c)$, where F_c is the cutoff frequency corresponding to the waveform A.

The clipping mixers modulate the pulse by the magnitude of the differential. Two are provided so as to handle both transition directions; one or the other yields an output. For an upward transition, the differential B modulates the pulse passing through clipping mixer 1. For a downward transition, the inverted differential C modulates the pulse passing through clipping mixer 2, which pulse is then inverted in polarity. In this way, a pulse is obtained at the adder which follows the transition amplitude and polarity, but is very short. The short pulse is then integrated by a capacitor-resistor circuit to obtain an asymmetrical triangular spike, characterized by a fast rise and slow fall dictated by the time constant RC. This spike, shown at F, is then added to the original waveform suitably delayed, shown at G, in order to obtain the resulting output H. The time delay shown is $(0.45/\pi F_c)$. The time constant RC is chosen so that the rate of fall of the spike F would nearly compensate for the rate of rise of the signal G. Thus the output H is only limited in shortness of rise time by the pulse duration of the pulse-forming line. More complex means could be used instead of the simple RC integrator to obtain better compensation.

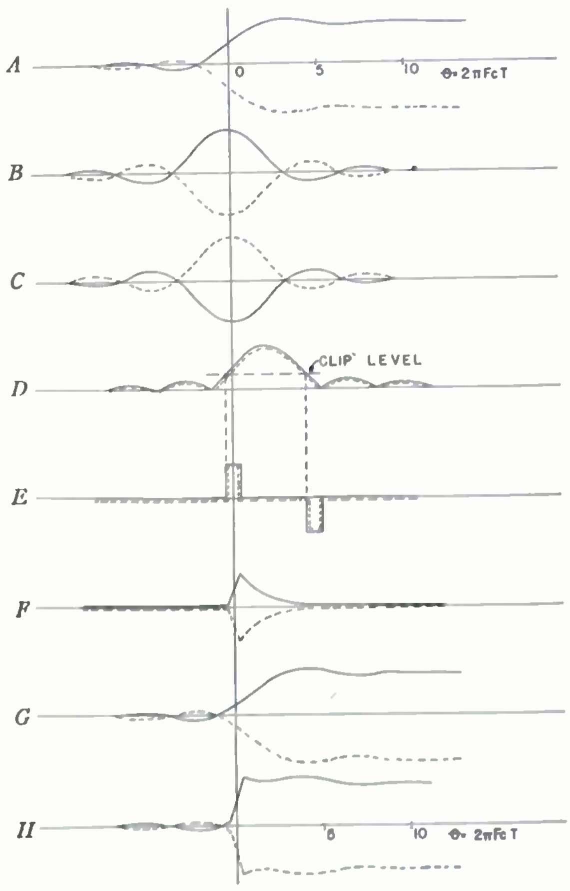

Fig. 17—Waveforms at designated points of Fig. 16.

While Fig. 16 would appear to be quite complex, many of the functions can be performed by simple circuit elements. For example, the differentiator and polarity inverter may be a tapped coil in the plate circuit of a triode, the push-pull rectifier a pair of crystals, and the limiter a 6BN6. For 3.4-mc input cutoff frequency the delay lines are only 0.094 and 0.042 microseconds long.

It can be seen from this example that a decrease in rise time appreciably greater than 2 to 1 is obtainable. The example chosen to demonstrate this point is only one of a number of possible methods; presumably simpler schemes or arrangements of more nearly perfect performance could be devised.

Glossary of Terms

The glossary below gives the meaning of certain terms as used in this paper.

Crispening Decreasing rise time for isolated step inputs, by means of nonlinear circuits.

Crispness In a picture, the degree to which edges of large objects approach discontinuous changes in brightness. For television waveforms, this might be measured as the ratio of active horizontal trace time to the rise time for an isolated step input.

Definition The number of alternate black-and-white lines that can be reproduced by a television system in a distance equal to the picture height. Used here as a single quantity combining vertical and horizontal definition.

Rise Time The time required for the response to an isolated step input to rise from 10 to 90 per cent of the ultimate amplitude.

Steepness The maximum slope of a waveform of unit ultimate amplitude, measured in inverse time.

Transition Rate Inverse of rise time.

The above definitions are given to assist the reader, and are not suggested as standard nomenclature. There is, however, a growing need for a nomenclature that can be used interchangeably in the photographic and electronic fields, in view of the increasingly close relation between the film and television industries.

The photographic concept of "sharpness" was not used in place of "crispness" as used here because, firstly, it would have required translation from the language of inverse distance to that of time ratio and, secondly, the photographic concept deals with the maximum first derivative of a curve, like "steepness" as defined above. The arbitrary nature of the curves obtainable with crispening makes the use of a concept involving rise time preferable to a concept involving the maximum first derivative, which could be large without having a satisfactory curve shape. Another photographic concept, "turbidity," involving the second derivative, was not used here for similar reasons. Attempts have been made[3] to evaluate the subjective impressions obtained from a curve of a given shape, but these were not utilized since a concept of crispness in terms of the generally accepted and readily described "rise time" seemed adequate for the purposes of this paper.

[3] Bedford and Fredendall, "Analysis, synthesis, and evaluation of the transient response of television apparatus," Proc. I.R.E., vol. 30, pp. 453–455; October, 1942.

Spectrum Utilization in Color Television*

ROBERT B. DOME†, FELLOW, IRE

***Summary*—The frequency spectrum of the 6-mc channel, now standard in the United States for black-and-white- or monochrome-television transmissions, may be utilized in several ways for the transmission of color-television images. The three sets of data associated with color-television systems may be transmitted by time-division multiplex, by frequency-division multiplex, or by combinations of these two methods. One of the latter methods, called "alternating lows," is discussed in some detail, and some of the working circuits for this method are presented.**

Introduction

THE 6-MC TELEVISION CHANNEL, now standard in the United States for monochrome or black-and-white television transmissions, may be used in a number of ways for color-television transmissions. It is the purpose of this article to describe some of these.

There are in general, for color television, three sets of data to be transmitted instead of the single set for monochrome. These may correspond to brightness, hue, and saturation, or to three proper primary colors, or to some linear transformations of the latter. If each set of data were transmitted over separate 4-mc channels, a total bandwidth of at least 12 mc would be required. Such a transmission method would not fit in too well with the present vhf channel-allocation plan. It would also cut in half the number of new channels which would be made available in any additional portion of the radio-frequency spectrum opened up for television broadcasting. It is highly desirable, therefore, to see what can be done to utilize to best advantage the present 6-mc channel for packaging color-television signals.

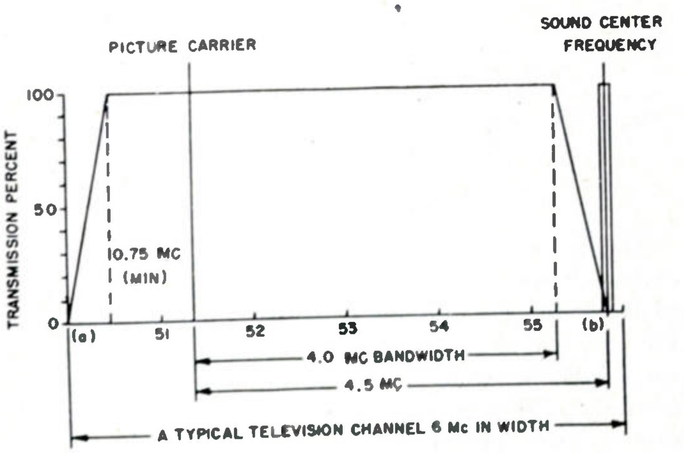

Fig. 1—U. S. standard television channel for monochrome transmission. (a) Transmission at lower edge of channel not greater than 0.1 per cent. (b) Transmission of picture sideband at sound carrier not greater than 0.1 per cent.

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Fig. 1 shows the present channel utilization in black-and-white transmission, with the picture carrier located 1.25 mc above the lower edge of the channel and the sound carrier located 0.25 mc below the upper edge of the channel. When due allowance is made for a guard band for sound-carrier rejection circuits in the picture channel of a television receiver, an upper video-frequency limit of 4 mc is about the maximum that can be made available in a practical receiver. A simple calculation based on this bandwidth and on a frame rate of 30 frames per second shows that, neglecting blanking intervals, the number of picture elements making up the structure of the picture is 267,000. This may be used as a yardstick in determining the structural quality of pictures portrayed by any of the several color-television systems to be considered here.

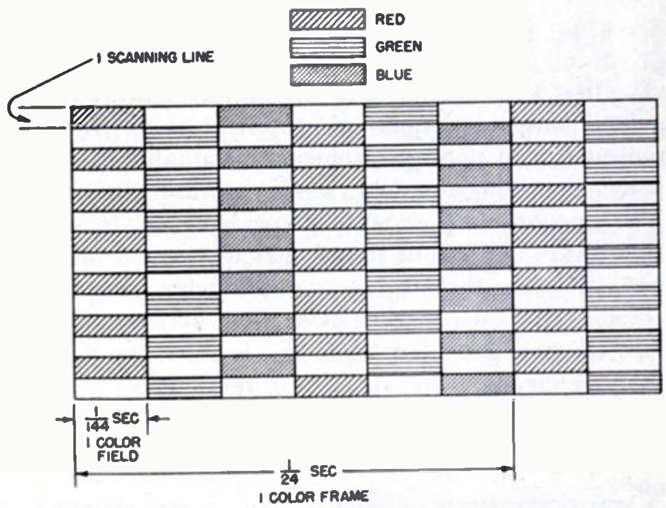

Fig. 2—Field-sequential color-television system.

The multiple data of the color signals must be multiplexed in some manner, and a careful examination should be made of any proposed method or system in order to determine whether efficient use is being made of the available spectrum. Use may be made, therefore, of the known techniques of time-division multiplex, of frequency-division multiplex, or of some combination of the two.

Time-Division Multiplex

Time-division multiplex methods will be examined first. Since only one set of data is being dealt with at any instant, the time allocated to one set of data, before shifting to a second set of data, must be decided upon. Fig. 2 shows that one logical switching point is at the beginning of each new field of scanning, and Fig. 3 shows that a second logical switching point is at the beginning of each new line of scanning. A third switching interval may be at some small subdivision of a line. Such a system is shown in Fig. 4. These three methods of time-division multiplex color television may be recognized by their more familiar names of (1) field-sequential, (2) line-sequential, and (3) dot-sequential color-television systems.

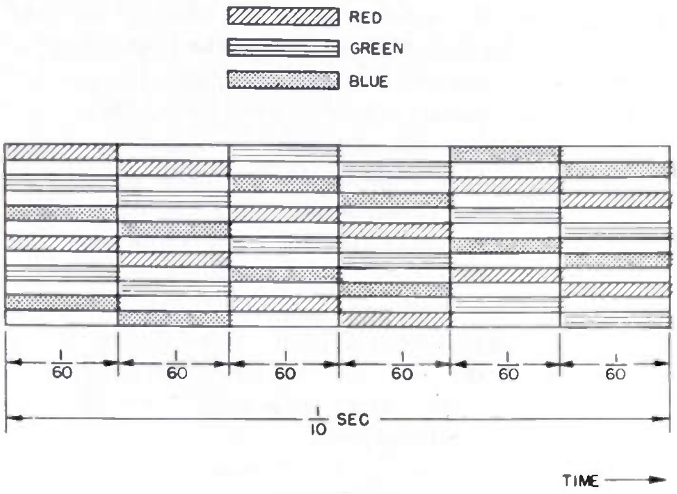

Fig. 3—Line-sequential color-television system.

The first two of these time-division systems, namely, the field- and line-sequential systems, can provide the same quality of picture resolution obtainable in monochrome, providing the field rate is maintained the same as in monochrome (i.e., 60 fields per second). However, if this is done, it will be found that flicker is a problem because it takes three times as many fields to complete a color cycle. To reduce flicker, it is necessary to increase the field rate; but when this is done, the number of picture elements for structural detail is correspondingly reduced so that the resolution becomes degraded as compared to present-day monochrome.

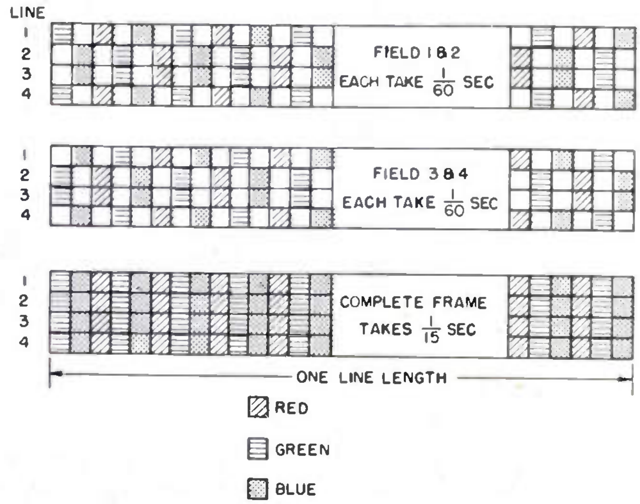

Fig. 4—Dot-sequential color-television system.

The third system, dot-sequential, when accomplished by the combination of sampling and the employment of mixed highs, offers advantages. The mixed-highs principle is that of combining the higher video frequencies associated with each individual color signal by addition and of displaying this signal as shades of gray. The bandwidth gained by employing this principle is considerable when it is realized that the saving amounts to two of the higher portions of the three video-frequency bands. Thus, if the mixed highs include frequencies from 2 to 4 mc, a saving of 4 mc is obtained over a fully simultaneous system. Since a fully simultaneous system would require three 4-mc bands, or 12 mc, the bandwidth is at once reduced to 8 mc. The sampling of low frequencies, when accomplished in horizontal interlace form, saves an additional 4 mc; consequently, the entire signal can be packed into a single 4-mc band.

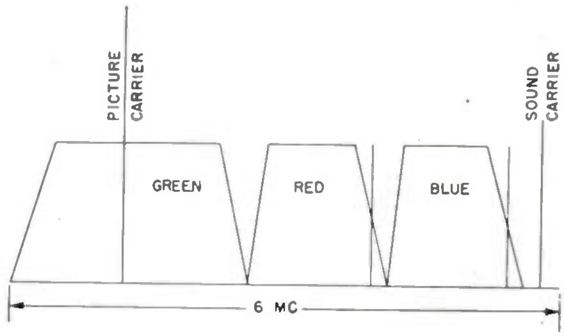

Fig. 5—Simultaneous system employing frequency-division multiplex with no overlap.

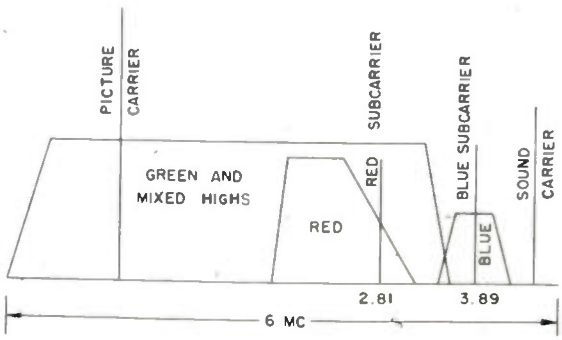

Fig. 6—Spectrum of frequency-interlace system with overlapping mixed highs and red modulated subcarrier.

Frequency-Division Multiplex

The second method of multiplexing is frequency-division multiplex. An obvious way to achieve this is to divide the 4-mc channel into three parts, as shown in Fig. 5. The green component of the image may be carried as direct modulation of the picture carrier while the red and blue components may be carried as modulation on two subcarriers. When no overlapping is employed, the theoretical maximum bandwidth per color (assuming equal bandwidths for each color) is 1.33 mc, resulting in a considerable reduction in resolution. When, however, the subcarriers are chosen to be frequencies of the less visible type, that is, frequencies corresponding to odd multiples of half the line-scanning frequency, overlapping may be employed with the result that resolution practically equal to monochrome may be realized. This last system may be recognized as that which has been named "frequency interlace." Fig. 6 shows how this has been done in an actual investigation of this system.

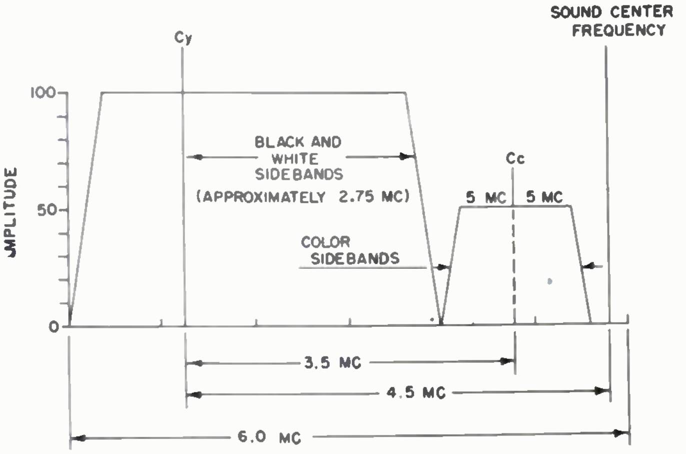

Fig. 7—Color modulation on subcarrier without overlap.

The dot structure present in the reproduced picture in color systems employing complete overlap has led to variants of the dot-interlace and frequency-interlace systems in attempts to reduce dot structure. One such system is shown in Fig. 7. In this system the 4-mc band is divided so that 0–3 mc is employed for the transmission of essentially the brightness signal. Meanwhile, two color-identifying signals are carried by modulation on a subcarrier at approximately 3.5 mc by employing amplitude modulation of an inphase component of the subcarrier for one of the two required color-identifying signals and amplitude modulation of a quadrature component of the subcarrier frequency for the second of the two color-identifying signals. By this system upwards of 75 per cent of the resolution of monochrome may be realized.

Another variant of this system is now under investigation in which it is probable that vestigial sidebands may be employed for the transmission of the color-identifying signals so that an additional amount of

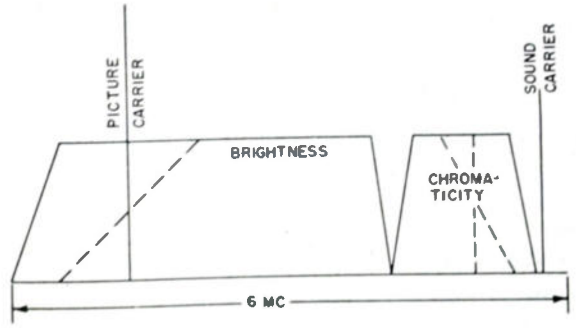

Fig. 8—Nonoverlapping system with quadrature component of subcarrier reversed 180 degrees in phase at end of each field.

band saving may be realized (Fig. 8). It appears that this system may yield upwards of 85 per cent of monochrome resolution, which, for all practical purposes, is scarcely discernible from 100 per cent. In this system, the carrier phase of one of the two-color-identifying subcarriers is reversed in phase at the beginning of each new field of scanning; in other words, on one field the quadrature carrier would be displaced 90 degrees from the other carrier, but on the next field it would be displaced 270 degrees.

These last two systems of color television are essentially nonband-sharing simultaneous systems inasmuch as either reduced overlap or very little overlap of color-identifying signals into the brightness signal part of the spectrum is contemplated. Another approach to the separation of color identifying and structural-detail information so as to avoid the simultaneous use of any portion of the available spectrum may be achieved by combining frequency-division and time-division techniques. Two such systems have been investigated in the laboratories of the General Electric Company. One is known as "alternating lows" and the other as "alternating highs."

Combined Techniques

The alternating-highs method may take on a wide variety of forms, one of which is shown in Fig. 9. During a first interval of time, such as a field or a line, green lows are transmitted as direct modulation of the principal picture-carrier wave, as are also the mixed highs of the 1- to 2.4-mc band. Red lows are carried as modulation of a subcarrier and occupy the 2.4- to 3.6-mc position in the spectrum. Blue lows modulate a second subcarrier in the 3.6- to 4.2-mc position. Care is taken to

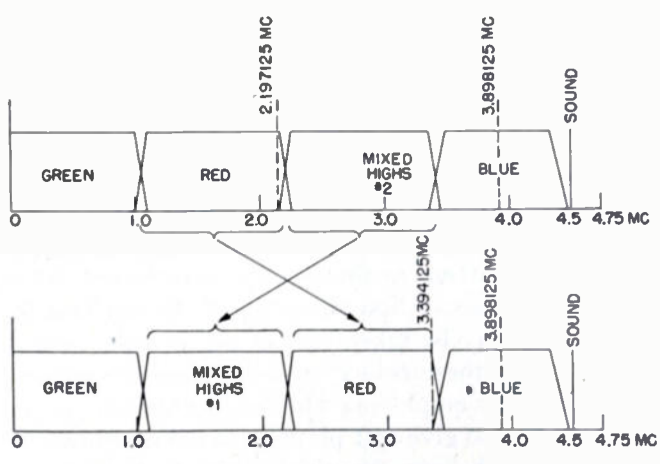

Fig. 9—Spectra of alternating-highs system for the two distinct intervals.

see that no red or blue sidebands overlap into adjoining parts of the frequency spectrum. During a second interval of time, the green lows and that portion of the mixed highs previously omitted, namely, from 2.4 to 3.6 mc, are employed as direct modulation of the principal picture-carrier frequency, while red lows modulate a new subcarrier so chosen that this subcarrier and its sidebands occupy the cleared channel from 1.2 to 2.4 mc. The blue lows occupy the same channel as before.

It is clear that this system thus provides for the continuous flow of low-frequency color information for all three primaries, but provides for a discontinuous or sequential flow of mixed-high information. By this arrangement cleared channels have been provided for all color information so that the data of each channel may

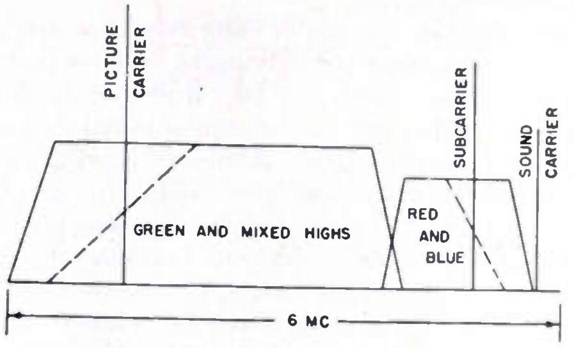

Fig. 10—Spectrum of alternating-lows system with subcarrier, employing vestigial sideband transmission.

be well filtered to remove all traces of dot structure without fear of generating spurious cross-talk signals between color information and mixed highs. A disadvantage of this system is that on some lines certain kinds of high-frequency information will be lacking, although it may be possible, by employing reversing sequences, to collect all high-frequency data if four fields are employed in a complete cycle.

The second of the combined simultaneous and sequential systems is the alternating-lows method. This method takes advantage of the fact that since the eye is less acute for red or blue images than for green images adequate color information may be produced by providing green lows and mixed highs on every line in the picture but limiting the flow of red and blue low-frequency componets so that, for instance, red lows are transmitted for an interval of two lines followed by blue lows transmitted for one line. This cycle of alternating red and blue lows is repeated continuously; since 3 is divisible into 525 without a remainder, a noncrawling pattern in these colors is obtained. At the receiver, the coarser line structure of the red and blue components may be taken care of on the tube or tubes which display these colors by defocusing the cathode-ray spots or by employing vhf spot wobble in the vertical direction to give soft pictures in red and blue. The green display is kept sharply focused to provide high resolution in the customary manner.

The available frequency spectrum may be used in several ways to transmit color pictures when the alternating-lows principle is used. One method closely akin to that employed in some of the systems previously considered is shown in Fig. 10. A subcarrier in the 3.5- to 4.0-mc range is employed to carry the red and blue low video frequencies alternately. Vestigial-sideband transmission may be employed to conserve more spectrum space for mixed highs.

Another method of utilizing the available spectrum is shown in Fig. 11. No subcarriers are employed with this method. Since only two data are being dealt with at any one time, namely, green and red, or, at a later time, green and blue, it is possible to amplitude-modulate the principal picture carrier by the green and mixed-

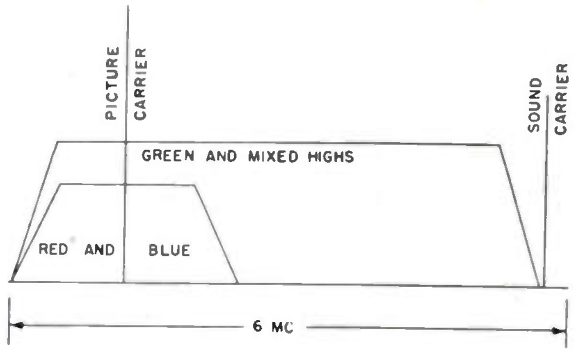

Fig. 11—Spectrum of alternating-lows system with quadrature modulation of principal carrier wave by red and blue lows.

highs signals, and to simultaneously modulate a quadrature component of the principal picture carrier by the red or blue video signals to transmit such data separately. Alternatively, the red and blue signals may be employed to frequency- or phase-modulate the carrier wave rather than to amplitude modulate a quadrature carrier component. A transmitter block diagram of the

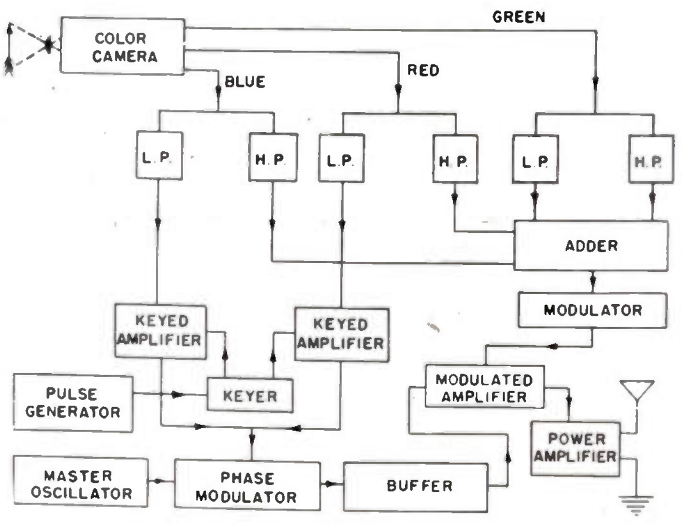

Fig. 12—Block diagram of single-carrier alternating-lows transmitter employing phase modulation for red and blue lows and simultaneous amplitude modulation for green lows and mixed highs.

phase-modulation method is shown in Fig. 12. A receiver block diagram for the phase-modulation method is shown in Fig. 13.

Referring once again to Fig. 11, some advantages of this system will become evident. For one thing, an additional 0.75 mc of frequency spectrum is opened up for use for data transmission not separately utilized in the other methods. The spectrum for the transmission of structural detail may thus occupy the entire band from 0 to 4 mc.

Working circuits for the alternating-lows method,

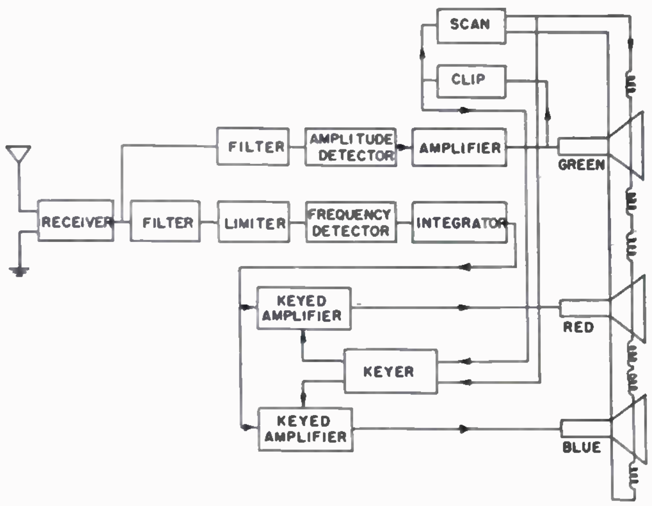

Fig. 13—Block diagram of receiver for the single-frequency, phase-modulation, alternating-lows color system.

shown as block diagrams in Figs. 12 and 13, were developed in the laboratory and the system performance was studied for a period of several months.

A flying-spot scanner is employed as a signal source, with the material to be transmitted consisting of a Kodachrome 35-mm transparency. Color separation is made by dichroic mirrors, and the optical-electrical transducers are multiplier-type photocells. The three signals resulting correspond respectively to the red, green, and blue portions of the transparency.

The first step in the preparation of the signals for the transmitter is that of splitting the frequency band employed for each of the color signals into "lows" and "highs," as indicated by the low- and high-pass filters in Fig. 12. Actually, low-pass filters in conjunction with subtracters to obtain the high-frequency portions were employed in the practical system so that a smooth "fit" between the separated portions could be obtained.

The schematic diagram of a typical filter and subtracter unit is shown in Fig. 14. The wide-band video signal is directed through two separate channels. The lower channel includes a cathode follower, an *m*-derived low-pass filter, and bridged-T phase-compensation sections, terminating in two resistors in the form of potentiometers. The second path for the wide-band video includes a delay line which terminates in a resistor. The subtracter consists of two triodes with a common cathode resistance. One signal is connected to the grid

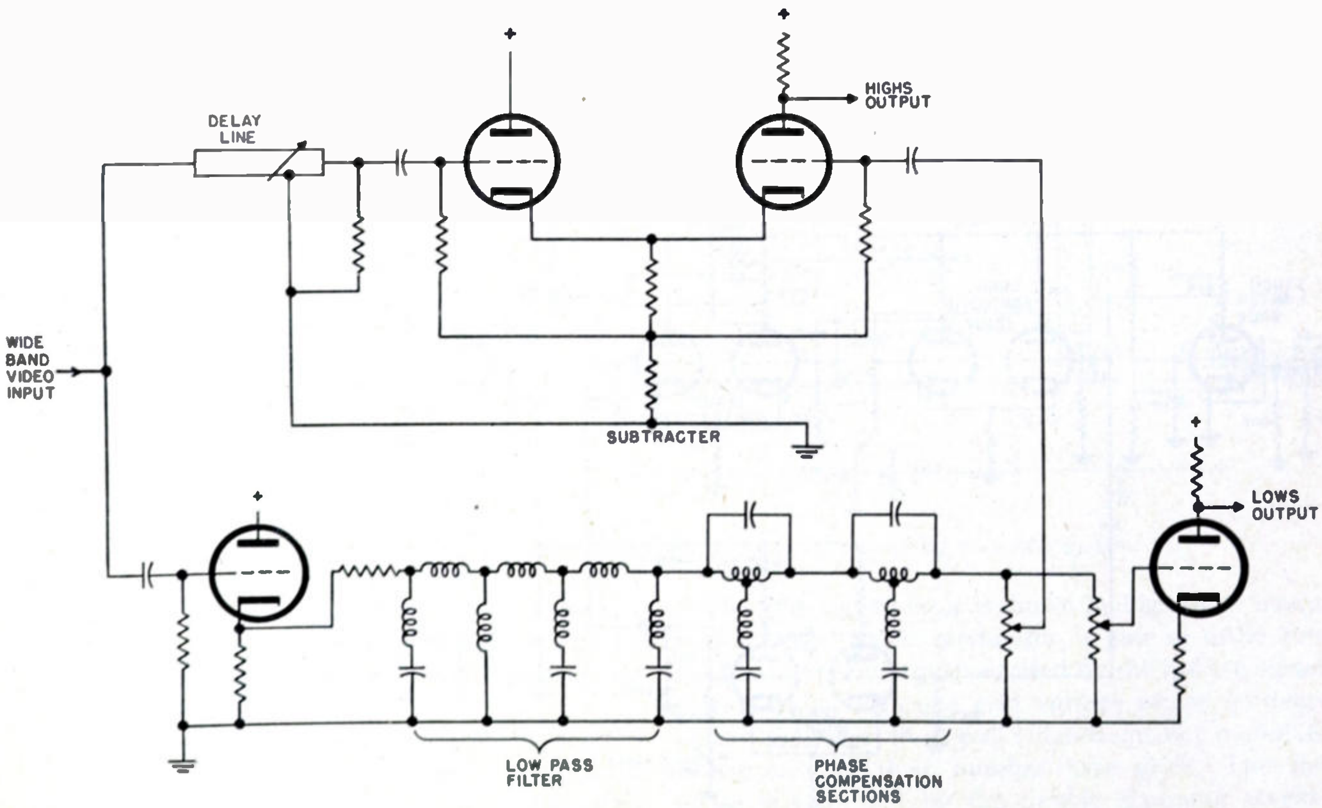

Fig. 14—Low-pass filter and subtracter for dividing a wide-band frequency spectrum to obtain signals for mixed-highs and for color-modulation circuits.

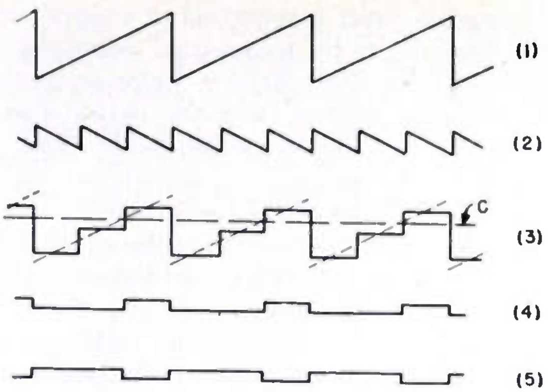

Fig. 15—Steps in the generation of suitable keying waveforms for the keyed amplifiers in the alternating-lows system.
(1) Positive-going sawtooth waveform at the *n*th submultiple of the line frequency.
(2) Negative-going sawtooth waveform at the line frequency with an amplitude $1/n$ of the low-frequency sawtooth.
(3) The sum of waveforms (1) and (2).
(4) Clipped output of waveform (3), clipping done at the level "C" in (3) for one of the keyed amplifiers.
(5) The inverse of waveform (4) for the second of the keyed amplifiers.

of one triode while the other signal is connected to the grid of the other triode. The difference signal appears in the plate circuit of one of the triodes. Adjustment is made to the gain control of the low-pass filter output voltage to balance out the low-frequency portion of the wide-band signal in amplitude while the delay-line length is adjusted to balance out the residual low-frequency components caused by the differences in the times of transmission in the two paths.

The keyer shown in Fig. 12 is driven from horizontal driving pulses from a conventional pulse generator. The object of the keyer is to provide two rectangular keying waveforms, one of which is positive-going for two horizontal lines and negative for one line while the other is negative-going for two lines and positive-going for one line. Such a pair can be obtained by adding two sawtooth waves and then clipping the resultant wave at the proper relative level. Fig. 15 shows (1) a positive-going sawtooth waveform at the *n*th submultiple of the line frequency, (2) a negative-going sawtooth waveform at the line frequency with an amplitude $1/n$ of the low-frequency sawtooth, (3) the sum of waveforms (1) and (2) giving a stair-steps waveform with the clipping level indicated by "C," (4) the clipper output, one of the desired keying waveforms, and (5) the inverse of waveform (4), the other desired keying waveform.

The circuitry to perform the keying waveform generation is shown in Fig. 16. This particular unit is equipped with a two-position switch to enable the operator to select at will either a 2:1 or a 3:2 final keying waveform. In the 2:1 case, the low-frequency multivibrator operates at

$$\frac{1}{2+1} = \frac{1}{3}$$

line frequency while in the 3:2 case the low-frequency multivibrator operates at

$$\frac{1}{3+2} = \frac{1}{5}$$

line frequency. The reason for making either ratio available was to enable quick comparisons to be made between the two ratios. Tests showed that the 2:1

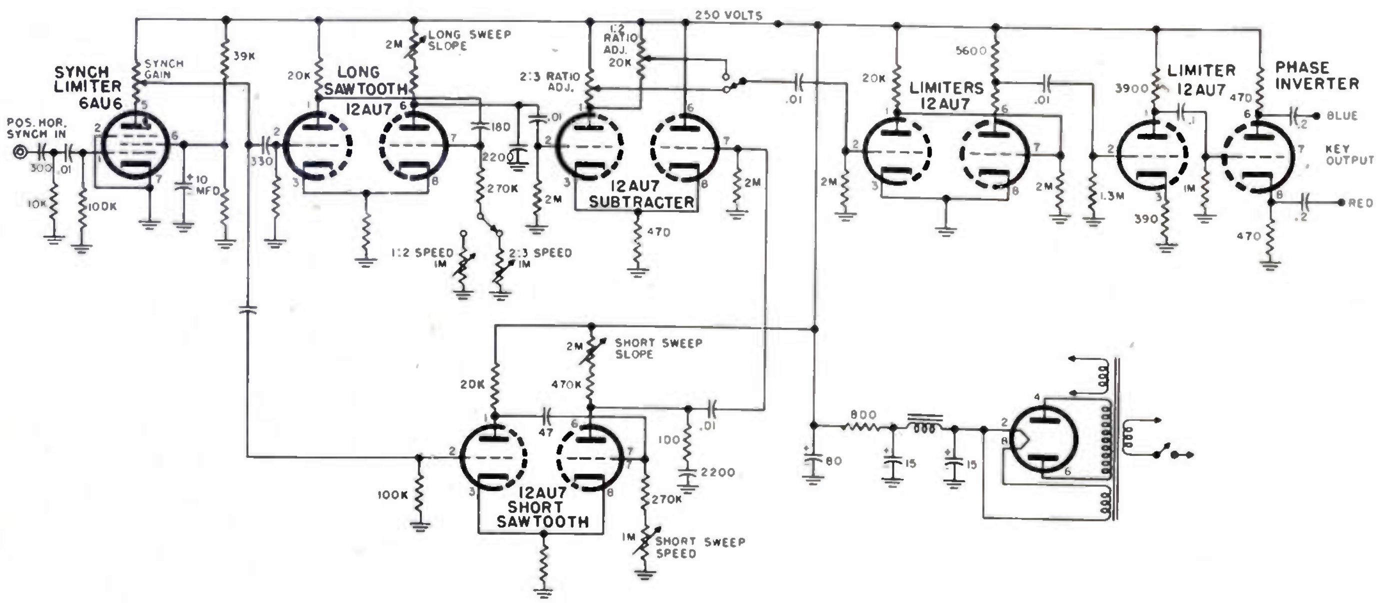

Fig. 16—Schematic diagram of the keying-wave generator for generating waveforms (4) and (5) of Fig. 15.

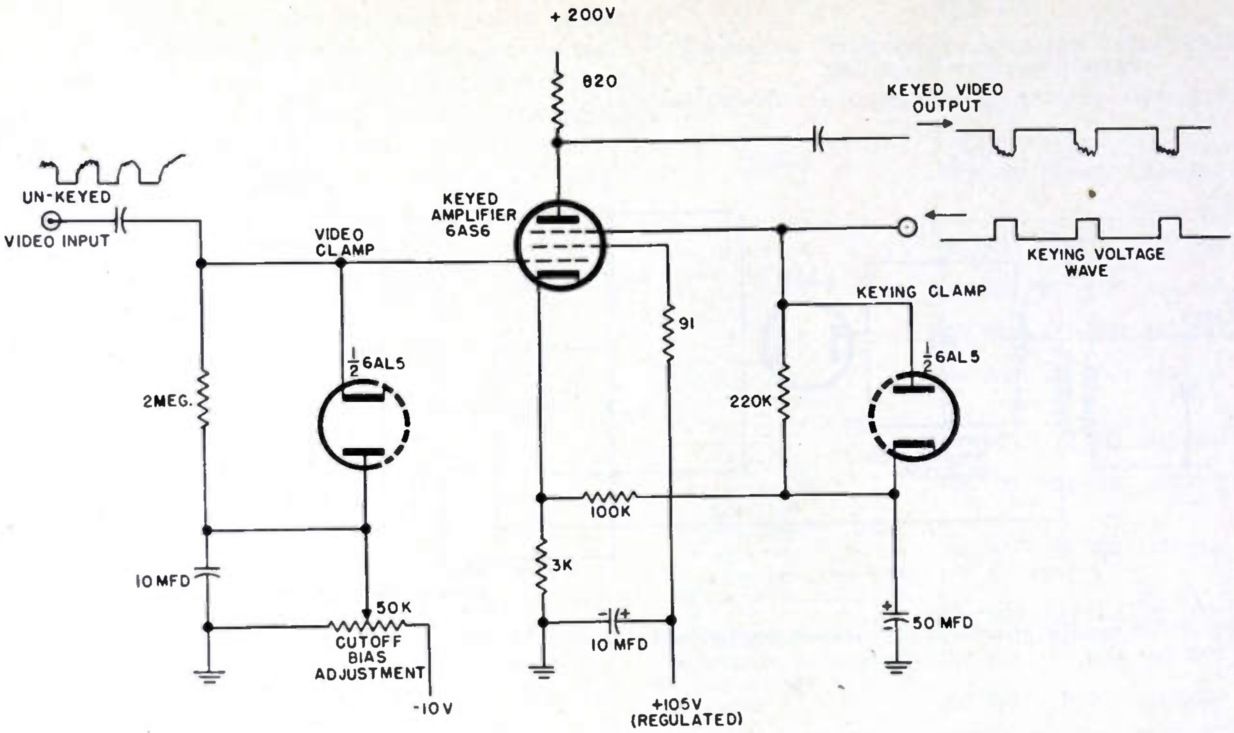

Fig. 17—Schematic diagram of a keyed amplifier for use in the alternating-lows color system.

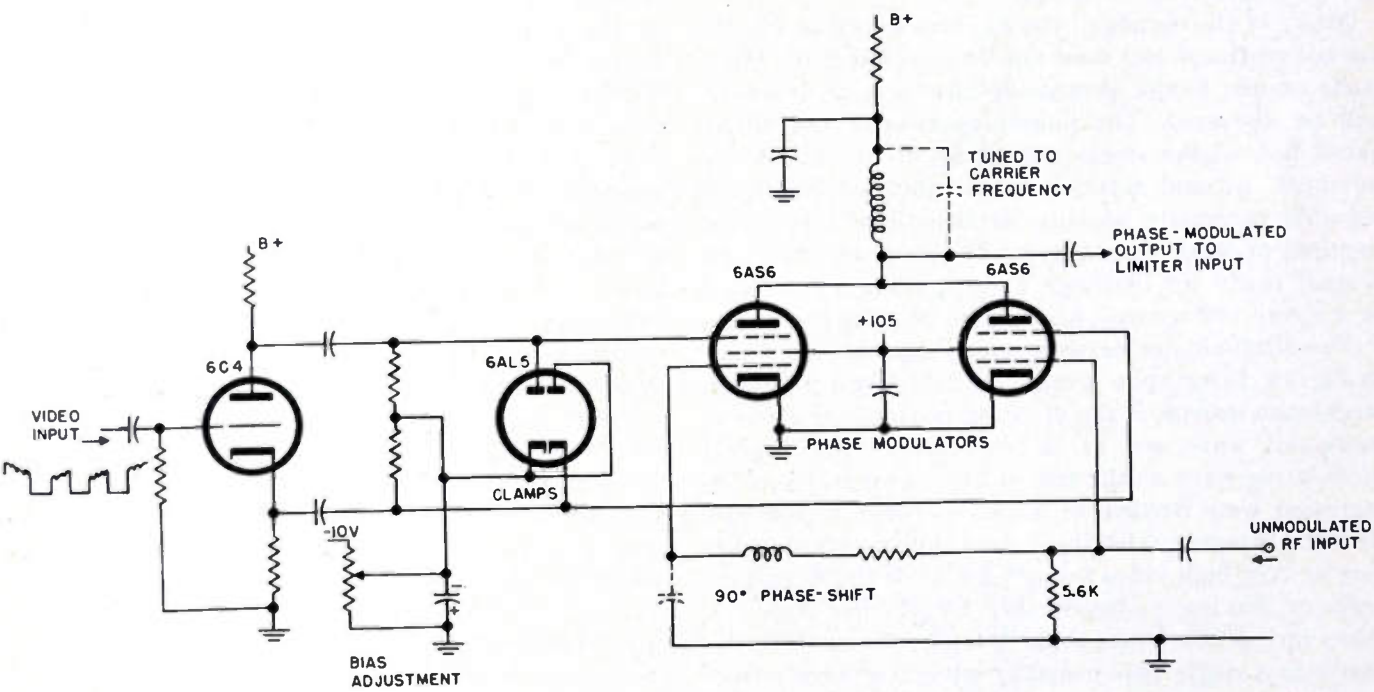

Fig. 18—Schematic diagram of the phase modulator for use in the alternating-lows color system.

ratio is preferable because the line structure of the red and blue components is less objectionable and can be more easily defocused out without impairing the detail in these colors so much.

The circuit diagram of a keyed amplifier (see the block-diagram Fig. 12) is shown in Fig. 17. Clamps are employed to insure clean operation from fixed reference points to take care of changes in picture content without manual monitoring of adjustments.

The phase modulator is shown in Fig. 18. A modulation-balanced phase modulator, a pair of 6AS6 tubes, has its number-one grids excited by the radio-frequency carrier wave, with one grid voltage vector 90 degrees behind the other. Push-pull video-frequency modulation is supplied to their number-three grids. The mean phase is stabilized by the double clamping action of the duo-diode 6AL5 to the quiescent condition represented by black level or blanking.

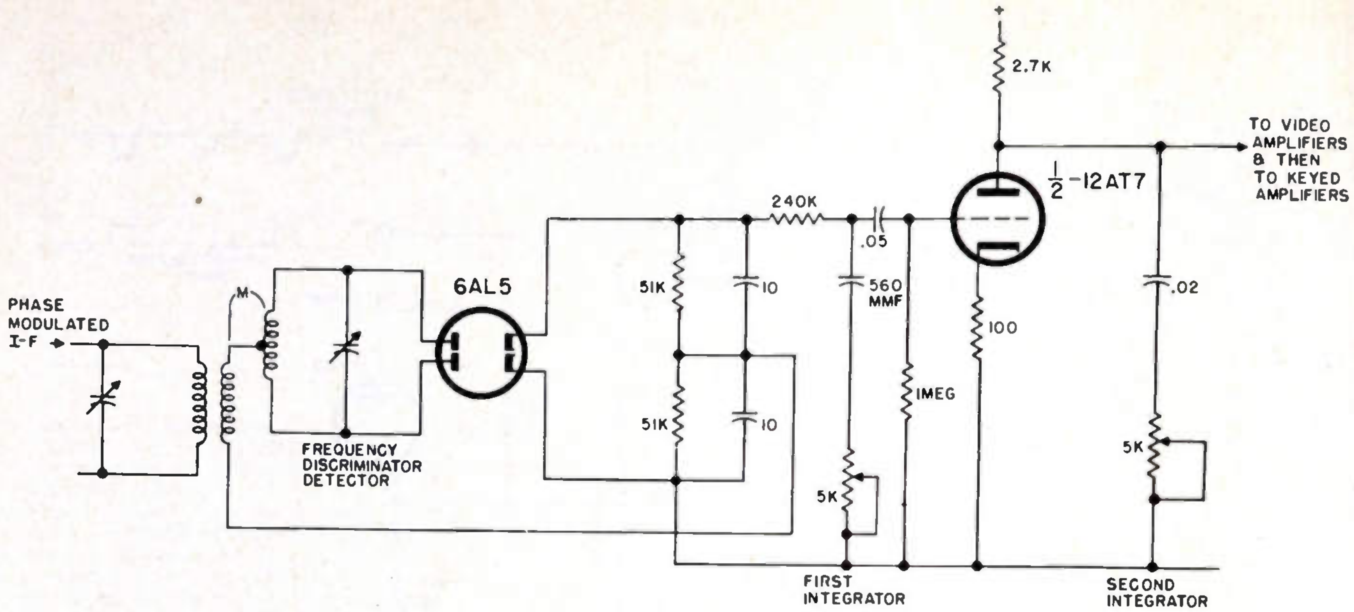

Fig. 19—Schematic diagram of the receiver discriminator detector and integrators for use in the alternating-lows system.

The rest of the transmitter is conventional and need not be diagrammed in detail.

Many of the details of the receiver shown in Fig. 13 are conventional and need not be repeated here. Those parts unique to the alternating-lows system, however, will be discussed. The limiter consists of two 6BN6 gated beam tube stages connected in cascade. Grids numbers two and three in these tubes are connected together externally because number-three grid is not required to be keyed or separately tuned since the tube is used solely for limiting. These grids are connected to a screen voltage supply of about 50 volts positive.

The discriminator detector and integrators are shown in Fig. 19. Integration is required following a *frequency-modulation detector* if the detected products of a *phase-modulated* wave are to be restored to the original modulating wave at the transmitter. Two stages of integration were needed to obtain untilted waveforms. The first integrator, having a short time-constant, takes care of very high video frequencies while the second integrator, having a considerably longer time-constant, takes care of low frequencies. Attempts to combine the two into a single time-constant integrator were unsuccessful.

The keyed amplifiers employed in the receiver are duplicates of the transmitter keyed amplifiers already shown in detail in Fig. 17. Clamps were provided as in the transmitter and for the same purposes. The keying wave generator is quite similar to the transmitter generator shown in Fig. 16, except that the low-frequency sawtooth multivibrator is synchronized in the proper sense by special sync pulses transmitted every third line or every fifth line depending upon the keying ratio being used.

The system performance using the equipment and circuits described above gave acceptable pictures as far as the color receiver was concerned. The distortion caused by the nonlinear transfer characteristics of the 6AS6 keyed amplifiers was noticeable, however, so that some readjustment to the gain controls in the color channels had to be made when the Kodachrome transparency was changed to a radically different type, particularly when the illumination levels were markedly different. It is not believed that this distortion is inherent in the system; however, for some additional development work on linearizing the amplifiers, had the time been available, it would undoubtedly have produced improved and completely satisfactory results.

The rf signal was tuned in on a standard black-and-white television receiver to check the compatibility of the system. When the phase modulation was at a fairly high level, fringing structure in the black-and-white picture was visible and was sufficiently great so as to render the resultant picture unacceptable to the average observer. This was completely corrected by making a small change in the transmitter. Instead of employing phase modulation alone for red and blue lows, a combination of phase and frequency modulation was employed. The transition from phase to frequency modulation was made gradual, and was accomplished by adding some integration to the video input to the phase modulator. The integration actually employed consisted of a series resistor followed by a shunt condenser. These units were selected so that the capacitive reactance of the condenser equalled the resistance of the resistor at approximately 150 to 200 kc; the cross-over frequency does not appear to be at all critical. A corresponding change in the color-receiver integrating stages had to be made to restore the color picture to its former quality, but the end result was substantially the same as in the original arrangement. At the same time, the picture on the black-and-white receiver was rendered completely free from fringing so that the observers were unable to detect when the phase- and frequency-modulated signals were present.

Table I summarizes in chart form, for comparison purposes, numerical values for the number of picture elements devoted to the transmission of structural detail, the number of picture elements devoted to color data, the total number of picture elements, and the percentage of color elements to this total for several of the systems described.

In conclusion, then, it appears that the available spectrum may be used in a comparatively large number of ways to transmit color-television pictures. Before deciding which system or systems offer the greatest promise, careful comparative study of these methods should be conducted, taking into consideration such factors as flicker, crawl, dot structure, liability to interference, liability to multipath transmission effects, color fidelity, compatibility, and receiver complexity and cost.

TABLE I

SUMMARY OF UTILIZATION OF AVAILABLE PICTURE ELEMENTS IN COLOR-TELEVISION SYSTEMS

System	*Detail Elements*	*Color Elements*	*Total Elements*	*Percentage Color to Total*
Monochrome	267,000	0	267,000	0
Field-sequential (144 field/sec)	111,000	222,000	333,000	67
Line-sequential (60 fields/sec)	267,000	533,000	800,000	67
Dot-sequential (overlapping)	267,000	133,000	400,000	33
Frequency Interlace (mixed highs and red overlapping)	240,000	77,000	317,000	24.3
Alternating-highs (nonoverlapping)	160,000	93,000	253,000	36.8
Dot-sequential (nonoverlapping) color 0.5 mc, detail 3.0 mc	200,000	67,000	267,000	25
Alternating-lows with 4-mc subcarrier and 3.5-mc detail	233,000	33,000	267,000	12.5
Alternating-lows with 3-mc detail and 4-mc subcarrier	200,000	67,000	267,000	25
Alternating-lows with no subcarrier	267,000	50,000	317,000	15.8

CORRECTION

F. W. Smith, author of the correspondence, "Network Representation of Input and Output Admittances of Amplifiers," which appeared on page 439 of the April, 1951 issue of the PROCEEDINGS OF THE I.R.E., has brought the following error to the attention of the editors:

An exponent has been omitted in the next to the last equation. The quantity ($V^{+1}Q^{-1}T^{+1}$) should obviously be squared.

Observer Reaction to Low-Frequency Interference in Television Pictures*

A. D. FOWLER†

Summary—This paper presents results of tests to determine how much low-frequency interference can be tolerated in black-and-white television pictures. Various levels of single low-frequency interference were superimposed on a locally transmitted television picture. Observers viewed the picture and rated the disturbing effect of each level of the interference. Ratings were made in terms of preworded comments ranging from "not perceptible" to "unusable." Interfering frequencies from 48 to 90 cycles per second were employed.

Just visible interference appears as a flicker. The rate of flicker is the difference between interfering and 60-cycle field frequencies. The most disturbing interference produced a flicker rate of 5 or 6 cycles per second. To be tolerated, the peak-to-peak amplitude of this interference had to be 54 decibels weaker than the peak-to-peak amplitude of the television signal (including synchronizing pulse). For flicker rates of 0.5 and 12 cycles per second, the amount of interference which could be tolerated was larger by 14 and 3 decibels, respectively.

Introduction

THE TRANSMISSION of television signals from one point to another inevitably takes place in the presence of noise, and often in the presence of spurious signals or tones, such as power-frequency pick-up. One of the responsibilities of the transmission engineer is to insure the arrival of the television signals at their destination with an adequate margin over the interference. To do this, he must know not only what interference to expect, but also, what constitutes a satisfactory margin. The purpose of the experimental work described below was to determine these margins for single-frequency interferences in the range of 48 to 90 cps for black-and-white pictures.

In general, the method of attack was one outlined in a previous paper.[1] Briefly, this method made use of a selected group of observers to view a television picture on which was superimposed, in random order, a variety of levels of the interference in question. Each observer was provided with a list of seven preworded comments ranging from "not perceptible" to "unusable." For each level of the interference, each observer chose the comment which best suited his reaction to, or his rating of, the interfering effect.

Before the experiments are described in more detail, perhaps a few words should be said regarding the nature of low-frequency interference as it appears on the picture tube. If strong enough, a single interfering frequency in the neighborhood of 60 cps appears on the screen as a broad horizontal bar pattern. If the interfering frequency is precisely equal to the 60-cycle field rate, or for that matter, is any multiple of the field rate, the bar pattern will be stationary. On the other hand, if the interfering frequency differs somewhat from the field rate, the bar pattern will travel either up or down the screen, depending on whether the interference is less or greater than the field frequency. The rate of travel, expressed in cycles of bar pattern per second, is equal to the difference between the interfering and field frequencies.

When the interference is superimposed on a television picture—a normal scene containing high lights, shadows, and various values of gray—and the interference is just visible, it may not be noticed as a bar pattern at all, but as a flicker in some sensitive areas of the picture. The rate of flicker will, of course, be the beat frequency between the interfering and field frequencies. This flicker is much more noticeable and disturbing than the brightness distortion caused by an interfering frequency which is synchronized with some component of the 60-cycle field frequency. It will be shown later how the interfering flicker effect varies with the flicker rate.

The analysis of the flicker phenomenon is rather complicated and outside the scope of this paper. It is sufficient for present purposes to say that, near threshold, the noticeable flicker arises from the beat between the interfering frequency and the nearest harmonic of the 60-cycle field frequency. There will, of course, arise beats with other 60-cycle harmonics, but these result in much higher flicker rates to which the eye is less sensitive. For this reason, the maximum flicker rate in evidence (apart from the ever-present 60-cycle flicker which is not generally seen) was 30 per second, which occurs when the interfering frequency lies halfway between two 60-cycle components.

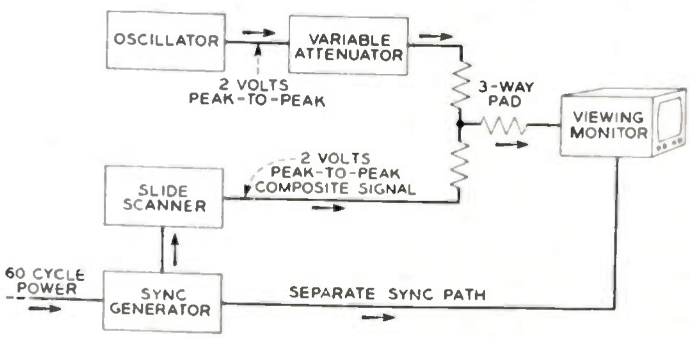

Fig. 1—Block schematic of test setup.

Apparatus and Circuit Arrangement

In Fig. 1 is shown a simplified block schematic of the test setup. The box labeled *slide scanner* represents

* Decimal classification: R583.7×R430. Original manuscript received by the Institute, May 16, 1951.

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[1] P. Mertz, A. D. Fowler, and H. N. Christopher, "Quality rating of television images," Proc. I.R.E., vol. 38, pp. 1269–1283; November, 1950.

a conventional flying-spot scanner in which the picture signal was derived from a standard 2-inch by 2-inch slide. The output signal of the scanner had an amplitude of 2 volts peak-to-peak (including the synchronizing pulse), and was transmitted via a 3-way mixing pad to the viewing monitor shown on the right. The box in the upper left, labeled *oscillator*, represents the source of low-frequency interference. The sinusoidal output of this oscillator was adjusted to have a 2-volt peak-to-peak amplitude, and was transmitted through the variable attenuator to the 3-way pad, where it was added to the video signal going to the monitor. The peak-to-peak amplitude of the interference—expressed in decibels below that of the 2-volt video signal—was given directly by the dial reading of the variable attenuator.

The viewing monitor was one developed and built at Bell Telephone Laboratories. The picture tube was a 10-inch metal-backed tube (Type 1816 P4) operated at about 11 kv. Normally, this monitor employs a clamper which operates on the "back porch" of the signal to set black level. For the purposes of these tests, the clamper was replaced by a dc restorer circuit which had negligible effect in reducing low-frequency interference. Moreover, since the monitor was not equipped for "fly-wheel" synchronization, separate synchronization, direct from the sync generator, was employed. This eliminated imperfections in synchronization when the interference was strong.

Many viewing tests have been made in the study of the interfering effects of noise, cross talk, and echoes on television pictures. In the course of this work use was made of many slides and movie films as subject pictures. On the basis of this experience, and for the purposes of the tests described here, there was chosen a single slide which had previously been found to be fairly sensitive to noise and low-frequency interference. This slide shows a close-up of a lady drinking tea; the high light is in the lady's hat, and the background, which is not in sharp focus, contains many shades of gray.

When this picture was reproduced on the monitor, and adjustments had been made to give the best possible rendering, it was found that the high-light luminance was 45 foot-lamberts and the contrast range was 120 to 1. To insure that the same conditions of brightness and contrast obtained in all the tests, these values were frequently checked. For this purpose, use was made of a Macbeth Illuminometer equipped with a lens to adapt it to the measurement of luminances of small areas.

Viewing Conditions and Observers

All viewing was done in a darkened room in which the ambient light, resulting mostly from reflections of light from the picture tube, was of the order of 0.02 foot-candles as measured near the face of the picture tube. The television image, which was 6 inches high by 8 inches wide, was viewed by one observer at a time from a distance of 24 inches, or four times the picture height. The observers for these tests were both technical and nontechnical employees of the Murray Hill Laboratories. In each test group there were ten or more observers, some of whom were known to be rather critical, that is, intolerant of picture impairments, some less critical, and others fairly uncritical. These observers were experienced and they were known to be reasonably stable in their judgments. They were selected on the basis of giving a fairly uniform distribution of all types of observers, critical and uncritical.

Testing Procedure

During the test the room was darkened and the observer was shown the picture of the tea-drinking lady without any added interference. He was told that this was the best picture, and that any imperfections he then saw (such as noise and the like) were, as far as possible, to be ignored in making his subsequent judgments of picture impairments. He was then shown the same picture to which a moderate, but visible, amount of a single low-frequency interference had been added. He was told that this was the type of interference which would be present during the test, but that the level would probably be different for each test condition. The observer was then given a list of seven numbered comments from which he was to select the one which best described his reaction to the interference present in each test condition. These comments were listed in the following manner:

1. Not perceptible
2. Just perceptible
3. Definitely perceptible, but only slight impairment to picture
4. Impairment to picture, but not objectionable
5. Somewhat objectionable
6. Definitely objectionable
7. Unusable.

The comments are arranged in logical order, progressing step by step from "not perceptible" to "just perceptible" through various degrees of adverse reaction to "unusable." Associated with the comments are the comment numbers. The numbers are used not only to identify the various comments, but also as a numerical scale of observer reaction. It will help, in connection with some of the discussion to follow, to remember two of these comments: No. 2, which means "just perceptible"; and No. 4, which means "impairment to picture, but not objectionable." The latter is the severest comment which can be made without rating the interference objectionable.

A series of twenty test conditions were used for each interfering frequency. These conditions comprised ten different levels of interference covering a range of 18 db subdivided into 2 db steps. Each level appeared twice in the series, and the order of presentation was randomized, use being made of Tippetts Random Numbers for this purpose. The same order of presentation was submitted to each observer. As each test condition was presented, the observer, after due consideration, called the number of the comment he felt most nearly described his reaction to that level of the interference.

Test Results and Interpretation of the Data

An examination of the data obtained from individual observers shows that the observers apparently use the comment numbers as a scale of their reactions. This will be seen in Fig. 2, in which, for purposes of illustration, are plotted the reactions of only two observers to a 60.5-cycle interference. Here, the interference level is given by the abscissas which indicate stronger interference to the right. The ordinates show the comment number called out by the observer for the particular level of interference. Where the data points occur midway between comment numbers, the observer had once called the comment immediately above and once the one immediately below the point shown. Only the average of the two comment numbers called is shown here to avoid confusing the representation. The curves for other observers, in general, fan out between the two curves shown. Although these curves are labeled "most critical observer" and "least critical observer", these terms cannot always be correctly applied over the whole

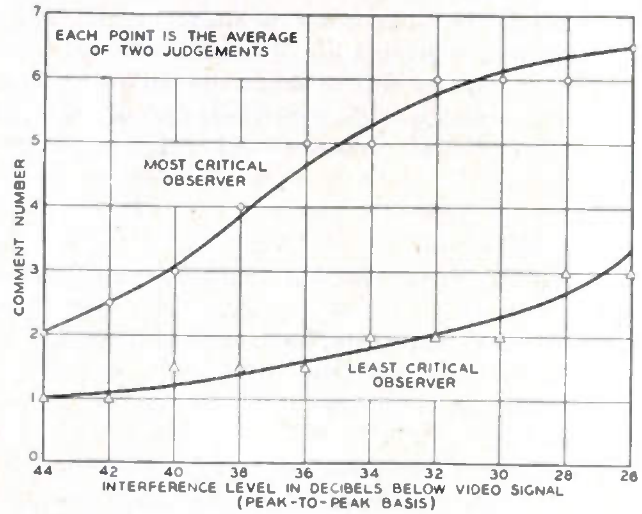

Fig. 2—Reactions of individual observers to 60.5-cycle interference.

range of interference levels. For example, when there are two fairly critical observers, one of them may be somewhat more critical than the other for part of the range and less so for another part. For this reason it was decided to pool the data for all the observers, and from this pool of data derive what might be called the characteristic reactions of the group. This treatment is illustrated in part in Fig. 3.

Fig. 3 shows the distribution of the comments chosen by the entire group of observers for the various levels of 60.5-cycle interference. At each of the lattice points (marked with solid circles) are shown the total number of comments of the indicated comment number for a given interference level. Since there were ten observers making two judgments for each level of interference, the sum of the lattice-point numbers in each column is twenty. For example, when the interference level was, say, 38 db below the picture signal, there were three observers who voted comment No. 1 (not perceptible); seven voted comment No. 2 (just perceptible); seven voted comment No. 3 (definitely perceptible, but only slight impairment to picture); and three voted comment No. 4 (impairment to picture, but not objectionable).

The data shown in matrix form in Fig. 3 can be further classified by drawing in, for example, the curve

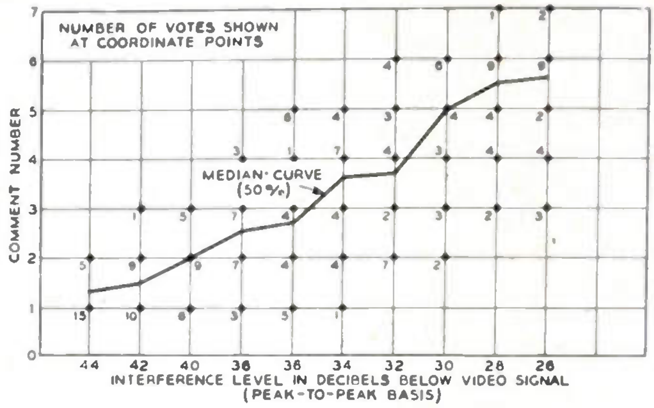

Fig. 3—Distribution of comments from 10 observers (60.5-cycle interference).

(or broken line) below, and above, which 50 per cent of the votes fall. This is the broken-line curve designated in Fig. 3 as *median curve*. To avoid ambiguities in the count of votes, it was assumed that the votes for each comment are spread uniformly over a range of ±one-half comment number; at the ends of the scale, comments No. 1 and No. 7, the spread was assumed to be only over one-half comment towards No. 2 and No. 6, respectively, since there were no possible comments less than No. 1 or greater than No. 7.

In a similar way other contours, below which a given percentage of the votes fall, can be drawn. This was done for several different percentages, as shown in Fig. 4. Here, with the addition of the contours, are

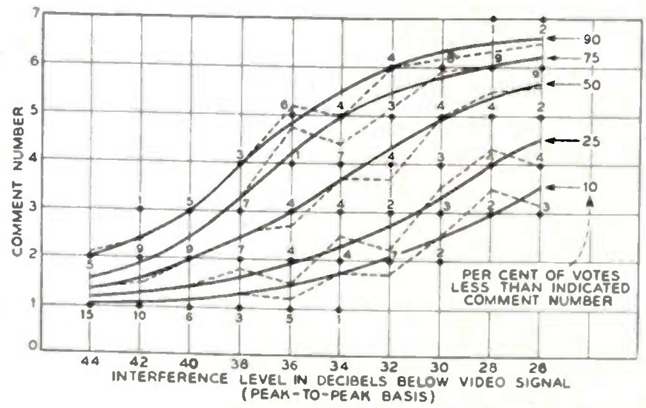

Fig. 4—Distribution contours of comments from ten observers (60.5-cycle interference).

shown the same data as in Fig. 3. These data were computed on the basis just described and shown as dashed broken lines. The heavier smooth curves were drawn in, more or less by eye, to show the general trends for engineering purposes. As was rather evident, the 90-per cent contour corresponds to a curve for a critical observer, the 50-per cent contour to one for a median observer, and the 10-per cent contour to an uncritical observer.

The contours of Fig. 4 reveal several interesting things. First of all, they show that the observer reactions are fairly uniformly distributed over the range from critical to uncritical, viz., there is no pronounced bunching of the contours. Looking now at the 90-per cent contour, which represents the reactions of a critical observer, it is seen that the 60.5-cycle interference is just perceptible to him when the interference is 44 db below the picture signal, and that he still does not object to it (that is, he votes no more than comment #4) when the interference is 6 db larger, or 38 db below, the picture signal. At the same time, the median observer (50-per cent contour) doesn't begin to perceive the interference (votes comment #2) until it is 40 db below the picture signal; and the uncritical observer (10-per cent contour) doesn't begin to see it until it is 8 db stronger, or 32 db below the picture signal.

However interesting these various facts gleaned from the data may be, what the transmission engineer usually wants to know is just one number: What maximum level of interference of this particular frequency (60.5 cps) can be considered to be tolerable? To answer this question the following criterion is proposed:

In general, the maximum tolerable level of interference (a) must not cause the critical (90-per cent) observer to object to it (i.e., he must vote comment No. 4 or less), nor (b) must not cause the median (50-per cent) observer to find it more than just perceptible (i.e., he must vote comment No. 2, or less). For the particular case at hand, 60.5-cycle interference, the maximum tolerable level would be 40 db, which was just perceptible to the median observer, and which caused the critical observer to vote comment No. 3, "definitely perceptible, but only slight impairment to picture." In most instances the data show that the "just perceptible" level for the median observer is a slightly stiffer requirement than the comment No. 4 level for the 90-per cent observer.

The foregoing test results, which have been given by way of example, apply when the interfering frequency is 60.5 cps. As explained earlier, this frequency results in a 0.5-cycle flicker rate. The results for the other test frequencies, when treated as in Fig. 4, are similar in general characteristics; they differ, however, in such important particulars as the level values at which certain comments occur and in the steepness of rise of the contours. Instead of separate displays of those results, summaries are presented to show how the comments of the median and critical observers varied with level of interference and flicker rate.

Fig. 5 shows the reaction of the median observer to various interfering frequencies. Here the abscissas indicate flicker rates in cps; the ordinates, level of interference; and the parameter, comment number. The words "just perceptible" with the arrow pointing to the top curve were put there merely as a reminder of the meaning of comment No. 2, to which the top curve refers. The interesting point about this family of curves is, of course, the way they rise to a maximum at about 6 cps flicker rate. This means that an interfering frequency of either 54 or 66 cps would have to be 54 db

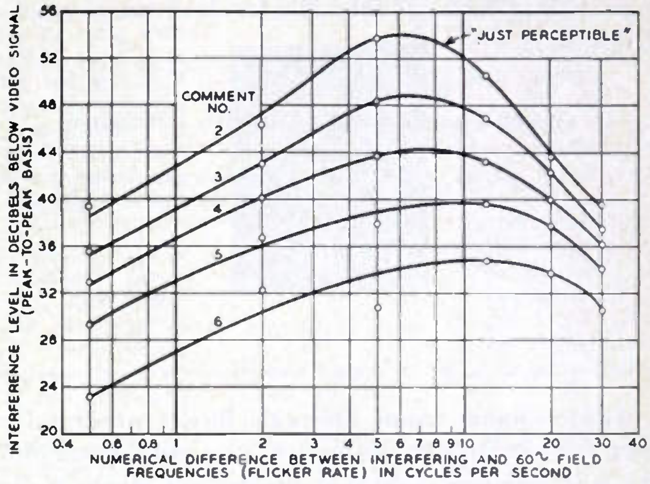

Fig. 5—Median observer's reaction to various flicker rates.

below the picture signal in order to be just perceptible to the median observer. Moreover, as the level of interference increases so that the observer objects more and more to it, the maximum points on the curves move toward higher flicker rates. The curves all terminate on the line for 30-cycle flicker rate, since that was the highest flicker rate occurring in the tests or, for that matter, that could be noticed.

Fig. 6 shows another family of curves similar to that of Fig. 5, but pertaining to a critical observer. According to the proposed criterion, the No. 4 curve ("impairment to picture, but not objectionable") is the one of interest here. However, it is everywhere slightly lower than the No. 2 curve of Fig. 5 for the median observer, and, therefore, the latter is controlling in setting the tolerable values. In the family of curves of Fig. 6, the maxi-

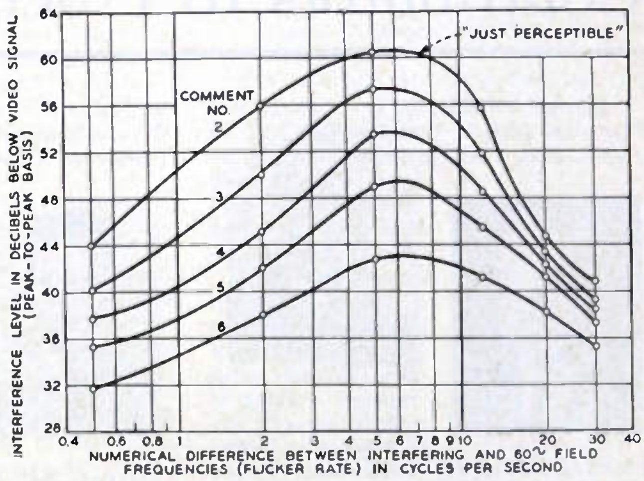

Fig. 6—Critical observer's reaction to various flicker rates.

mum points do not move so pronouncedly towards higher flicker rates with comment number, as in the previous figure. This is probably because, for a given comment number, the interference levels were not so great for the critical observer as for the median observer.

Summary of Results

The results of the several tests are summarized and expressed in terms of tolerable levels of interference in Table I.

TABLE I
Resume of Test Results
Tolerable Limits of Single-Frequency Interference

Flicker rate in cps	*Signal-to-interference ratio in decibels (peak-to-peak basis)*
0.5	40
2.0	46
5.0	54
12	51
20	44
30	39

The left-hand column shows the flicker rates resulting from the test frequencies used; the second column shows the corresponding tolerable interference levels in decibels below the picture signal, both the interference and the picture signal (including the sync pulse) being considered on a peak-to-peak basis. To make the table apply to root-mean-square values of the interference referred to peak-to-peak values of the video signal, add 9 db to the values given.

All of the flicker rates shown in the table were obtained by using interfering frequencies higher than 60 cps. Adding 60 to the flicker rates gives the actual test frequencies. However, in two instances, those for 5- and 12-cycle flicker, the tests were repeated using interferences less than 60 cps to obtain the desired flicker rates. The results were substantially the same as for those made earlier. Within the limited range of frequencies used in the tests, it was the flicker rate that was important and not whether the interference was higher or lower than 60 cps.

Recapitulation

The purpose of the tests was to obtain some fairly reliable data on how much low-frequency interfernce could be safely tolerated in black-and-white television pictures. To obtain these data, use was made of a still picture, rather than a moving picture, in order that the interference might be the more readily noticed; and use was made of a picture known to be sensitive to the type of interference in question.

Special attention was paid to the quality of reproduction of the picture. The noise was small; the high-light brightness, adequate; and the contrast range and rendering, better than average. The viewing conditions were controlled and the observers were experienced. The levels of interference, taken from the data and presented as tolerable values, could not be seen by about half of the observers, and were rated as not objectionable by the critical observers.

Acknowledgments

In conclusion, the author acknowledges his indebtedness to many of his colleagues for their counsel and aid in carrying out the tests. In particular, mention should be made of the following: H. N. Christopher, who was a close associate in conducting the experiments; J. M. Barstow, under whose direction the work was done; and Pierre Mertz, technical advisor to the project, who suggested the testing technique. Finally, the author's thanks go to those members of the Murray Hill technical and staff departments who participated as observers, and who so willingly sat through many short, but tedious, sessions of judging picture impairments.

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Donald S. Bond

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J. W. Christensen

A native of Southern Utah, Mr. Christensen received the B.S. degree in physics from the University of Utah in 1937, and was recipient of the National Phi Kappa Phi scholarship for graduate study.

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Mr. Dome became affiliated with the General Electric Company in 1926. In 1928, he joined their radio (transmitter) engineering department, where he remained until 1934. Since 1934, he has been in the radio (receiver) engineering department of the same company.

In 1951, Mr. Dome received the I.R.E. Morris Liebmann Memorial Prize for many technical contributions to the profession, but notably his contributions to the intercarrier sound system of television reception, wide-band phase-shift networks, and various simplifying innovations in FM receiver circuits.

Mr. Dome served on the I.R.E. Papers Committee from 1940 to 1945, and has been serving on the Board of Editors since 1946. He is a member of The Scientific Research Society of America, and of Sigma Xi.

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Mr. Faulkner is a member of Kermos and of the American Ceramic Society.

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Donald Glen Fink (A'35–SM'45–F'47) was born on November 8, 1911, in Englewood, N. J. He was graduated in 1933 from the Massachusetts Institute of Technology with the B.Sc. degree in electrical communications. After a year as a research assistant of the staff of the departments of geology and electrical engineering at MIT, Mr. Fink joined the staff of the journal *Electronics*, as editorial assistant. In 1937 he became managing editor; in 1945, executive editor; and in 1946, editor-in-chief. In 1942 he was awarded the degree of M.Sc. in electrical engineering by Columbia University.

Obtaining a leave of absence from *Electronics* in 1941, Mr. Fink became a member of the staff of the Radiation Laboratory at MIT, where, in 1943, he headed the loran division. He then transferred to the Office of the Secretary of War as consultant on radio navigation and radar, and traveled from Egypt, to Australia, siting loran stations and arranging for the use of the loran system by the Allied forces. He participated in the atom bomb tests at Bikini, also.

Donald G. Fink

Mr. Fink is the author of numerous books, including "Engineering Electronics," "Principles of Television Engineering," and "Radar Engineering." As editor of the Proceedings of the National Television System Committee, member of the Television Panel of the Radio Technical Planning Board, and currently as a member of the Joint Technical Advisory Committee, he is active in standardization work, particularly in the field of television.

In 1948, Mr. Fink was chairman of the IRE Television System Committee, and in 1950 he was a member of the Senate Advisory Committee on Color Television (the "Condon Committee"). For the past three years he has represented the United States at television conferences in Zurich, London and Geneva. At present he is vice-chairman of the National Television System Committee and chairman of NTSC panel 12 on color system analysis. He is a fellow of the AIEE and a member of Tau Beta Pi, Sigma Xi, and Eta Kappa Nu.

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Stanley V. Forgue (M'45) received his B.S. degree in Physics in 1939 and the B.E.E. and M.S. degrees in 1940 from Ohio State University. He was a graduate assistant in the Physics Department there from 1939 to 1940. While taking additional graduate work, he was a research engineer at the Ohio Engineering Experiment Station from 1940 to 1941 and a research fellow in the Ohio State Research Foundation from 1941 to 1942. Since then he has been with the RCA Laboratories at Harrison and Princeton, N. J. Mr. Forgue is a member of the American Physical Society, Tau Beta Pi, Sigma Pi Sigma, Sigma Xi and is a Registered Professional Engineer.

S. V. Forgue

Contributors to Proceedings of the I.R.E.

A. D. Fowler was born on June 10, 1901, in Hopkinsville, Ky. He attended Cornell University for one year and transferred to the Massachusetts Institute of Technology, Interrupting his studies for a period of four years to engage in hydro-electric engineering at Muscle Shoals, Ala., he returned to MIT, where he received the degree of S.B. in 1928. Immediately after graduation he joined the department of development and research of the American Telephone and Telegraph Company, and with that department, transferred to the Bell Telephone Laboratories. Inc., in 1934. He is presently engaged in studies concerned with the subjective evaluation of television picture impairments.

A. D. Fowler

Prior to World War II, Mr. Fowler's principal contributions were in the field of analysis of special transmission problems and in the evaluation of proposed transmission systems. During the war he was actively employed in several projects for the Armed Services and for the National Defense Research Council.

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Norman S. Freedman was born September 8, 1920, in Mount Vernon, N. Y. He received the B.Ch.E. degree from the New York University in 1943. He has since done graduate work at Columbia University.

N. S. Freedman

During World War II, Mr. Freedman was active in the development of direct silver-to-glass seals for use in microwave tubes for airborne radar. He has been with the Tube Department, Radio Corporation of America, Harrison, N. J., specializing in electrochemical work and the process development of electron tubes.

Mr. Freedman is a member of the American Chemical Society.

❖

Albert W. Friend (A'34–M'39–SM'43) was born in Morgantown, W. Va. on January 24, 1910. He received the B.S.E.E. and M.S. (Physics) degrees from West Virginia University in 1932 and 1936, respectively, and the S.D. degree in communication engineering from Harvard University in 1948. Between 1929 and 1934, he was engaged in public utilities and radio interference engineering and communications consultation. From 1934 to 1937, he was an instructor, and from 1937 to 1944, an assistant professor of physics at West Virginia University, on leave after 1939. In 1939 he transferred his tropospheric-sounding research to Harvard University, where he was an instructor in physics and communication engineering and a re-research fellow in Cruft Laboratory until 1941, and a research fellow in the Blue Hill Meteorological Observatory until 1942.

A. W. Friend

In January, 1941, Dr. Friend transferred to the Radiation Laboratory of the Massachusetts Institute of Technology, as a research associate and later a staff member, where he worked on the development of microwave receivers, taught in the MIT Radar School, and extended his tropospheric echo studies. From July, 1942, to August, 1944, he acted as technical director of the Heat Research Laboratory at MIT, and at the same time as a consultant on guided-missile control with Division 5 of NDRC.

In 1944 he joined the RCA Victor Division, in Camden, N. J., continuing in television development until 1947. During 1946 and 1947, he was also on the research staff of the Electronic Research Laboratory at Harvard University. Since June, 1947, he has been a member of the research staff of the Radio Corporation of America, in the RCA Laboratories Division at Princeton, N. J., doing research work on magnetic recording and reproducing, vacuum tubes and the deflection and control of electron beams in tri-color picture tubes. In 1950 he received an RCA Laboratories award and a citation "For ingenuity in developing and designing magnetic circuits for tri-color kinescopes."

In June, 1951, Dr. Friend became Director of Engineering of the Daystrom Instrument Division of Daystrom, Inc., where he is now chiefly concerned with radar gun fire control apparatus and technical consultation with the management group of Daystrom, Inc.

Dr. Friend is a member of the AIEE, the Acoustical Society of America, the AAAS, the American Ordnance Association, the American Meteorological Society, the American Geophysical Union, Tau Beta Pi, Sigma Pi Sigma, Sigma Xi, and the Harvard Engineering Society. He is a registered professional engineer.

❖

Peter C. Goldmark (A'36–M'38–F'42) was born on December 2, 1906, in Budapest, Hungary. He is a graduate of Vienna Technical College, Vienna, Austria, from which institution he also holds the Ph.D. degree.

In 1950 Dr. Goldmark was appointed vice-president in charge of engineering research and development at the Columbia Broadcasting System. Formerly, he was director of engineering and research development where he and his associates developed the CBS color television system and its long-playing records.

P. C. Goldmark

Dr. Goldmark who developed the long-microgroove phonograph record through nearly three years of intensive laboratory work, joined CBS in 1936 to take part in research and television activities. Within a short time he was named chief television engineer, and in September, 1940, demonstrated the CBS full-color television system which he developed for ultra-high frequency broadcasting. During the war Dr. Goldmark and his associates were engaged exclusively in electronic research for the Armed Services. Much of this work took him to the European and South Pacific theaters of war.

He was awarded the IRE Morris Liebermann Memorial Prize in 1945 for his "contributions to the development of television systems, particularly in the field of color." He has served on several IRE committees.

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Harold R. Holloway was born in New Burnside, Illinois on July 17, 1920. He attended the Northern Illinois State Teachers College and the University of Illinois, from which he received the B.S. degree in electrical engineering. From 1942 to 1944 he was engaged in the study of propagation problems associated with direction finder errors. He has served two years in the Signal Corps.

H. R. Holloway

Mr. Holloway joined Sylvania Electric Products Inc., in 1948 as a member of the Navigation Group of the Physics Laboratories, at Bayside, L.I., N.Y. Later, as a member of the theoretical group, he has been concerned with problems associated with the transmission of video intelligence, and is now engaged with radar and navigation problems He is acting secretary of the Professional Group on Information Theory.

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Edward W. Herold (A'30–M'38–SM'43–F'48) was born on October 15, 1907, in New York, N. Y. He received a B.S. degree from the University of Virginia in 1930 and an

Contributors to Proceedings of the I.R.E.

M.S. degree from the Polytechnic Institute of Brooklyn in 1942. From 1924 to 1926, he was associated with the Bell Telephone Laboratories and from 1927 to 1929 with E. T. Cunningham, Inc. In 1930 he entered the Research and Development Laboratory of the RCA Manufacturing Company at Harrison, N. J., and since 1942, has been with the RCA Lab. Division at Princeton, N. J. Mr. Herold is a member of Phi Beta Kappa and Sigma Xi.

Edward W. Herold

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In July, 1946, John M. Hollywood (SM'50) joined the staff of Airborne Instruments Laboratory, Inc., Mineola, New York, as a consultant in the electronic engineering aspects of air navigation, traffic control systems development and of special devices.

J. M. Hollywood

Mr. Hollywood received the B.S. degree in communications in 1931 and the M.S. degree in electrical engineering in 1932 from Massachusetts Institute of Technology. In 1933, he became associated with the Electron Research Laboratories, and in 1935, joined the Ken-Rad Tube Corporation on cathode-ray tube development.

From 1936 to 1943, Mr. Hollywood performed color-television work for the Columbia Broadcasting System, and in 1943, he went to England as a consultant on radio and radar countermeasures for the Radio Research Laboratory of Harvard University. Two years later, he returned to join the Naval Research Laboratory. In October, 1949, he rejoined the Columbia Broadcasting System.

Recognized for his achievements in the field of color television, Mr. Hollywood holds the patent on a switching device for television color mixing.

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Harold B. Law was born on September 7, 1911, at Douds, Ia. He received the degree of B.S. from Kent State University in 1934, and the degree of B.S. in education. In 1936 he received his M.S. and in 1941 his Ph.D. in physics, both from the Ohio State University.

Harold B. Law

Dr. Law taught elementary mathematics at Maple Heights, Ohio and at Toledo, Ohio, in 1935 and 1937–1938, respectively. In 1941 he joined the Radio Corporation of America. At present, he is associated with the RCA Laboratories Division in Princeton, N. J.

Dr. Law is a member of the American Physical Society and Sigma Xi.

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B. D. Loughlin (A'40–M'45) was born in New York, N. Y., on May 19, 1917. He received the B.E.E. degree in 1939 and the E.E. degree in 1945 from Cooper Union. In 1946 he received the M.S. degree in electrical engineering from Stevens Institute of Technology.

B. D. Loughlin

Since 1939 Mr. Loughlin has been employed in research and development on FM and television receivers and IFF equipment at the Hazeltine Corporation. For the past two years he has been doing research on color-television systems.

Mr Loughlin is an associate member of the American Institute of Electrical Engineers and is an officer of the Radio Club of America.

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Meyer Leifer (A'46–M'48–SM'50) was born in New York, N. Y., in 1914. He received the B.S. and M.S. degrees from Brooklyn College and Columbia University, respectively, the former in mathematics and the latter in physics. After teaching for several years in the New York City secondary schools, he joined the United States Navy and served as a radio-radar officer during the war. Mr. Leifer became a member of the physics laboratories staff of Sylvania Electric Products Inc. upon his release from active duty, and has been engaged principally in the application of the theory of communication to navigation and television systems.

Meyer Leifer

Mr. Leifer is now the leader of the theoretical group of the circuits section, and is teaching in the Graduate School of the Brooklyn Polytechnic Institute. He is a member of the American Physical Society.

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Russell R. Law (A'34–M'40–SM'43) was born on January 11, 1907 at Hampton, Iowa. He received the B.S. and M.S. degrees in electrical engineering from Iowa State College in 1929 and 1931. From 1929 to 1931, he taught electrical engineering at Iowa State College. In 1933 he received the D.S. degree from the Harvard Engineering School. From 1933 to 1934 he was a research associate in geophysics at Harvard University. Following several months as seismologist with the Shell Petroleum Corporation in Houston, Texas, in 1934 he joined the Research and Engineering Department of the RCA Manufacturing Company in Harrison, N. J. In 1942 he transferred to the RCA Laboratories Division at Princeton, N. J. Dr. Law is a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and the American Physical Society.

Russell R. Law

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Nathan Marchand (A'39–M'44–SM'50) was born on June 20, 1916, in Shawinigan Falls, Canada. He received the B.S. degree from the College of the City of New York and the M.S. degree from Columbia University, both in electrical engineering.

Nathan Marchand

Mr. Marchand has been a lecturer in electrical engineering and has served as a consultant in the fields of cardiology and antenna and circuit design. He was formerly the head of the Circuits Section of the Physics Laboratories, at Bayside, L.I., N.Y. He is now head of Marchand Electronic Laboratories and a consultant in the fields of television, navigation systems, and information theory.

He is a member of the Board of Editors of the Institute and Chairman of the Professional Group on Information Theory.

Mr. Marchand is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.

❖

Kenneth M. McLaughlin (SM'48) was born in Baltimore, Md., on January 3, 1906. He attended Rutgers University and Newark College of Engineering.

K. M. McLaughlin

From 1924 to 1936, he was employed by Atwater Kent Manufacturing Company. Since 1936 Mr. McLaughlin has been with the Tube Department, Radio Corporation of America, Harrison, N. J., specializing on developmental tubes and methods for their manufacture.

Since 1942 he has been manager of the Tube Development Shop at Harrison, N. J.

Hannah C. Moodey (SM'51) was born in Plainfield, N. J., on August 6, 1906. She received the A.B. degree from Smith College in 1927, the M.Sc. degree in physics from Rutgers University in 1933, and the B.S. degree in electrical engineering from M.I.T. in 1936. For several years she was employed in the Long Lines Engineering Department of the American Telephone and Telegraph Company. Since 1936 she has been with the Tube Department of the Radio Corporation of America, at first in Harrison, N. J. and, since 1943, in Lancaster, Pa., where she specialized in cathode-ray tube design. For the past two years she has had responsibility for the design of the metal-shell tri-color kinescope.

H. C. Moodey

Donald G. Moore (S'46) was born on June 17, 1924, in Faribault, Minn. He received the B.E.E. degree from the University of Minnesota in 1947, after doing radar work in the U. S. Navy for two years. In 1947 he joined the technical staff of the RCA Laboratories, and at present he is engaged in circuit and systems research in television and radar. Mr. Moore is a member of Tau Beta Pi and Eta Kappa Nu.

Donald G. Moore

Frederick H. Nicoll (A'39–SM'43) was born in Saskatchewan, Canada, on June 6, 1908. He received the B.Sc. degree in physics in 1929 and the M.Sc. degree in 1931 from Saskatchewan University. He held an 1851 Exhibition Scholarship to Cambridge University, England, for three years' research and received the Ph.D. degree from that university in 1934.

F. H. Nicoll

From 1934 to 1939 Dr. Nicoll was associated, as research physicist, with Electric and Musical Industries, Ltd. in London, England. He was employed by the RCA Victor Division of the Radio Corporation of America at Camden, N. J. as research engineer from 1939 to 1941. Since 1941 he has been engaged in research on cathode-ray tubes and electron optics at the RCA Laboratories Division in Princeton, N. J.

Dr. Nicoll is a member of the American Physical Society and of Sigma Xi.

James J. Reeves (A'40) was born at Sao Paulo, Brazil, on February 1, 1911, and was educated in East Stroudsburg, Pa. From 1926 to 1930 he served in the U. S. Navy as a radio operator, and from 1930 to 1934 in the U. S. Coast Guard as a radio operator and instructor. In 1932 he was graduated from the U. S. Navy Radio Engineering School at Anacostia Station, D. C.

James J. Reeves

Mr. Reeves was in radio and television work from 1934 to 1939, and joined the television-engineering department of the Columbia Broadcasting System in the latter year. He participated in several phases of the early television field tests, and was assigned to research in the television laboratories soon thereafter.

During World War II Mr. Reeves worked in the field of radar countermeasures in the CBS laboratories and later in the American-British Laboratories in England as research associate of Harvard University. Since the war he has been in charge of color-television studio-equipment design.

Nathan Rynn (S'42–A'46–M'50) was born in New York, N. Y., on December 2, 1923. He received the degree of B.E.E. from the City College of New York in 1944.

During the early part of 1944, Mr. Rynn worked as a design and development engineer for the Hamilton Radio Corporation in New York. During World War II, he served with the United States Navy from 1944–1946. After leaving the Navy, he went to the University of Illinois as a research assistant in electrical engineering, where he also received the degree of M.S. in 1947. Mr. Rynn then joined the research organization of RCA Laboratories at Princeton, N. J., where he is presently employed.

Nathan Rynn

David D. Van Ormer (A'51) was born on April 19, 1923, in Beaver Falls, Pa. He received the B.S. degree in physics from the University of Delaware in 1947, and has since done graduate work at Indiana University and Franklin and Marshall College. Since March 1948 he has been with the Tube Department of the Radio Corporation of America in Lancaster, Pa., where he specializes in cathode-ray tube design.

Mr. Van Ormer is a member of Phi Kappa Phi, Pi Mu Epsilon, and Sigma Pi Sigma.

D. D. Van Ormer

Paul K. Weimer (A'43–SM'51) was born at Wabash, Ind., on November 5, 1914. He received the degree of B.A. from Manchester College in 1936, the degree of M.A. in physics from the University of Kansas in 1938, and the degree of Ph.D. in physics, from the Ohio State University in 1942.

During 1936–1937, Dr. Weimer was a graduate assistant in physics at the University of Kansas, and from 1937–1939, he taught physics and mathematics at Tabor College, Hillsboro, Kan. He was also a graduate assistant in physics at the Ohio State University. Since 1942, he has been engaged in television research at the RCA Laboratories, Princeton, N. J.

Paul K. Weimer

Dr. Weimer is a member of the American Physical Society and Sigma Xi.

W. T. Wintringham (A'26–SM'45–F'51) was born in Brooklyn, N. Y., on January 18, 1904. He received the B.S. degree in electrical communication engineering from Harvard University in 1924, and immediately joined the American Telephone and Telegraph Company in the department of development and reseach. In 1935 he transferred to the Bell Telephone Laboratories.

W. T. Wintringham

Before World War II, Mr. Wintringham was associated closely with the development of radio telephone systems for spanning natural barriers; the long-wave translantic telephone; the short-wave MUSA receiving system; and the multiplex telephone system used between the Virginia Capes and operated in the vhf region. During the war he worked on a number of classified projects. Recently his work has been in the color television fields, with particular emphasis on color.

Correspondence

Optimum Vertical Resolution in Microwave Probing of the Atmosphere*

In probing the atmosphere with microwave radar it is often necessary to study phenomena which are horizontally homogeneous, but which vary considerably with altitude. In order to study the fine structure of these vertical variations, it is, of course, desirable to utilize the probing system so that its resolving power in the vertical may be optimized. With most present-day systems, in which the width of the beam is larger than the depth of the pulse in space, maximum vertical resolution is obtained when the beam is directed vertically. However, when utilizing the shorter microwaves, where narrow beam widths are possible with reasonable-size antennas, the pulse length may exceed the beam width. Consequently, the elevation angle at which best vertical resolution is obtained is other than 90 degrees. This note deals with the angle of elevation for optimum vertical resolution.

Consider the case in which it is desired to observe a phenomenon at altitude h, with a probing system having a beam width ϕ, and space pulse length p. The space pulse length $p=c\tau/2$, where c is the velocity of light and τ is the duration of the pulse. Assuming the phenomenon in question to be horizontally homogeneous, what is the most desirable angle of tilt of the beam θ to minimize the vertical thickness t of the volume sampled? From Fig. 1 it is seen that the

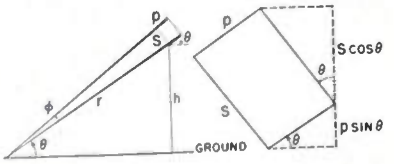

Fig. 1

vertical thickness of the pulse volume is very closely approximated by the sum of $s \cos \theta$ and $p \sin \theta$. Since $s=h\phi/\sin \theta$,

$$t=p \sin \theta \div \wedge + [t=p \sin \theta + h\phi/\tan \theta]. \quad (1)$$

The problem is then simply to minimize t with respect to θ. However, since there are two minima in the curve of t versus θ, it is necessary to select the absolute minimum. Fig. 2 shows various curves of t/p versus θ for several values of the parameter $\phi h/p$. It is evident that for all values of $\phi h/p > 0.3$, the optimum angle is 90 degrees; it is best to

* Received by the Institute, June 4, 1951.

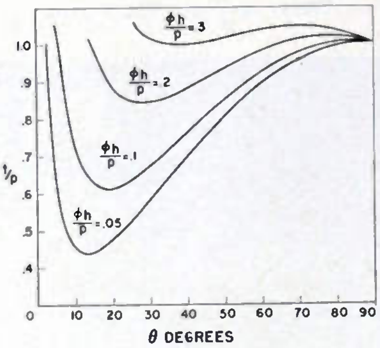

Fig. 2

observe at vertical incidence. However, for $\phi h/p < 0.3$ it is desirable to use oblique incidence. The exact angle may be determined from the roots of the equation

$$\cos^3 \theta - \cos \theta \div \wedge + \left[\cos^3 \theta - \cos \theta + \frac{\phi h}{p} = 0\right]. \quad (2)$$

The value of θ which gives the smallest t is plotted in Fig. 3 versus the product ϕh for

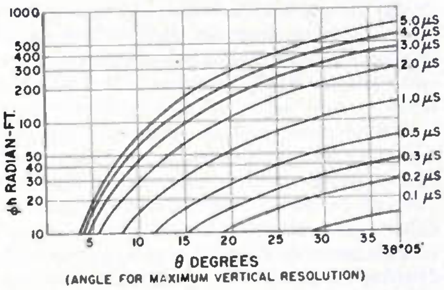

Fig. 3

various values of the pulse length p. The curves are plotted out to $\theta=38$ degrees, corresponding to $\phi h/p=0.3$. Beyond this point the optimum angle is 90 degrees.

In any particular experiment, of course, other considerations may govern the choice of elevation angle. For example, when the reflections from the phenomenon at height h are weak, use of an oblique angle of incidence may increase the path length prohibitively so that the signal may not be detected at the angle of optimum resolution.

DAVID ATLAS
LUDWIG KATZ
Geophysics Research Division
Air Force Cambridge Research Center
Cambridge, Mass.

Velocity-Modulation in Television-Image Reproduction*

For a number of years a fierce controversy raged over the question of whether or not there was a difference between frequency and phase modulation of a carrier wave. That such a difference did in fact exist was well illustrated by Howe, who cited the case of modulation by a square wave, and the controversy has long since died down.

It is unfortunate, then, that a similar confusion of terms should have arisen in the minds of Honnell and Prince when they wrote their paper.[1] The method of reproduction referred to is not velocity modulation, and would more correctly be termed "displacement," or "position-change-modulation."

If the horizontal displacement of the spot on a cathode-ray tube face is denoted by x, then in a normal intensity-modulated display

$$x=v_0 t$$

and $v=dx/dt=v_0$, which is a constant.

For a velocity-modulated display, the velocity contains a component which is proportional to the signal intensity[2]

$$v=v_0+k. \quad F(t).$$

Thus, the velocity-modulation reproduction of a square wave would consist of alternating bright and dark bars of unequal widths (not the picture shown in Fig. 2 of the paper referred to). This raises the fundamental difficulty of velocity-modulation systems, namely that of avoiding geometrical distortion due to the varying velocity.

In the paper referred to, the treatment is quite logical and the experiments described are very interesting, but the title and the paper itself need correcting by replacing the term "velocity modulation," wherever it occurs, and particularly in the definition implied in (1) and (2), by some more suitable phrase, possibly "displacement modulation." Velocity modulation should be reserved for cases where the velocity varies with the signal intensity, not its first derivative.

A. B. THOMAS
Standard Telephones and Cables Pty. Ltd.
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Alexandria, Sydney, Australia

* Received by the Institute, June 13, 1951.

[1] Honnell and Prince, "Television image reproduction by use of velocity-modulation principles," PROC. I.R.E., March, 1951.

[2] Zworykin and Morton, "Television," Wiley; 1940, pp. 238–239.

Institute News and Radio Notes

Professional Group Notes

Mr. Lewis Winner, Chairman of the **IRE Professional Group on Broadcast Transmission Systems,** has announced the results of the recent election for membership on the Group's Administrative Committee. The following members will serve on this Committee until June 30, 1954: R. J. Rockwell, T. L. Rowe, P. G. Caldwell, Karl Troelgen, and J. B. Epperson. The Group held a very successful UHF Symposium on September 17, at the Franklin Institute, Philadelphia, Pa., at which papers were presented by members of such companies as General Electric, RCA Laboratories, DuMont Laboratories, General Radio Company, Sylvania, and NBC. S. L. Bailey was Moderator for the Symposium, and D. D. Israel, who is the Chairman of the **IRE Professional Group on Broadcast and Television Receivers,** was Chairman of the afternoon session.

The **IRE Professional Group on Antennas and Propagation** sponsored a Fall Technical Meeting jointly with the USA National Committee of the International Scientific Radio Union (URSI), on October 8, 9, and 10, at Cornell University, Ithaca, N. Y. Of particular interest at the meeting was a session on Extraterrestrial Radio Noise.

The new Administrative Committee of the **IRE Professional Group on Instrumentation** will hold its first meeting on Tuesday, October 23, in Chicago, during the National Electronics Conference. This Group is also in the process of polling its members as to the possible assessment for publication and distribution of TRANSACTIONS. The results of this poll will be announced by Ernst Weber, Chairman, upon his return from a European vacation.

D. K. Martin of Bell Telephone Laboratories, has been named to represent the **IRE Professional Group on Airborne Electronics** on a subcommittee which will work towards preparing a program for the 1952 Annual Convention of the IAS, on "Electronics in Aviation."

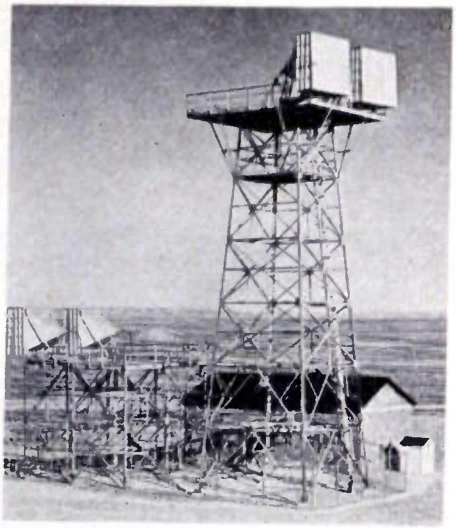
The **IRE Professional Group on Audio** has selected a new Vice-Chairman to succeed K. C. Morrical, recently deceased, from among the members of it Administrative Committee which now stands as follows: B. B. Bauer, Chairman; J. K. Hilliard, Vice-Chairman; S. L. Almas, J. J. Baruch, L. L. Beranek, and A. M. Wiggins, members. The Group also appointed the following committee chairmen: Midwestern Editor of NEWSLETTER, D. W. Martin; Eastern Editor of NEWSLETTER, J. J. Baruch; Western Editor of NEWSLETTER, V. Salmon; Program Committee for the IRE/RTMA Fall Meeting, F. H. Slaymaker; Program Committee for the IRE Spring Meeting, W. S. Bachman; Membership Committee, A. M. Wiggins; Sections Group Committee, S. L. Almas; Papers Study Committee, R. R. Buss; Papers Procurement Committee, L. L. Beranek. The July, 1951 issue of the Audio Group NEWSLETTER has taken on a new format to resemble the external cover of the PROCEEDINGS. In addition to the editorials, technical programs, and section notes, a new series of technical editorials was instituted, written especially for the NEWSLETTER. This issue contained an editorial by Leo L. Beranek, entitled, "Design of Loudspeaker Grilles." Also announced was the adoption by the Group of a $2.00 assessment to cover publication and distribution of the NEWSLETTER, technical papers, etc.; notices of assessment billings were sent to all members.

The **IRE Professional Group on Broadcast and Television Receivers** will hold an Administrative Committee meeting at the Radio Fall Meeting in Toronto, on October 29, 30, and 31, to consider increasing the size of the committee to 15 members. The members will serve for a period of three years each. Another point to be discussed will be the previous action of the IRE Board of Directors whereby the Institute will match the treasury of each Group up to a maximum amount of $1,000, based on the balance in the Group's treasury prior to June 30, 1952. It is also planned to create the office of Treasurer in the Group and to levy an assessment of approximately $2.00 per member for the publication and distribution of newsletters, technical papers, and the like. In addition to the members of the Administrative Committee now serving a term of office, nine other members have been invited to serve on this Committee by its Chairman, D. D. Israel; an election will be held at the time of the Fall Meeting.

A new **IRE Professional Group on Microwave Electronics** is in the process of being formed. Those interested in membership in this Group are requested to contact Ben Warriner, IV, 151 Jefferson Avenue, Thornwood, N. Y.

Newly appointed members of the **IRE Professional Group on Quality Control** are: L. Bass, J. W. Greer, F. Miller, P. K. McElroy, W. Oliver, E. P. Reardon, R. R. Stansel, and E. K. Wimpy.

Coast-to-Coast Television



Shown above is one of a chain of 107 Bell System radio-relay stations which now link New York and San Francisco with telephone and television service. Spaced about 30 miles apart, these stations operate on a frequency of 3,700 to 4,200 mc.

Calendar of COMING EVENTS

1951 National Electronics Conference, Edgewater Beach Hotel, Chicago, Ill., October 22–24

AIEE Fall General Meeting, Cleveland, Ohio, October 22–26

Optical Society of America 36th Annual Meeting, Hotel Sherman, Chicago, Ill., October 23–24

Professional Group on Vehicular Communications Annual Conference, Sheraton Hotel Chicago, Ill., October 25, 26

Radio Fall Meeting, Kind Edward Hotel, Toronto, Ont., Canada, October 29–31

American Physical Society Meetings on Electron Emission from Surfaces, and Division of Electron Physics. National Bureau of Standards, Washington, D. C., November 1–3

Third Annual Technical Conference, Kansas City Section, Hotel President, Kansas City, Mo., November, 16, 17.

First JETEC General Conference, Absecon, N. J., November 29–December 1

IRE Nuclear Symposium, Brookhaven National Laboratory, Upton, L. I., N. Y., December 3, 4.

Joint IRE/AIEE Computer Conference, Benjamin Franklin Hotel, Philadelphia, Pa., December 10–12

IAS-IRE-ION-RTCA Conference on Electronics in Aviation, IAS 20th National Convention, New York, N. Y., January 28–31.

1952 IRE National Convention Waldorf-Astoria Hotel and Grand Central Palace, New York, N. Y., March 3–6

IRE National Conference on Airborne Electronics, Biltmore Hotel, Dayton, Ohio, May 7–9

4th Southwestern IRE Conference and Radio Engineering Show, Rice Hotel, Houston, Tex., May 16–17

Institute News and Radio Notes

Program Announced for IRE Nuclear Symposium

The Institute, with the co-operation of the Atomic Energy Commission, will hold the IRE Nuclear Symposium at the Brookhaven National Laboratory, Upton, L. I., N. Y., on December 3 and 4, 1951. The program has been planned as follows.

Monday, December 3, 1:30–4:30 P.M.: "Brookhaven Facilities," L. J. Haworth, Brookhaven National Laboratory; "Nuclear Research of Engineering Interest," Donald Hughes, Brookhaven National Laboratory; "Electronic Research at Brookhaven," J. P. Blewett, Brookhaven National Laboratory; "Some Recent Nuclear Developments at MIT," Martin Deutsch, Massachusetts Institute of Technology; "Recent Developments in Nuclear Instrumentation in the Field of Health Physics," H. M. Parker; "The Secrecy Problem on Nuclear Engineering Information," J. G. Beckerley, Atomic Energy Commission; "The Problems of Liaison Involved in Conducting Information Services for Engineers," N. H. Jacobsen, Atomic Energy Commission.

The evening program has been arranged as follows: 5:30, Cocktails; 7:00, Dinner, Toastmaster, L. V. Berkner, American Universities, Inc.; 8:15, Panel Discussion, "The Role of Electronics Engineering in the Atomic Energy Commission," T. K. Glennan, Atomic Energy Commission, Keith Henney, *Electronics*, and Clark Goodman, Massachusetts Institute of Technology.

Tuesday, 9:15–12:00 A.M., December 4, the talks will resume on the following subjects: "Applications of Scintillation Counters to High Energy Physics," Robert Hofstader, Stanford University; "Assessing the Function of Small Research Reactors," C. K. Beck, North Carolina State College; "Industrial Interest in Nuclear Reactors," P. N. Powers, Monsanto Chemical Company; "Using Fission Products in Industry, P. J. Lovewell, Stanford Research Institute.

D. H. Loughridge, of the Atomic Energy Commission, is the Program Chairman for Symposium, and Urner Liddel, of the Office of Naval Research, is in charge of the Planning Committee. A registration fee of $5.00, which is requested to be in by November 15, includes the dinner on December 3.

Kansas City Section Conference Slated

Details are being completed for the Third Annual Technical Conference sponsored by the Kansas City Section of the IRE, to be held on November 16 and 17, at the Hotel President, Kansas City, Mo.

"Instrumentation" has been selected as the theme of this year's conference and the schedule of papers will include those pertaining to instrumentation problems in Aircraft and Air Navigation, Television, Broadcasting and Communication, and general instrumentations of laboratories.

DuMont Names New Network Director

Chris J. Witting has been appointed director of the DuMont Television Network and of the three DuMont-owned and operated stations—WABD in New York, WTTG in Washington, and WDTV in Pittsburgh. Mr. Witting has been general manager of the network for the last 18 months.

The appointment was made by Mortimer W. Loewi, who simultaneously announced his retirement as network director to return to his former position as executive assistant to the president of the Allen B. DuMont Laboratories, Inc.

Joint IRE/AIEE Computer Conference Slated

A joint IRE/AIEE Computer Conference for a discussion of the principal operating digital computers will be held in Philadelphia, December 10, 11, and 12. This will be the first meeting held specifically to review accomplishments in the relatively new field of large-scale digital computer engineering. Selection of the conference location has been influenced by the large number of computer manufacturers and users in the area. Inspection tours to these centers will be scheduled.

Arrangements for the meeting are being completed by a committee under the Chairmanship of John C. McPherson of IBM Corporation, consisting of members of the Computing Devices Committees of both sponsoring societies, as well as invited members of the Association for Computing Machinery. Conference meetings will be held Monday and Wednesday, December 10 and 12, in the Benjamin Franklin Hotel, and on Tuesday in the auditorium of the Edison Building. A luncheon is scheduled for Wednesday noon at the Benjamin Franklin, and inspection trips to local computer manufacturing centers are planned for Monday and Wednesday.

The committee has chosen as its aim in preparing the conference agenda the discussion of the useful results obtainable from the present large-scale digital computers. It is hoped that an indication of the shortcomings revealed by working on actual problems will be an aid in showing the direction along which improvements should be made.

To accomplish this aim, papers from computing groups which have realized an operating system have been invited. Parallel sessions will be avoided, and sufficient time will be allotted to each paper so that complete treatment, including discussion, can be made. The keynote of the conference is to be evaluation of achievements. Future possibilities will be de-emphasized so that computers and engineers may discover what has been accomplished so far in this rapidly expanding field.

Oak Ridge Announces Special Training Course

A course in the techniques of preparing problems for high speed digital computing machinery will be given at Oak Ridge from December 3 to 14, by the Special Training Division of the Oak Ridge Institute of Nuclear Studies, in co-operation with the Oak Ridge National Laboratory.

The course will be centered around the computing machine to be installed at the Oak Ridge National Laboratory, although modifications of machines and preparation techniques will be discussed. The Oak Ridge National Laboratory machine will be an electronic automatic computer, single address type, patterned after the Institute for Advanced Study computer.

Dr. Alston S. Householder, Chief of the Mathematics Panel, Oak Ridge National Laboratory, will be the course director. Assisting him will be staff members of Argonne National Laboratory, the Los Alamos Scientific Laboratory, the Computer Branch of the Office of Naval Research, and the Institute for Advanced Study.

The course will be limited to 30 participants. A registration fee of $25 will be charged, and participants are expected to pay their own living and traveling expenses.

Application blanks and additional information may be obtained from Ralph T. Overman, Chairman, Special Training Division, Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tenn.

LAST CALL!

AUTHORS FOR IRE NATIONAL CONVENTION!

W. H. Doherty, Chairman of the Technical Program Committee for the 1952 IRE National Convention, to be held March 3–6, requests that prospective authors submit the following information:

1. Name and address of author
2. Title of paper
3. A 100-word abstract and additional information up to 500 words (both in triplicate) to permit an accurate evaluation of the paper for inclusion in the Technical Program.

Please address all material to W. H. Doherty, Bell Telephone Laboratories, Inc., Murray Hill, N. J. The deadline for acceptance is November 5, 1951. Your prompt submissions will be appreciated.

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The Annual Index to these Abstracts and References, covering those published in the PROC. I.R.E. from February, 1950, through January, 1951, may be obtained for 2s.8d. postage included from the *Wireless Engineer*, Dorset House, Stamford St., London S.E., England. This index includes a list of the journals abstracted together with the addresses of their publishers.

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ACOUSTICS AND AUDIO FREQUENCIES

534+621.395 **2082**

1951 I.R.E. National Convention Program—(PROC. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

167—A Single-Ended Push-Pull Audio Amplifier—A. Peterson and D. B. Sinclair.
168—The Application of Damping to Phonograph Reproducer Arms—W. S. Bachman.
169—Transient Testing of Loudspeakers—O. K. Mawardi.
195—Amplitude and Phase Measurements on Loudspeaker Cones—M. Corrington.
196—Design Elements for Improved Bass Response in Loudspeaker Systems—H. T. Souther.
197—Direct Radiator Loudspeaker Mounting—H. F. Olson.
198—Physical and Electrical Constants of Direct Radiator Loudspeakers—L. L. Beranek.

534-14 **2083**

The Sonic Scattering Layer in the Sea—A. C. Burd and A. J. Lee. (*Nature* (London), vol. 167, pp. 624–626; April 21, 1951.) A report of observations of variable scattering layers in seas near Great Britain. No general explanation of their origin can be given, but some layers are most probably due to small marine organisms, others to shoals of young fish.

534.22-14:534.321.9 **2084**

A Method of Measuring the Velocity of Propagation of Ultrasonic Waves in Fluids—T. S. Velichkina and I. L. Fabelinski. (*Compt. Rend. Acad. Sci.* (URSS), vol. 75, pp. 177–180; November 11, 1950. In Russian.) The method is based on the production of interference by transmission through a stratified medium; the principle has previously been used for determining the velocity of sound in solids.

534.232 **2085**

An Electromechanical Source of Elastic Waves in the Ground—F. F. Evison. (*Proc. Phys. Soc.* (London), vol. 64, pp. 311–322; April 1, 1951.) A large moving-coil transducer is described which, when attached rigidly to rock, radiates sinusoidal vibrations of controllable amplitude, frequency, and duration. Its operation is analyzed by the method of electromechanical analogy. Measurements made in a chalk mine are reported; 20-ms square pulses of 300-, 600- and 1,000-cps energy were radiated, the power being about 0.05 w. The detecting system included a piezoelectric microphone and oscillograph, with an over-all magnification of about 10^9.

534.321.7.08:621.317.755 **2086**

Precise Calibration of Tuning Forks—Addink (*See* 2234.)

534.373:534.414 **2087**

The Damping of Acoustic Resonators—K. Voelz. (*Z. angew. Phys.*, vol. 3, pp. 67–72; February, 1951.) The damping is investigated for the general case where the compressional viscosity of the resonating medium is not necessarily equal to zero. The two terms, due respectively to the internal friction of the medium and the boundary friction, are calculated for a resonator of arbitrary form. When applied to cylindrical and spherical resonators, the results obtained agree with the formulas of Kirchhoff and Lamb. The influence of thermal conductivity is discussed.

534.62 **2088**

Anechoic Chamber for Acoustic Measurements—D. W. Robinson. (*Elec. Commun.* (London), vol. 28, pp. 70–77; March, 1951.) The room was constructed in accordance with fundamental designs outlined by Beranek and Sleeper (3529 of 1946), and uses fiberglass wedges as the main sound-absorbing material. Results of performance tests are given.

534.85 **2089**

Thorn Needles—A. M. Pollock. (*Wireless World*, vol. 57, pp. 145–146; April, 1951.) Further discussion, including description of the method of sharpening. See also 1831 of September.

534.862.4:534.861.3:534.421 **2090**

Bass without Big Baffles—K. A. Exley. (*Wireless World*, vol. 57, pp. 132–134; April, 1951.) Description of a method of increasing the content of harmonics of the lower bass frequencies, by introducing harmonics from a second channel in which amplitude distortion has been allowed to occur.

621.395.62:621.395.667 **2091**

A Continuously Variable Equalizer—Fling. (*See* 2129.)

621.395.623.7:537.52 **2092**

Variations of Discharge Parameters in Preliminary Discharges, and Measurement of Variations—Fucks. (*See* 2143.)

621.395.623.73 **2093**

Proposal for the Quality Rating of Dynamic Cone Loudspeakers—E. Hüttmann. (*Elektrotechnik Berlin*, vol. 5, pp. 128–132; March, 1951.) It is suggested that assessment of the quality of loudspeakers should be based on definite characteristic-physical data, and that it should be possible to determine the necessary data by relatively simple methods. The principal characteristics of cone loudspeakers are discussed, and measurement methods are outlined and applied to a typical loudspeaker.

621.395.625.3 **2094**

New Professional Tape Recorder—W. E. Stewart. (*Audio Eng.*, vol. 35, pp. 21–23, 37; April, 1951.) A detailed description of the design and construction of RCA Type-RT-11A equipment. Remote control, involving relay and solenoid operation of all functions, is provided; a safety switch stops the machine automatically in case of tape breakage. Design of the recording and reproducing amplifiers is indicated by schematic diagrams and follows conventional practice; frequency compensation by inverse feedback is provided in both circuits, and precautions are taken to reduce hum.

621.396.645.029.4 **2095**

A 15-Watt Direct-Coupled Amplifier—Fraser. (*See* 2134.)

534.321.9 **2096**

Ultrasonics [Book Review]—P. Vigoureux. Publishers: Chapman and Hall, London, Eng. 1950, 163 pp., 25s. (*Phil. Mag.*, vol. 42, p. 439; April, 1951.) "The author has dealt with the technique and with the theory of ultrasonics in simple terms which bring the work within the scope of a wide circle of readers, including undergraduates."

ANTENNAS AND TRANSMISSION LINES

621.392.09 **2097**

Surface-Wave Propagation over a Coated Plane Conductor—S. S. Attwood. (*Jour. Appl. Phys.*, vol. 22, pp. 504–509; April, 1951.) Propagation of the type described by Goubau (281 of March and 812 of May) is discussed, the case of the plane conductor being chosen to simplify calculations. "Basic equations are developed for both dielectric layer and air regions, which indicate a criss-cross or multiply-reflected wave in the dielectric and an unidirectional wave in the air. Equations are developed also for the electric-flux line shapes, power propagated over the cross section, concentration of power flow in neighborhood of the film, attenuation due to conductor-wall loss, and dielectric-film loss. Numerical calculations are given for five film thicknesses varying from 0.0001 to 0.01 meter, and for five frequencies ranging from 3×10^8 to 3×10^{10} cycles per second."

621.392.09 2098

Propagation on Dielectric Coated Wires—E. T. Kornhauser. (*Jour. Appl. Phys.*, vol. 22, p. 525; April, 1951.) Comment on work noted in 812 of May (Goubau).

621.392.2:621.396.611.39 2099

Approximate Theory of the Directional Coupler—F. Bolinder. (Proc. I.R.E., vol. 39, p. 291; March, 1951.) The construction is discussed of directional couplers providing the optimum relation between the width of the passband and the pass-band level of the reverse wave I_{rev} in the coupled line. Curves are given for an 8-element-directional coupler with a tolerance of 5 per cent in the value of I_{rev}/I_{max} in the passband, and for two-directional-couplers consisting of continuous slots of varying width. Mumford's assumptions (2007 of 1947) are considered valid. See also 562 of April.

621.392.26+621.396.67 2100

1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

12—The Design and Use of the Automatic Antenna Pattern Recorder—J. W. Tiley.
13—Stagger-Tuned Loop Antennas for Wide-Band Low-Frequency Reception—D. K. Cheng and R. A. Gailbraith.
14—Theory of the Concentric-Slot Antenna—T. Morita.
15—Optimum Current Distributions for Antenna Arrays with Circular Symmetry—R. H. DuHamel.
16—Directional Antenna Arrays of Elements Circularly Disposed about a Cylindrical Reflector—R. F. Harrington and W. R. LePage.
54—Performance of Sectionalized Broadcasting Towers—C. E. Smith.
73—Development of Waveguide Switches for Commercial and Military Applications—T. N. Anderson.
74—Low-Loss Waveguide Transmission—S. E. Miller and A. C. Beck.
75—Dominant Wave Transmission Characteristics of a Multimode Round Waveguide—A. P. King.
76—Radial Probe Measurements of Mode Conversion in Large Round Waveguide with TE_{01} Mode Excitation—M. Aronoff.
77—A Broadband Microwave Quarter-Wave Plate—A. J. Simmons.
78—The Precision Measurement of the Equivalent Circuit Parameters of Dissipative Microwave Structures—A. A. Oliner and H. Kurss.
102—On the Excitation of Surface Waves—G. Goubau.
103—Interaction between Surface Wave Transmission Lines—A. A. Meyerhoff.
104—A New Directional Coupler permitting Full Power Transfer—K. Tomiyasu and S. B. Cohn.
105—Multi-Element Directional Couplers—S. E. Miller and W. W. Mumford.
106—The Effect of Radiation on the Q of Resonant Sections of Unshielded Parallel-Wire Transmission Line—R. A. Chipman, E. F. Carr, and N. A. Hoy.
124—Single-Tapped Coil Delay Line—S. G. Lutz.
125—Nickel Acoustic Delay Line—T. F. Rogers and S. J. Johnson.
132—The Study of Artificial Dielectrics of the Obstacle Type—C. Susskind.
133—Isotropic Artificial Dielectric—R. W. Corkum.
134—A Virtual Source in Microwave Optics—K. S. Kelleher.
135—Experimental Prototype of the Rinehart-Luneberg Lens—E. C. Fine.
136—Propagation of Microwaves between Parallel Conducting Surfaces—K. S. Kunz.
137—Phase Shift of Microwaves in Passage through Parallel-Plate Arrays—D. J. Epstein.
162—The Half Space as a Spherical Transmission Line—L. Felsen and N. Marcuvitz.
163—The Calculation of Progressive-Phase Shaped Beam Antennas—A. S. Dunbar.
164—Physical Limitations on Minimum Side Lobes in Broadside Arrays—J. Ruze.
165—The Behavior of Microwaves in Focal Regions—F. J. Zucker.
166—A Microwave Schmidt System—H. N. Chait.

621.392.26† 2101

Analysis of Symmetrical Waveguide Junctions—D. M. Kerns. (*Bur. Stand. Jour. Res.*, vol. 46, pp. 267–282; April, 1951.) "An arbitrary electric (or magnetic) field in a waveguide junction is expressible linearly in terms of a finite number of linearly independent electric (or magnetic) basis fields. From any given ordered pair of electric (or magnetic) basis fields, one can, in principle, calculate a complex number, an element of the admittance (or impedance) matrix characterizing the junction (relative to the choice of basis fields). The geometric concept of rotation and reflection of fields (and structures) is discussed in terms of a rotation-reflection operator, and the symmetry of a junction is characterized by a group of rotation-reflection operations under which the structure is invariant. A general procedure is given for the construction of a basis in which the basis fields transform, according to irreducible representations of the symmetry group involved."

621.392.26† 2102

Diffractive Apertures in Waveguides—M. Jessel. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1546–1548; April 23, 1951.) The propagation of waves in rectangular waveguides with rectangular or polygonal apertures was studied. At a frequency permitting only one mode of propagation, the section containing the aperture can be regarded as a quadripole. The relations between reflected and transmitted components of the wave are expressed in matrix form. Satisfactory agreement is found between calculated and measured values of the transmitted component in two special cases, at wavelengths in the neighborhood of 3 cm.

621.392.26†+621.396.67]:517.944 2103

Separation of Variables in Electromagnetic Theory—D. E. Spencer. (*Jour. Appl. Phys.*, vol. 22, pp. 386–389; April, 1951.) Separability conditions are obtained for the partial differential equations of electromagnetic theory. Problems of waveguides and antennas are expressed in terms of the vector Helmholtz equation, and solutions are indicated by use of the simple method of separation of variables without recourse to Green's functions.

621.392.26†:621.392.52 2104

Waveguide Filters for Pulse Transmission Studies—P. A. Reiling. (*Bell Lab. Rec.*, vol. 29, pp. 164–168; April, 1951.) Describes channel-separation filters for a multichannel microwave waveguide system. Two waveguides carrying identical groups of four frequencies feed into opposite ends of a square waveguide, diagonal polarization being used. Four filter units arranged at intervals along the guide reflect the four frequencies respectively, with rotation of the polarization through 90°. Hybrid units consisting of rectangular guides mounted on the edges of the square guide, together with metal sheets placed diagonally across the square guide, divert the reflected waves into amplifiers. A similar system combines the waves after amplification. See also 294 of 1949 (Lewis).

621.392.26†:621.396.67 2105

Properties of Longitudinal Slots in Circular Waveguides—C. E. Feiker and S. C. Clark, Jr. (*Tele-Tech*, vol. 10, pp. 42–44, 82; March, 1951.) Measurements of slot admittance indicate properties similar to those of slots in the broad faces of rectangular waveguides. Tables and diagrams present experimental results of admittance measurements, radiation patterns and power breakdown characteristics for narrow and wide slots.

621.392.5 2106

Calculating Transmission-Line Load Impedance—S. G. Lutz. (*Elec. Eng.*, vol. 70, p. 128; February, 1951.) A digest of an AIEE, 1951, Winter General Meeting paper. A discussion of some features of the transmission-line equations and their use for determining the load impedance giving greatest transmission efficiency. The characteristic impedance is not necessarily the optimum load.

621.392.5:538.652 2107

Magnetostrictive Delay Line—E. M. Bradburd. (*Elec. Commun.* (London), vol. 28, pp. 46–53; March, 1951.) A comparison of various signal-delay systems is presented. The magnetostrictive type provides a continuously adjustable delay and accommodates a multiplicity of pulses simultaneously. The fundamental design equations for this type are given, and methods for improving pulse response and eliminating undesired reflections at the ends of the line, are described.

621.396.67 2108

The Effect of a Grounded Slab on the Radiation from a Line Source—C. T. Tai. (*Jour. Appl. Phys.*, vol. 22, pp. 405–414; April, 1951.) A method of investigation based on Fourier transforms is used. The principal part of the electric field above the dielectric slab can be found either by evaluating the resultant contour integral, using the saddle-point method of integration, or by evaluating the integral containing the tangential H field along the interface. The radiation pattern of the principal field is identical with the field resulting from a direct and a reflected ray, as derived from geometrical optics. When the slab is thick enough to support wave propagation, in addition to the space wave, a surface wave appears in the neighborhood of the interface; the latter attenuates rapidly as the distance from the interface increases. The deformation of the path of integration corresponding to different angles of observation is displayed graphically.

621.396.67 2109

The Calculation of the Radiation from Ultra-Short-Wave Aerials—É Divoire and J. Delcambe. (*HF Brussels*, no. 8, pp. 201–214; 1950.) When the wavelength becomes less than the linear dimensions of the antenna, methods of calculating radiation based on Huyghens' principle have to be used, as in acoustics and optics. The modifications necessary in applying the standard theory to the case of radio waves are discussed, and formulas derived for the field at a distance from a radiating surface are shown to conform to Maxwell's equations and to be in good agreement with experiment.

621.396.671 2110

Diffraction Errors in an Optical Measurement at Radio Wavelengths—G. A. Woonton, J. A. Carruthers, H. A. Elliott, and E. C. Rigby. (*Jour. Appl. Phys.*, vol. 22, pp. 390–397; April, 1951.) Errors arising in the investigation of an antenna pattern, by means of a lens, are examined. The effect of the lens aperture is separated from that of lens aberrations, and only the former is discussed. A theoretical solution is obtained for a uniformly illuminated aperture in conjunction with short electromagnetic horns; agreement is found with measured results. Computed and measured results are used to investigate the mutilation of the pattern by the aperture. A lens 40 λ wide can be used for precision measurements with antennas 10 to 20 λ wide. The technique is useful for λ≦3.2 cm.

621.396.679.4:621.315.212 2111

Circular-Aperture and Slot Couplings between Coaxial Lines—H. Kaden. (*Z. angew. Phys.*, vol. 3, pp. 44–52; February, 1951.) Formulas are derived for designing circular-aperture and slot couplings, the discussion being restricted to cases in which the wavelength is large compared with the size of the aperture. For the circular aperture, both the capacitive and the inductive couplings are proportional to the cube of the aperture radius; for the slot, both couplings are proportional to the square of the slot width. The magnitudes of the two couplings are equal for the slot, but for the circular aperture the inductive coupling is twice as great as the capacitive coupling. When two aligned coaxial sections are separated by an apertured short-circuiting diaphragm, only inductive coupling is present, its magnitude being inversely proportional to the square of the distance of the aperture from the axis. The finite thickness of the diaphragm is taken into account. Applications to coaxial-line band-pass filters and directional couplers are described.

621.316.93 2112

Protection of Transmission Systems against Lightning [Book Review]—W. W. Lewis. Publishers: Chapman and Hall, London, Eng. 418 pp., 64s. (*Elec. Times*, vol. 119, p. 364; March 1, 1951. "Five of the 11 chapters discuss basic details of lightning and of traveling waves. The rest of the book presents practical rules for minimizing the effects of lightning on transmission lines."

621.392.26†+621.396.615.141/.142 2113

Electromagnetic Problems of Microwave Theory. [Book Review]—H. Motz. Publishers: Methuen and Co., London, Eng. 180 pp., 9s.6d. (*Electrician*, vol. 146, p. 824; March 9, 1951.) Theory of velocity modulation, klystrons, cavity magnetrons, and waveguides is covered, the method of analysis being illustrated by thoroughly worked examples.

CIRCUITS AND CIRCUIT ELEMENTS

621.314.12:621.314.3† 2114

A Simple Magnetic Modulator for Conversion of Millivolt D.C. Signals—G. Wennerberg. (*Elec. Eng.*, vol. 70, pp. 144–147; February, 1951.) Modulation is achieved by a suitable arrangement of excitation (ac) and signal (dc) windings on two saturable cores. The output voltage is a stable sinusoidal signal of amplitude proportional to the dc signal level, and in phase or antiphase with the excitation voltage, depending upon the polarity of the dc input.

621.314.224 2115

Double-Ratio Current Transformers—A. A. Halacsy. (*Elec. Times*, vol. 119, pp. 475–478; March 22, 1951.) In transformers with two equal sets of windings which can be connected either in series or in parallel to obtain different ratios, the actual ratios and phase angles obtained differ from the nominal values by amounts which are dependent on the particular combination used. Formulas are tabulated showing the errors for the various possible winding connections.

621.314.3† 2116

Some General Properties of Magnetic Amplifiers—J. M. Manley. (Proc. I.R.E., vol. 39, pp. 242–251; March, 1951.) General discussion of the magnetic amplifier, as a carrier system, with a modulation gain and a small demodulation loss.

621.317.723:621.38 2117

An Electrometer Impedance Convertor—E. J. Harris. (*Electronic Eng.* (London), vol. 23, pp. 109–110; March, 1951.) A circuit is described in which the input tube has extremely low-grid current, and in which the electrometer stage derives its operating potentials from the cathode of the succeeding amplifier stage, when injection from either the control grid or the suppressor grid is used. The circuit may be used to measure ionization currents, bioelectric potentials or hydrogen-ion concentrations.

621.318.42 2118

Characteristic Impedance of Shielded Coils—C. Susskind. (*T V Eng.*, vol. 2, pp. 26–27, 31; March, 1951.) Measurements made on shielded coils of low-resistance wire and presented graphically, demonstrate the dependence of characteristic impedance, both on coil-to-shield spacing and on the ratio of coil diameter to shield diameter.

621.318.572 2119

Transition of an Eccles-Jordan Circuit—J. R. Tillman. (*Wireless Eng.*, vol. 28, pp. 101–110; April, 1951.) A mathematical study of that part of the transition time occupied in charging the shunt capacitances of the circuit. An externally triggered system with two stable states is discussed. Transition takes place when the curve representing the gain of the closed loop containing the grids and anodes of the two tubes encloses the point 1/0 on the Nyquist diagram. Analyses are made of tubes with linear and parabolic characteristics, the calculated time variation of anode potentials being shown graphically. A method of calculation by successive approximation is shown to give results in good agreement with analytical curves, provided sufficiently small steps are taken. Triggering is shown to be ineffective if the length of the pulse is too small, but the threshold value is often only a few millimicroseconds. The departures of the characteristics of practical circuits, from those of the simple system analyzed, are discussed in some detail.

621.318.572:621.384.5 2120

Ring Counter using Neon Lamps—L. N. Korablev. (*Compt. Rend. Acad. Sci.* (URSS), vol. 75, pp. 375–378; November 21, 1950. In Russian.)

621.319.4 2121

Styroflex Capacitors, their Properties and Application Possibilities—H. Geschka and F. Lange. (*Elektrotechnik Berlin*, vol. 5, pp. 133–137; March, 1951.) Methods are described for the production of capacitors from polystyrol ribbon and Al foil. Such capacitors have low losses, high breakdown voltage, and a capacitance temperature coefficient of -140×10^{-6} per 1°C. Different available types are described. A comparative table shows the principal electrical and physical characteristics of capacitors with dielectric of styroflex, mica, and various titanate ceramics.

621.39 2122

1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

17—Calculations for Class-C Amplifiers with a Reactive Load—D. A. Cawood.
33—The Servo-Modulator: A Low-Level D.C. Instrument—G. M. Attura.
34—Transient Response of Self-Saturating Magnetic Amplifiers—E. J. Smith.
35—Direct Current Amplifiers employing Magnettors—E. P. Felch, V. E. Legg, and F. G. Merrill.
36—Some Aspects of Magnetic Amplifier Technique—R. Willheim and F. E. Butcher.
37—Drift Compensation in D.C. Amplifiers for Analogue Computers—W. E. Ingerson.
38—Signal Flow Graphs—S. J. Mason.
39—Some Biological Applications of Random Nets—A. Rapoport.
41—Electric Network Models for Problems of Probability—W. E. Bradley.
62—Network Synthesis applied to Feedback Control—J. G. Truxal.
63—Network Synthesis by the Use of Potential Analogues—R. E. Scott.
64—Transfer Ratio Synthesis by RC Networks—J. T. Fleck and P. F. Ordung.
65—Electrical-Mechanical Equivalent Network Synthesis—A. A. Gerlach.
66—Linear Network Neighborhood Equivalence—D. R. Crosby.
67—Constant Resistance Varying-Parameter Networks—L. A. Zadeh.
71—Generation of Sidebands due to Gain and Phase Shift Modulations in a Traveling Wave Tube Amplifier—M. Arditi, A. G. Clavier, and P. Parzen.
91—Time Domain Filters—J. Snyder.
92—Pulse Reception Filters—D. L. Waidelich.
93—Optimum Nonlinear Filters—H. E. Singleton.
94—Nonlinear Sampling Filters—W. D. White.
95—Statistical Filter Theory for Feedback Systems Subject to Saturation—G. C. Newton, Jr.
96—Electronic Filter—H. T. Sterling.
122—A Linear Operational Calculus of Empirical Functions—R. G. Piety.
123—Pulse Transformer considered as a Wide-Band Network—M. G. Rudenberg.
126—Amplifier Synthesis on Equal-Ripple Basis—D. L. Trautman and J. A. Aseltine.
152—R. F. Amplifier Design for Low Noise Figure—R. Guenther.
153—H. F. Amplifiers with Direct Coupling—E. L. Crosby, Jr., and K. F. Umpleby.
154—Distributed Amplification: Additional Considerations—J. Weber.
155—Distributed Amplification for Pulses—G. F. Myers.
156—Cathode-Coupled Clipper Response—P. F. Ordung and H. L. Krauss.
167—A Single-Ended Push-Pull Audio Amplifier—A. Peterson and D. B. Sinclair.
180—Oscillator Frequency Indeterminancy—L. Riebman.
181—Simultaneous Oscillations in Oscillators—H. Schaffner.
182—Amplitude Stabilization of Oscillators by Nonlinear Networks—L. Rosenthal.
183—Stability of Oscillations in a Nonlinear System—N. R. Scott.
184—Tuned Coupled Circuit for Oscillator Application—R. A. Martin and R. D. Teasdale.
191—1,700- to 2,400-Mc/s Triode Amplifier—E. M. Ostlund and H. G. Miller.
194—Guiding Principles in Production of Submillimeter Waves—H. von Foorster and J. S. Schaffner.

621.392 2123

Properties of Some Wide-Band Phase-Splitting Networks—F. E. Bond and D. G. C. Luck. (Proc. I.R.E., vol. 39, pp. 285–287; March, 1951.) Comment on 1614 of 1949 and author's reply.

621.392:621.3.016.352 2124

On Stability of Linear Varying-Parameter Systems—L. A. Zadeh. (*Jour. Appl. Phys.*, vol. 22, pp. 402–405; April, 1951.) A linear varying-parameter system is defined to be stable if and only if every bounded input produces a bounded output. The necessary and sufficient conditions for stability are derived analytically, the result representing a generalization of the frequency-domain criterion commonly used for fixed systems. The theory is applied to investigate the stability of a variable-feedback system.

621.392.4.012 2125
Loci of Complex Impedance and Admittance Functions—E. L. Michaels. (*Elec. Eng.*, vol. 70, p. 127; February, 1951.) A Digest of an AIEE 1951 Winter General Meeting paper. Complex impedance diagrams are given for four basic 2-terminal 3-element dissipative networks, and the relations between them are discussed.

621.392.5:621.317.755 2126
Experimental Testing of Electrical Networks by means of the Unit Function Response—van Slooten. (*See* 2235.)

621.392.52 2127
Filter Design Simplified: Part 1—B. Sheffield. (*Audio Eng.*, vol. 35, pp. 13–14, 36; March, 1951.) Presents a method for calculating the constants for low-pass and high-pass filters which eliminates the need for a large number of formulas. The basis of the method is synthesis from half-sections.

621.392.6 2128
Synthesis of 2*n*-Terminal Networks—V. Belevitch. (*Wireless Eng.*, vol. 28, pp. 128–129; April, 1951.) By considering the scattering (or efficiency) matrix used in similar investigations (1321 of 1949 and 305 of February), more general results have been obtained and also a solution of the problem of finding all 2*n*-terminal networks equivalent at all frequencies to a given network. The results are briefly described; detailed proof will be given in a forthcoming paper.

621.395.62:621.395.667 2129
A Continuously Variable Equalizer—W. D. Fling. (*Audio Eng.*, vol. 35, pp. 16–17, 31; March, 1951.) Electrical details of the Fairchild Type-627 nonpassive equalizer, which enables adjustment of the frequency characteristic of a reproducer to be made at either the low-frequency or high-frequency end of the audio range, or at both ends simultaneously.

621.396.6+621.317.7+621.38.001.8 2130
Physical Society's Exhibition 1951—Wood. (*See* 2236.)

621.396.611.1 2131
Pendular and Relaxation Oscillations—R. Fortrat. (*Jour. Phys. Radium*, vol. 12, pp. 41–50; January, 1951.) Both electrical and mechanical oscillations are considered. Van der Pol's definition of relaxation oscillations is discussed; it is not applicable to most of the oscillations generally accepted as being of relaxation type, which are distinguished from pendular oscillations by their irreversibility. Relaxation oscillations arise in systems which alternate between two states, passing from one state to the other via a cycle made in a given direction. Though in certain cases the element fixing the limiting states may impose an amplitude limit, this is not a general condition in relaxation oscillations. The coupling of relaxation-oscillaton systems to pendular-oscillation systems is discussed briefly.

621.396.611.33 2132
The General Design of Triple- and Quadruple-Tuned Circuits—T. C. Wagner. (Proc. I.R.E., vol. 39, pp. 279–285; March, 1951.) Relatively simple formulas are derived for the circuit parameters required for a desired amplitude response in triple-tuned and quadruple-tuned circuits. When using these formulas, an almost arbitrary choice of the *Q* values of the various circuits is permissible. The formulas give virtually explicit values for the coupling coefficients for a given bandwidth and peak-valley ratio. A condition for the physical realizability of triple-tuned circuits is developed. A convenient procedure for tuning multiple-circuit arrangements and setting the coupling coefficients is outlined.

621.396.615:621.384.612.2† 2133
Pulser for Cyclotron Oscillator—Henry and Keys. (*See* 2255.)

621.396.645.029.4 2134
A 15-Watt Direct-Coupled Amplifier—W. B. Fraser. (*Audio Eng.*, vol. 35, pp. 15–17, 36; April, 1951.) Description, with detailed circuit diagram, of an amplifier suitable for high-quality reproduction of music. The full output of 15 w is attained with an input voltage of 0.35 v rms. Hum and noise voltages are both low.

621.396.822 2135
Theory of the Shot and Johnson Effects—H. Danzer. (*Ann. Phys.* (Lps.), vol. 8, pp. 176–186; November 10, 1950.) A unified mathematical treatment of the two effects is developed.

GENERAL PHYSICS

519.211 2136
Method for the Study of Perturbations of Limited Duration—G. Rideau. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1338–1340; April 2, 1951.) General formulas are derived for calculating the probabilities of transition of a system acted on, during a finite time, by an external potential.

535.312 2137
Reflection in an Inhomogeneous Medium—K. Försterling and H. O. Wüster. (*Ann. Phys.* (Lpz.), vol. 8, pp. 129–133; November 10, 1950.) The reflection coefficients are calculated for the case where the dielectric constant varies as a power of one of the co-ordinates.

535.42 2138
An Asymptotic Treatment of Diffraction Problems: Part 2—N. G. van Kampen. *Physica, 's Grav.*, vol. 16, pp. 817–821; December, 1950.) The theory discussed earlier (3119 of 1949) is simplified by making certain approximations. The method is described and applied in examples.

535.43 2139
On the Scattering of Plane Waves by Soft Obstacles: Part 1—Spherical Obstacles—R. W. Hart and E. W. Montroll. (*Jour. Appl. Phys.*, vol. 22, pp. 376–386; April, 1951.) An obstacle is considered "soft" if it subjects an incident wave to only a small phase shift. An approximate theory is developed for the case, where $\lambda_0/\lambda_1 < 1.5$, where λ_1 and λ_0 are, respectively, the wavelengths in the obstacle and in the surrounding medium. The approximate results obtained are compared, in the optical case, with results obtained numerically by the Bureau of Standards Computing Laboratory.

537.217+538.65 2140
Electric and Magnetic Forces between Sphere and Wire—W. R. Smythe. (*Jour. Appl. Phys.*, vol. 22, pp. 521–522; April, 1951.) Formulas are derived for the interaction force and scalar potential of a dielectric sphere and a charged wire, and for the interaction force and vector potential of a permeable sphere and a current-carrying cylinder.

537.228.2 2141
Notes on the Theory of Electrostriction in Onsager Liquids—H. Falkenhagen and H. Jacob. (*Ann. Phys.* (Lpz.), vol. 8, pp. 105–108; November 10, 1950.) Values of the static electrostriction constant for a number of liquids are calculated from Onsager's theory.

537.311.31:537.311.5 2142
The Resistance of a Rectangular Metal Plate with an Internal Electrode—S. D. Daymond. (*Quart. Jour. Mech. Appl. Math.*, vol. 4, pp. 23–28; March, 1951.) A steady current enters a rectangular metal sheet of uniform thickness and conductivity, through a small circular electrode within the plate, and flows out through an electrode coinciding with the rectangular boundary. The effective resistance of the plate is considered from the theoretical standpoint, a few representative numerical values being derived.

537.52:621.395.623.7 2143
Variations of Discharge Parameters in Preliminary Discharges, and Measurement of Variations—W. Fucks. (*Z. Naturf.*, vol. 5a, pp. 89–98; February, 1950.) Calculated and observed values are presented for the discharge current, slope, and sensitivity in corona and Townsend discharges, for different values of discharge parameters. The relations between the various partial sensitivities, and the behavior when several parameters are varied simultaneously, are discussed. Applications of the theory in measurement technique are illustrated, including the recording of the vibrations of a loudspeaker diaphragm.

537.523 2144
Positive-Ion Formation in Air prior to High-Frequency Breakdown—R. Fatehchand. (*Nature* (London), vol. 167, pp. 566–567; April 7, 1951.) Results of experiments appear to show that positive ions oscillating in an air gap just prior to breakdown are effective in reducing the hf breakdown voltage below the 50-cps value.

537.523.3 2145
Electrical and Optical Characteristics of D. C. Corona Discharge—H. M. Gaunt and J. D. Craggs. (*Nature* (London), vol. 167, pp. 647–648; April 21, 1951.)

537.525 2146
The Role of the Self Magnetic Field in High Current Gas Discharges—P. C. Thonemann and W. T. Cowhig. (*Proc. Phys. Soc.* (London), vol. 64, pp. 345–354; April 1, 1951.)

537.525 2147
A Study of a High-Current Toroidal Ring Discharge—A. A. Ware. (*Phil. Trans. A.*, vol. 243, pp. 197–220; March 13, 1951.) The exciting primary is a metal coating on the outside of the torus, the excitation frequency being 150 kc. The waveforms of the currents and electric fields and the light from the discharge were studied, the gases used being H and A. Very large currents flow in the gas, with peak values $>10^4$ A; the current is in phase with the electric field. The hf oscillations of frequency 1 to 5 mc, thought to be plasma ion oscillations, are observed in the gas.

537.529:621.315.611 2148
The Mechanism of Electrical Breakdown in Solid Insulating Materials—W. Franz. (*Z. angew. Phys.*, vol. 3, pp. 72–80; February, 1951.) A survey paper. The difficulties inherent in breakdown measurements are discussed, and earlier theoretical explanations are reviewed. Experiments made by von Hippel in 1936 proved that the breakdown current in solid insulators is carried by electrons. The mechanism may in some cases be impact ionization, involving increase of breakdown field strength with rise of temperature. An alternative possibility is that free electrons are produced by tunnel effect (internal field emission), a temperature-independent process. At temperatures above room temperature, a decrease in dielectric strength with temperature rise is observed for all materials; only tentative qualitative explanations of this phenomenon have so far been advanced.

537.533:538.3.029.6 2149
Quantum Effects in the Interaction between Free Electrons and Electromagnetic Fields—C. Shulman. (*Phys. Rev.*, vol. 82, pp. 116–117; April 1, 1951.) Description of a method by which the quantum dispersion in the energy

exchange between free electrons and an em field has been observed. See also 3196 of 1950 (Ward).

537.562 2150

Dynamics of Plasma: Part 1—Fundamental Equations, Plasma in Crossed Fields—A. Schlüter. (*Z. Naturf.*, vol. 5a, pp. 72–78; February, 1950.) Equations of motion and diffusion are derived, taking into account friction and electromagnetic interaction. The system is considered for static electric and magnetic fields. It is meaningless to say that conductivity is reduced by a magnetic field, or to refer to a Hall effect in the plasma, since the ponderomotive forces of the current in the magnetic field must be compensated by pressures, which in turn affect the current in such a way that its intensity has everywhere exactly that value which it would have in the absence of the magnetic field, with the same pressure. In the case when the magnetic field is due only to the current flowing as a result of a uniform electric field, the plasma contracts to a thread.

537.562:538.561 2151

Plasma Oscillations in a Static Magnetic Field—E. P. Gross. (*Phys. Rev.*, vol. 82, pp. 232–242; April 15, 1951.) A theory for small-amplitude oscillations of an ionized gas in a static magnetic field is developed, including the effects of temperature motions. Exact expressions are obtained for the distribution function and dispersion relation. The latter shows that gaps in the spectrum exist at frequencies which are approximate multiples of eH/mc, the gap widths being temperature-dependent. These gaps may be expected to give rise to selective reflection of incident radiation of appropriate frequency. The results of the exact theory are compared with simplified treatments based on the transport equations, and also with the work of Malmfors (2764 of 1950).

537.562:538.566 2152

On Waves in an Ionized Gas—E. Åström. (*Ark. Mat. Astr. Fys.*, vol. 2, pp. 443–457; January 25, 1951.) A theoretical treatment of the interaction between electromagnetic fields and gaseous ions, in which motion of the ions and of neutral molecules is taken into account. For a plasma, the dielectric properties are expressed in tensor form. Plane waves are propagated at various angles to the magnetic field, their velocities being related to the direction angle and to the frequency by three-dimensional characteristics, some of which are illustrated. At frequencies well below the ion gyrofrequencies, both "ordinary" and "extraordinary" magneto-hydrodynamic waves are propagated. The electric field and displacement, magnetic induction, current density, propagation velocity, and energy are evaluated. In general, a transition to longitudinal pressure waves results.

538.21:534.111 2153

The Oscillations of Magnetic Suspensions—K. Millsaps and J. C. McPherson. (*Jour. Appl. Phys.*, vol. 22, pp. 429–432; April, 1951.)

538.221 2154

Collective Electron Ferromagnetism: Rectangular Energy Bands—E. P. Wohlfarth. (*Phil. Mag.*, vol. 42, pp. 374–390; April, 1951.) Calculations similar to those of Stoner are carried out for an energy band, for which the energy density of states is constant.

538.311 2155

The Field Induced by an Oscillating Magnetic Dipole outside a Semi-infinite Conductor—A. N. Gordon. (*Quart. Jour. Mech. Appl. Math.*, vol. 4, pp. 106–115; March, 1951.) "Formulas are given for the external field produced by an oscillating magnetic dipole, located outside a uniform semi-infinite conductor. The normal component of the field, induced by a circular alternating current filament at the surface of the conductor, is also considered."

538.51 2156

Electromagnetic Induction in a Uniform Semi-infinite Conductor—A. N. Gordon. (*Quart. Jour. Mech. Appl. Math.*, vol. 4, pp. 116–128; March, 1951.) A systematic treatment of the problem of the induction of currents in a uniform semi-infinite conductor by external magnetic or electric fields is given, attention being drawn to the complementary nature of the magnetic and electric cases. A one-dimensional heat-flow analogue is considered, which enables the familiar methods developed in connection with heat conduction to be applied directly to the solution of corresponding problems in em induction.

538.56+535.13 2157

Two Theorems concerning the Propagation of Waves in Stratified Media—F. Abelès. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1415–1417; April 9, 1951.) Formulas are proved, expressing amplitude and phase relations for wave components transmitted and reflected by a system comprising a transparent stratified medium between two transparent uniform media. It is concluded, that measurements made on such a system can provide data permitting determination of the characteristics of the stratified medium, if the parameters of the adjacent media are known, but will not enable the parameters (e.g. refractive index) of the two uniform media to be determined.

538.56 2158

A 1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

112—Microwave Methods in Gas Analysis—J. Weber.

136—Propagation of Microwaves between Parallel Conducting Surfaces—K. S. Kunz.

137—Phase Shift of Microwaves in Passage through Parallel-Plate Arrays—D. J. Epstein.

538.56:535.42 2159

Diffraction Pattern of Microwaves near Rods—C. L. Andrews. (*Jour. Appl. Phys.*, vol. 22, pp. 465–468; April, 1951.) Rigorous calculations of the field in the neighborhood of a $\lambda/2$ rod were compared with measured values, for a wavelength of 8 cm. The closeness of agreement found suggests that microwave measurements within a few wavelengths of diffracting objects will afford a useful method of dealing with diffraction problems.

538.566:535.421 2160

On the Diffraction of Electromagnetic Waves by Small Circular Disks and Holes—C. J. Bouwkamp. (*Philips Res. Rep.*, vol. 5, pp. 401–422; December, 1950.) The case is considered of a plane-polarized wave incident normally on a conducting disk. "Integro-differential equations are derived for the currents induced in the disk. These equations are approximately solved on the assumption that the radius of the disk is small compared to the wavelength. Six terms of a power-series solution in the basic variable ka are derived, where k is the wave number and a the radius of the disk. The scattered field on the surface of the disk is calculated, to the same degree of accuracy, and also the field in the wave zone. An expression is obtained for the scattering coefficient of the disk. Finally, Babinet's principle is applied to obtain the corresponding solution for the diffraction of a plane wave, by a circular hole in an infinite plane conducting screen."

538.569.4 2161

Microwave Spectroscopy—R. Honerjäger. (*Naturwiss.*, vol. 38, pp. 34–39; January, 1951.) Current methods of investigating molecular spectra, using reflex-klystron generators, waveguides, and crystal detectors, are surveyed briefly. Spectra obtained with ammonia and hydrogen are discussed.

538.569.4 2162

Absorption of U.H.F. Radio Waves in some Substituted Benzene Compounds—S. N. Sen. (*Indian Jour. Phys.*, vol. 24, pp. 163–170; April, 1950.) Measurements made in the frequency range 250 to 530 mc and the temperature range 27°C to −94°C are reported and discussed. The substances investigated were chlorobenzene, toluene, ethyl benzene, and nitrobenzene.

538.632:538.221 2163

On the Hall Effect in Ferromagnetics—N. Rostoker and E. M. Pugh. (*Phys. Rev.*, vol. 82, pp. 125–126; April 1, 1951.) The anomalous behavior of the Hall constant in the neighborhood of the Curie point, indicated by experimental data, is eliminated by separation of the extraordinary Hall effect, due to intrinsic magnetization from the ordinary Hall effect due to a uniform field. See also 620 of April (Pugh, Rostoker and Schindler).

621.3.011.4 2164

The Capacitance of a Parallel-Plate Condenser with an Anisotropic Dielectric Cylinder in Torsion between its Plates—C. Mack. (*Phil. Mag.*, vol. 42, pp. 428–431; April, 1951.) Summary only. The case in which the cylinder is midway between the plates is considered in detail; an approximate solution is also obtained for the general case.

537/538 2165

Static and Dynamic Electricity [Book Review]—W. R. Smythe. Publishers: McGraw-Hill, New York, N. Y. 2nd edn., 1950, 583 pp., $8.50. (Proc. I.R.E., vol. 39, p. 321; March, 1951.) "The new edition offers substantial improvements of old material and important additions of new material. . . The presentation is extremely thorough. . . It should appeal to research men and to capable graduate students in mathematics, physics, and electrical engineering."

GEOPHYSICAL AND EXTRATERRESTRIAL PHENOMENA

523.72+523.854]:621.396.822 2166

Electromagnetic Radiation from Cosmic Protons in the Intense Magnetic Fields of Celestial Bodies—B. Kwal. (*Jour. Phys. Radium*, vol. 12, pp. 66–67; January, 1951.) The possibility of interpreting the rf radiation from the sun and the galaxy, as due to radiation, from cosmic protons subjected to intense magnetic fields (1142 of June), is supported by estimates of the frequency and intensity of the radiations, based on reasonable assumed values for the energy and concentration of the protons and for the field strength at active areas of the sun's surface.

523.72:621.396.822 2167

Motion in the Solar Atmosphere as Deduced from Radio Measurements—G. Reber. (*Science*, vol. 113, pp. 312–314; March 23, 1951.) The rf radiations from the sun are assumed to have their origin at different levels of the solar atmosphere, the higher frequencies being associated with the lower levels. Hence motion of material thrown up during a flare may possibly be detected by observing the starting times of the transients, of progressively lower frequencies, produced by its passage through the solar atmosphere. Data from several observatories, obtained on July 12, 1950, are presented. The peak intensity of the disturbance recorded varied from 3 times quiet-sun level at 9.5 kmc to 10,000 times quiet-sun level at 51 mc. It is inferred from the observations that material was thrown up to a height corresponding to 35-mc radiation, after which some of it fell back and dispersed. Heights corresponding to the generation of various frequencies are deduced. Speculative values given for the velocity of the material are commensurate with the velocities of particles causing ionospheric and geomagnetic storms on the earth.

523.72:621.396.822 2168

Radio Observations of Two Large Solar Disturbances—W. N. Christiansen, J. V. Hindman, A. G. Little, R. Payne-Scott, D. E. Yabsley, and C. W. Allen. (*Aust. Jour. Sci. Res., Ser. A*, vol. 4, pp. 51–61; March, 1951.) Two exceptionally large disturbances were observed respectively on February 17 and 21–22, 1950, on seven radio receivers working on different frequency bands in the range 62 mc to 9.4 kmc. The rf power flux was recorded continuously at each frequency, the polarization of the radiation was examined at four frequencies, and the apparent position of origin of the radiation was determined at one frequency. The commencement times and the durations of the disturbances at the different frequencies were compared with each other and with corresponding observations of solar flares, radio fadeouts and geomagnetic effects. Similarities and differences between the two disturbances are tabulated.

523.72:621.396.822 2169

Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wave-lengths: Part 3—Isolated Bursts—J. P. Wild. (*Aust. Jour. Sci. Res., Ser. A*, vol. 3, pp. 541–557; December, 1950.) "Observations are described of the spectrum of 'isolated bursts' of solar radio-frequency radiation in the frequency range 70 to 130 mc. These bursts last for a few seconds and have a bandwidth of the order of tens of megacycles per second. Prior observations indicate that they are not circularly polarized. They occur sporadically, often in small groups; many hours sometimes elapse between successive bursts or groups. Although, in general, their spectra show diverse features, some of them (referred to as "type III" bursts) are of a distinct type characterized by a rapid drift, with time of the frequency of maximum intensity towards the lower frequencies, at a rate of the order of 20 mc. Characteristics of the spectra of type III bursts are described in detail. The results are discussed and hypotheses of origin examined. It is shown in particular that the frequency drift of type III bursts cannot be attributed to the selective group retardation of waves in the solar atmosphere, emanating from a fixed source. The frequency drift may, however, be associated with the rapid motion of a source traveling outwards through the solar atmosphere." Part 2: 1630 of August.

523.72:621.396.822 2170

Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wave-lengths: Part 4—Enhanced Radiation—J. P. Wild. (*Aust. Jour. Sci. Res., Ser. A*, vol. 4, pp. 36–50; March, 1951.) "Observations are described of the spectrum of 'enhanced radiation' from the sun (i.e. the radio-frequency radiation which maintains a high but variable level for periods of hours' or days' duration) in the frequency range 70 to 130 mc. This radiation is known to be received from the direction of sunspots and to show circular polarization. For the purpose of presenting results, two components are recognized, viz., a background continuum which varies gradually with time and frequency, and short-lived, narrow-band bursts "storm bursts." The behavior of the two components, and the relation between them during periods of high level "noise storms" are described. A detailed analysis is given of the properties of recorded storm bursts. The distribution of recorded bursts with frequency was found to be markedly nonuniform, e.g., a pronounced minimum at 89 mc was present. The possibility that the background continuum is due to the resultant of a large number of bursts is discussed." Part 3: 2169 above.

523.72:621.396.822 2171

A Long-Period Change in Radio-Frequency Radiation from the 'Quiet' Sun at Decimetre Wave-Lengths—W. N. Christiansen and J. V. Hindman. (*Nature* (London), vol. 167, pp. 635–637; April 21, 1951.) The effective temperature of the sun at decimeter and centimeter wavelengths is related approximately linearly to the existing sunspot area, and extrapolation to zero sunspot area gives the quiet-sun or base temperature. A marked decrease in this quantity has been observed in the later months of 1950 on wavelengths of 10 to 50 cm, with the greatest effect (45 per cent) at 25 cm; no change has been found at wavelengths of 3 cm and 150 cm. These results confirm the solar-cycle variations of the base temperature predicted by van de Hulst (*ibid.*, vol. 163, p. 24; 1949) on the basis of an observed decrease in the coronal electron density towards sunspot minimum.

523.852.2:621.396.822 2172

Fluctuations in the Intensity of Radio Waves from Galactic Sources—C. G. Little and A. Maxwell. (*Phil. Mag.*, vol. 42, pp. 267–278; March, 1951.) A description of observations of the two most intense sources, in the constellations of Cygnus and Cassiopeia, taken over a wide range of angles of elevation. At high angles of elevation, the radio fluctuations are shown to be correlated with the occurrence of "spread" ionospheric echoes from the *F* region. When the sources are low on the northern horizon, fluctuations are always observed; these are probably introduced by the passage of radio waves through the continuously disturbed ionospheric regions at high magnetic latitudes. Spaced-receiver observations taken over base lines of 0.1, 4, and 11 km enable the scale of the radio energy diffraction pattern across the ground to be determined. See also 1365 (Smith) and 1366 (Little and Lovell) of July.

538.12:523.8 2173

The Origin of the Magnetic Fields of Stars and in Interstellar Space— L. Biermann. (*Z. Naturf.*, vol. 5a, pp. 65–71; February, 1950.) When stationary, rotational, nonmass-proportional forces act in a plasma, electric currents must flow. Such currents must generate fields of considerable strength in the interior of the stars. These effects are investigated qualitatively for various cases.

550.38"1950" 2174

Indices of Geomagnetic Activity of the Observatories Abinger (*Ab*), Eskdalemuir (*Es*), Lerwick (*Le*), January to December 1950—(*Jour. Atmos. Terr. Phys.*, vol. 1, no. 4, pp. 254–260; 1951.) Three-hour *K* indexes are tabulated.

550.385 2175

Geomagnetic "Sudden Commencements" at Lerwick—D. H. McIntosh. (*Jour. Atmos. Terr. Phys.*, vol. 1, no. 4, pp. 223–232; 1951.) A study covering a period of about 15 years is reported, movements of the magnetograph trace being classified according to their form and according to the size of the following disturbance. The forms of movements corresponding to "sudden commencements" vary widely, but are related to the hour of occurrence. No marked relation is found between this systematic variation of form and normal diurnal movements on either geomagnetically quiet or disturbed days. The average effect of all Lerwick sudden commencements is shown to be opposed to the main disturbance field.

551.510.3:535.325 2176

Fluctuations in the Refractive Index of the Atmosphere at Microwave Frequencies—G. Birnbaum. (*Phys. Rev.*, vol. 82, pp. 110–111; April 1, 1951.) The instantaneous refractive index varies rapidly and irregularly about a mean value. Some indication of the size of the random inhomogeneities is obtained by observing the instantaneous difference in refractive index at varying distances and determining a correlation coefficient. Typical fluctuation records and variation of correlation coefficient with distance are shown.

551.510.535 2177

Determination of Electron Densities in the Ionosphere from Experimental (h', f) Curves—H. A. Whale. (*Jour. Atmos. Terr. Phys.*, vol. 1, no. 4, pp. 244–253; 1951.) Calculations of electron-density distributions in the ionosphere from observed ($h'f$) curves are facilitated by use of a differential analyzer. The simple method, neglecting the earth's magnetic field, leads to inacceptable results; a modified method making an approximate allowance for this field is described, and the results obtained are shown to be feasible.

551.510.535 2178

Fine Structure of the Ionospheric Region E—H. A. Whale. (*Jour. Atmos. Terr. Phys.*, vol. 1, No. 4, pp. 233–243; 1951.) Examples are given of complex structure in the normal *E* layer over South East England, observed during the period April, 1949 to March, 1950, and the ionization distributions deduced are discussed in terms of simplified models. Both thin and thick "ledges" are found above and below the level of maximum ionization of the normal *E* layer, and the complex variations of their height with time are studied.

551.510.535 2179

Winds and Turbulence in the Upper Atmosphere—(*Nature* (Lond.), vol. 167, pp. 626–628; April 21, 1951.) Report of a geophysical discussion held in the rooms of the Royal Astronomical Society on February 23, 1951. Most of the radio methods of investigation described involved spaced-receiver measurements on waves reflected from or transmitted through the ionosphere; the characteristics examined included amplitude, direction of arrival and equivalent path. The results obtained show that horizontal irregularities of sizes ranging from 200 m to 500 km occur at heights of 90 km or more, with random turbulent speeds of 1 to 25 m per second. Drift velocities of 30 to 350 m per second in various directions have been noted. Meteorological evidence relating to these data suggests that temperature differences provide the most probable source of energy for the wind-like motions.

551.510.535 2180

A Review of Upper Atmosphere Research from Rockets—H. E. Newell, Jr. (*Trans. Amer. Geophys. Union*, vol. 31, pp. 25–34; February, 1950.) The features of the rocket as a research tool are discussed, and results obtained in various branches of research are presented. Rough measurements of the electron density in the ionosphere indicate values of less than 10^4 per cm^3 below 80 km, rising to 2×10^5 per cm^3 between 100 and 111 km.

551.510.535:523.3:621.396.11 2181

Moon Echoes and Transmission through the Ionosphere—Kerr and Shain. (*See* 2264.)

551.594.21 2182

The Electrical Processes in the Intervals between the Strokes of a Lightning Discharge—D. J. Malan and B. F. J. Schonland. (*Proc. Roy. Soc. A*, vol. 206, pp. 145–163; April 10, 1951.) The fluxmeter described in 2281 of 1950 was used to record the fields of thunder clouds in the intervals between 388 strokes of 105 flashes to ground at various distances. Most of the interstroke interval is occupied by slow field change which is negative for distances <5 km and positive for distances >12 km.

The charged regions involved in separate strokes are thought to form a single continuous column extending nearly vertically and sometimes over 6 km in extent. A mechanism is proposed to account for the intermittent discharge of this column, and evidence from field-change records is adduced in support of the theory.

551.594.22 2183
Lightning Discharges upwards from Thunderclouds—R. Mühleisen. (*Naturwiss.*, vol. 38, p. 140; March, 1951.) Discharges observed on July 1, 1950, at Rüdern über Esslingen a.N., are briefly described.

551.594.6 2184
On the Reflection of Atmospherics from the Ionosphere at Night. Part 1.—M. W. Chiplonkar and M. S. Hattiangadi. (*Proc. Indian Acad. Sci. A*, vol. 21, pp. 265–271; June, 1945.) A brief description of apparatus for recording the waveforms of atmospherics. The main features are an amplifier with uniform gain from 50 cps to 300 kc, a cro display, and a drum camera. Results quoted were derived from echo-type waveforms recorded at night, the storms being mainly at distances between 200 and 800 km. Values derived for the height of reflection were nearly all between 80 and 100 km.

551.594.6 2185
On the Reflection of Atmospherics from the Ionosphere at Night: Part 2—M. W. Chiplonkar and M. S. Hattiangadi. (*Proc. Indian Acad. Sci. A*, vol. 30, pp. 223–236; November, 1949.) Waveforms of atmospherics, recorded by a previously reported method (2184 above) are analyzed statistically. Histograms of the following quantities are plotted: height of reflection, distance of origin, reflection coefficient of the ionosphere, duration of main pulse, field strength. The number and nature of the ionospheric echoes, the peak power of the atmospherics, and the occurrence of precursors are also discussed.

LOCATION AND AIDS TO NAVIGATION

621.396.9 2186
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

13—Stagger-Tuned Loop Antennas for Wide-Band Low-Frequency [loran] Reception—D. K. Cheng and R. A. Galbraith.
108—Aircraft and Airport Characteristics—L. P. Tabor.
109—Economic Demand—F. B. Lee.
110—Human Engineering—P. M. Fitts.
111—Traffic Control Theory—D. H. Ewing.
138—On the Measurement of the Radar Echoing Areas of Conducting Bodies—J. R. Mentzer.
139—Polarization Properties of Target Reflections—E. M. Kennaugh.
140—The Use of Circular Polarization as a Means of Reducing Radar Precipitation Return—W. D. White.
141—An I.C.W. System for Distance Measurement—J. Lyman, G. B. Litchford and C. Grunsky.
142—Effects of Vertical Radiation Pattern on Omnirange-Beacon Characteristics—S. Pickles.

621.396.9 2187
Development of Radar in the [French] Navy—E. Giboin. (*Onde élect.* vol. 31, pp. 53–64; February, 1951.) Illustrated review discussing particularly wartime experiments and equipping of warships, the requirements for centralized control, and the suitability of different wavelengths for air surveillance, surface radar, etc.

621.396.932 2188
Marine Radio Position Fixing Systems—(*Jour. Inst. Nav.*, vol. 3, pp. 317–356; October, 1950.) A symposium of four papers read at a meeting of the Royal Geographical Society in May, 1950, giving an account of the four most widely used systems. The titles are:

Marine Position Fixing Systems in Use Today—H. E. Hogben.
Use of Direction Finding at Sea—F. P. Best.
The Adoption of Decca as an Aid to Navigation at Sea—E. Fennessy.
The Use of Consol in the Fishing Fleet—D. H. Harper.
The discussion is included.

621.396.933 2189
Microwave Direction Finding for Aircraft Navigation—V. D. Burgmann and K. V. Sheridan. (*Jour. Inst. Nav.*, vol. 3, pp. 251–269; July, 1950.) An aircraft direction finder operating in the 3-cm wavelength band is used to observe the bearings of fixed beacons on different spot frequencies. Frequency sweep on the receiver enables the frequency (for identification) and bearing to be displayed in rectangular co-ordinates on a cathode-ray tube. Tests to determine the value of the system for homing, for maintaining a track, and for various other purposes, are described.

621.396.933 2190
The Development of the Aircraft Automatic Radio Compass—J. H. Moon. (*Jour. Inst. Nav.*, vol. 3, pp. 393–403; October, 1950.) Major problems encountered in the development of airborne df equipment are reviewed, and a description is given of the latest electrical and mechanical improvements evolved to provide fast-moving aircraft with instantaneous position indication. Various ways of using the information provided by the direction finder are discussed, and questions of calibration and ultimate accuracy are considered.

621.396.933:621.396.61 2191
Design of a Loran Transmitter—Myers. (*See* 2300.)

621.396.933:629.13.053 2192
Automatic Course Plotting—(*Wireless World*, vol. 57, pp. 143–144; April, 1951.) Describes a device for connection to a normal Decca receiver to give a continuous map display of position. A chart is moved automatically in one direction while a cursor carrying a stylus is moved over it at right angles to this direction. The co-ordinates of each of the fifteen charts in the instrument are derived indirectly from the hyperbolic lattice in one of nine ways so as to give minimum distortion of the mapped area.

621.396.933.4:621.39.001.11 2193
Application of the Information Theory to System Design—Tuller. (*See* 2274.)

MATERIALS AND SUBSIDIARY TECHNIQUES

53+621.3 2194
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

100—New Vacuum-Tube Materials—E. B. Fehr and A. P. Haase.
101—Properties of Interfaces in Metal to Ceramic Seals—W. A. Christoffers and R. P. Wellinger.
113—Spark-Over of Air at Radio Frequencies—W. Caywood, Jr.

537.226.1 2195
On the Static Dielectric Constant of Dipolar Solids—J. H. Simpson. (*Canad. Jour. Phys.*, vol. 29, pp. 163–173; March, 1951.) Fröhlich's general formula for the static dielectric constant is applied to a material having a cubic arrangement of dipolar molecules, each of which has two equilibrium positions 180° apart and short-range ordering forces tending to make nearest neighbors antiparallel. Values yielded by the theory are compared with experimental results.

537.311.3:537.226:539.23 2196
Electron-Bombardment Conductivity of Dielectric Films—F. Ansbacher and W. Ehrenberg. (*Proc. Phys. Soc.* (London), vol. 64, pp. 362–379; April 1, 1951.) An experimental investigation is reported. The ratio of current through the film to bombarding current increases strongly with temperature; the value of this ratio may reach 40,000 for As_2S_3 films. The theory of the effect is discussed.

537.311.33 2197
Lattice-Imperfection Phenomena and Substitution Processes in Electron-Conducting Mixed Phases—K. Hauffe. (*Ann. Phys.* (Lpz.), vol. 8, pp. 201–210; November 10, 1950.) The Wagner-Schottky lattice-imperfection theory is extended to heterotype mixed phases in which conduction is electronic. It is established by means of models and experiments that conductivity variations consequent upon addition of high-valency or low-valency oxides to a first oxide, are in conformity with semiconductor theory, the following laws being found: (a) the conductivity of hole conductors is increased by addition of low-valency cations and decreased by addition of high-valency cations; (b) the variations are reversed for excess-electron conductors; (c) the conductivity of intrinsic semiconductors increases with addition of either high- or low-valency cations. The laws found enable predictions to be made about the effect of addition of foreign metals on the rate of scale formation in metal alloys.

537.311.33 2198
A Note on the Dielectric Dispersion in Polycrystalline Materials—E. Billig and K. W. Plessner. (*Proc. Phys. Soc.* (London), vol. 64, pp. 361–363; April 1, 1951.) An equivalent circuit is postulated, consisting of two parallel-RC circuits in series, to represent the lumped grain and boundary impedances, respectively. Using parameters typical of the selenium in standard rectifiers, the variation of apparent resistivity, permittivity, and power factor with frequency, are calculated.

537.311.33 2199
Electrical Properties of Grey Tin—A. I. Blum and N. A. Goryunova. (*Compt. Rend. Acad. Sci.* (URSS), vol. 75, pp. 367–370; November 21, 1950. In Russian.) Measurements of conductivity and Hall effect for grey tin and white tin are compared. Whereas white tin is a metal, grey tin is a semiconductor of the same group as Si and Ge, with a charge-carrier concentration of $10^{19}/cm^3$ at 20°C.

537.311.33:537.312.6:546.48-31 2200
The Variation with Temperature of the Electrical Properties of a Degenerate Electronic Semiconductor as exemplified by Cadmium Oxide—R. W. Wright. (*Proc. Phys. Soc.* (London), vol. 64, pp. 350–362; April 1, 1951.) Measurements of conductivity, Hall constant and thermoelectric power of CdO over the range 0 to 500°C indicate metallic properties, i.e., constant concentration of free electrons ($\sim 1.7\times 10^{19}/cm^3$). The theory of electronic conduction in an ionic lattice is discussed and related to the experimental data.

537.311.33:546.289:669-15 2201
Effect of Heat Treatment on the Electrical Properties of Germanium—H. C. Theuerer and J. H. Scaff. (*Jour. Met.*, vol. 191, pp. 59–63; January, 1951.) Germanium may be reversibly converted from n to p type by heat treatment.

Data for the conversion and the associated changes in resistivity are given, and the results are interpreted in terms of changes in the donor-acceptor balance.

538.221 2202

On the Conditions of the Occurrence of Ferromagnetism in Metal Compounds and in Solutions—P. F. Váradi. (*Physica,'s Grav.*, vol. 16, p. 920; December, 1950.) Statement of conditions based on Gisolf's theory (2237 of 1950) and earlier data.

538.221 2203

Ferromagnetism of the Alloy $FeBe_2$—A. J. P. Meyer and P. Taglang. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1545–1546; April 23, 1951.)

538.221 2204

Introduction to the Application of "Ferroxcube"—H. Van Suchtelen. (*Philips Tech. Commun.* (Australia), no. 1, pp. 14–24; 1951.) A general account of the essential properties required in magnetic materials for cores, and of the terminology used in discussing them.

538.221:538.24 2205

The Magnetization Process in Ferrites—J. J. Went and H. P. J. Wijn. (*Phys. Rev.*, vol. 82, pp. 269–270; April 15, 1951.)

538.632:621.315.592† 2206

Resistivity and Hall Constant of Semiconductors—C. N. Klahr. (*Phys. Rev.*, vol. 82, pp. 109–110; April 1, 1951.) Comment on 1357 of July (Jones).

546.431.82 2207

Temporary Enhancement of Hysteresis in Barium Titanate Samples—D. R. Young. (*Jour. Appl. Phys.*, vol. 22, pp. 523–524; April, 1951.) Comment on work reported by Rzhanov in *Zh. Eksp. Teor. Fiz.*, vol. 19, pp. 335–345; 1949.

548.0:537.228.1 2208

Contour Modes of Square Plates excited Piezoelectrically and Determination of Elastic and Piezoelectric Coefficients—R. Bechmann. (*Proc. Phys. Soc.* (London), vol. 64, pp. 323–337; April 1, 1951.) Piezoelectric measurements on square plates provide checks for the theoretical solution of the various modes, and in particular, for the distribution of displacement. The reliability of recently published solutions for square plates is discussed. The materials used were $NaClO_3$, $NaBrO_3$, quartz, ADP and EDT. New determinations were made of the elastic and piezoelectric coefficients of these materials, with the exception of EDT, for which results have already been published (see 128 of February).

548.0:547.476.3:537.228.1 2209

New Ferroelectric Tartrates—B. T. Matthias and J. K. Hulm. (*Phys. Rev.*, vol. 82, pp. 108–109; April 1, 1951.)

549.211:621.3.011.5 2210

Determination of the Dielectric Constant and Loss Angle of Diamond—F. P. Pietermaat and A. de Keuster. (*HF, Brussels*, no. 8, pp. 215–223; 1950.) A method is described using test specimens made from mixtures of diamond dust with glass or paraffin wax, and results are given for a frequency range of 1 to 40 mc.

621.3.011.5:553.623 2211

Electrical Constants of Sand at Ultra High Frequencies—S. K. Chatterjee. (*Indian Jour. Phys.*, vol. 24, pp. 143–150; April, 1950.) Measurements were made on dry and moist sand (moisture content up to 5 per cent) over the frequency range 300 to 500 mc, using a Lecher-wire method. For dry sand, dielectric constant varies from 2.6 to 2.7, conductivity varies from 0.26×10^{8} to 1.04×10^{8} esu and loss tangent varies from 64×10^{-3} to 153×10^{-3} over the frequency range, while the reflection coefficient remains practically unchanged at 0.24, though the phase change on reflection varies with frequency. All the constants increase with increasing moisture content.

621.314.6:621.315.59 2212

Thermal Instability of Contact Rectifiers: The Effect of the Constituent Materials on the Efficiency of a Rectifying Junction—E. Billig. (*Proc. Phys. Soc.* (London), vol. 64, pp. 342–345; April 1, 1951.) An expression is given for the power developed, per unit area of the contact, by the leakage current which flows when a voltage is applied in the blocking direction. Thermal instability results when the heat corresponding to this power cannot be dissipated by cooling. The highest inverse voltage that can be sustained indefinitely is governed by the thermal stability, the criterion for which is assumed generally applicable to all rectifiers. The maximum blocking voltage is calculated for the independent variation of semiconductor conductivity and potential-barrier height.

621.318.22 2213

The Performance and Stability of Permanent Magnets—A. J. Tyrrell. (*Proc. IRE* (Australia), vol. 12, pp. 77–84; March, 1951.) Reprint. See 2251 of 1950.

666.2:681.3 2214

Glass Selection and Production Techniques for X-Ray and Other Tubes—M. J. Zunick and J. B. Gosling. (*Glass Ind.*, vol. 32, pp. 117–120, 144; March, 1951.) Discussion of (a) changes in techniques necessitated by the transition from soft glasses to the hard borosilicate glasses, and (b) the parallel development of suitable sealing metals. Special glass-working lathes are illustrated and processes for the production of heavy glass bulbs are briefly described.

MATHEMATICS

517.512.2 2215

The Method of Discontinuities in Fourier Analysis—J. M. L. Janssen. (*Philips Res. Rep.*, vol. 5, pp. 435–460; December, 1950.) Results previously obtained by this method are discussed; a more general conception is practicable starting from the Fourier integrals rather than Fourier series, and the method can then also be used for investigating the frequency spectrum of continuous functions. The borderline between rapid changes and discontinuities is examined; correction factors are derived which take into account the form of the rapid changes. Examples of application of the method are given.

517.9 2216

The Factorization Method—L. Infeld and T. E. Hull. (*Rev. Mod. Phys.*, vol. 23, pp. 21–68; January, 1951.) An operational procedure is described for solving eigenvalue problems. The basic idea is to consider a pair of first-order differential-difference equations which are equivalent to a given second-order differential equation with boundary conditions.

517.93 2217

A Generalization of Reversion Formulae with their Application to Nonlinear Differential Equations—A. C. Sim. (*Phil. Mag.*, vol. 42, pp. 228–238; March, 1951.) The formulas for algebraic reversion are extended to revert a class of nonintegral power series, and are also generalized to revert series whose coefficients contain operators. These formulas are particularly applicable to the nonlinear differential equations met with in various problems of physics and engineering, which they expand into an infinite sequence of linear equations.

517.93 2218

Finite Representation of Impulse Functions—J. J. Smith and P. L. Alger. (*Elec. Eng.*, vol. 70, p. 143; February, 1951.) A digest of an AIEE 1951 Winter General Meeting paper. The use of differentials (d^nH) instead of differential coefficients (d^nH/dx^n) leads to equations in finite functions, which can be solved by conventional methods.

517.941.4:517.522.5 2219

The Remainder Theorem and its Application to Operational-Calculus Techniques—A. S. Richardson, Jr. (PROC. I.R.E., vol. 39, p. 287; March, 1951.) Corrections to paper abstracted in 677 of April.

681.142 2220

1951 IRE National Convention Program—(PROC. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

37—Drift Compensation in D.C. Amplifiers for Analogue Computers—W. E. Ingerson.
86—The Raytheon Selection Matrix for Computer and Switching Applications—K. M. Rehler.
87—Saturable Reactors as Substitutes for Electron Tubes in High-Speed Digital Computers—J. G. Miles.
88—Ferromagnetic Cores for Three-Dimensional Digital Storage Arrays—W. N. Papian.
89—Dependable Small-Scale Digital Computer—J. J. Connolly.
90—An Asynchronous Control for a Digital Computer—D. H. Gridley.
117—A Sampling Analogue Computer—J. Broomall and L. Riebman.
118—A Time Division Multiplier for a General Purpose Electronic Differential Analyzer—R. V. Baum and C. D. Morrill.
119—A High-Speed Product Integrator—A. B. Macnee.
120—Plug-In Units for Digital Computation—G. Glinski and S. Lazecki.
121—A Five-Digit Parallel Coder Tube—J. V. Harrington, K. N. Wulfsberg and G. R. Spencer.

681.142 2221

Programme-Controlled Digital Computers (Electronic Computing Machines)—H. Rutishauser, A. Speiser and E. Stiefel. (*Z. angew. Math. Phys.*, vol. 1, pp. 277–297 and 339–362; September 15 and November 15, 1950, and vol. 2, pp. 1–25 and 63–92; January 15 and March 15, 1951.) A comprehensive review of information at present available on the subject, including fundamental principles, general organization and methods of operation, arithmetical principles, program arrangements, physical principles and equipment. Automatic computers completed or under construction in various countries up to the end of 1949 are listed, with their principal features, and 67 references are given.

681.142(083.71) 2222

Standards on Electronic Computers: Definitions of Terms, 1950—(PROC. I.R.E., vol. 39, pp. 271–277; March, 1951.) Copies of this Standard, 50 IRE 8.S1, may be obtained while available from the IRE at $0.75 per copy.

MEASUREMENTS AND TEST GEAR

529.7 2223

The Determination of Time and Frequency—H. M. Smith. (*Proc. IEE* (London), vol. 98, part II, pp. 143–153; Discussion, pp. 164–172; April, 1951.) Where frequency is measured to an accuracy within 1 part in 10^8, possible small variations in the unit of time must be considered. The principles involved in the determination of time, an astronomical process, are reviewed. Instruments used or to be used for this purpose at Greenwich are mentioned. Clocks and other equipment are described, together with the methods currently used in the operation of the time service. The standard of accuracy attained is discussed; agreement between Greenwich and The United States Naval Observatory is normally within 1 part in 10^8 in respect of frequency. In practice, two time systems are now employed: Greenwich Mean Time, based directly on the astronomical observations and applicable to surveying and astronavigation, and a more uniform time system which is not yet precisely defined, suitable for accurate work in frequency measurement and in related scientific investigations.

621.3.018.4(083.74) 2224
Frequency Standardization—L. Essen. (*Proc. IEE* (London), vol. 98, part II, pp. 154–164; Discussion, pp. 164–172; April, 1951.) The development and performance of quartz oscillators as frequency standards and timekeepers is reviewed. Some of the causes of frequency drift of these standards are discussed, and suggestions are made for improvement in this respect. An outline is given of methods for measuring frequencies up to 50 kmc in terms of quartz standards, also of the frequency control of oscillators by high-Q cavity resonators, with application to the atomic clock based on the ammonia absorption line at 23.870 kmc.

621.3.018.41(083.74):621.317.361 2225
Measuring Time and Frequency in Hawaii—V. E. Heaton. (*Tele-Tech.*, vol. 10, pp. 36–38, 91; March, 1951.) Description of routine methods of comparison of WWV and WWVH frequencies.

621.317 2226
1951 I.R.E. National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

1—A Storage Tube as an Amplitude Distribution Analyzer—R. E. Nienburg and T. F. Rogers.
23—Precision Frequency Generators using Single-Sideband Suppressed-Carrier Modulators—H. R. Holloway and H. C. Harris.
25—Wide-Range Direct-Reading Precision Frequency Meter and Signal Source—B. Parzen.
27—Frequency Stabilization System for Measurement of Microwave Refraction of Gases—W. F. Gabriel.
33—The Servomodulator: a Low-Level D.C. Instrument—G. M. Attura.
53—Electronic Instrumentation in A.M., F.M., and TV Broadcasting through Use of the Cathode-Ray Oscillograph—P. S. Christaldi.
72—Beam Analyzer—L. R. Bloom, D. F. Holshouser, H. S. Wu and W. W. Cannon.
76—Radial Probe Measurements of Mode Conversion in Large Round Waveguide with TE_{01} Mode Excitation—M. Aronoff.
81—Four-Gun Oscilloscope—M. A. Ziniuk.
85—New Techniques in Impulse Testing—W. G. Fockler.
115—Noise Figure Standards—M. Solow, I. W. Hammer and P. H. Haas.
116—New Limits for Low-Level R.F. Energy Measurements—W. K. Volkers.
146—Precise Measurement and Regulation of Magnetic Fields with Radio-Frequency Techniques using Nuclear Resonance—H. A. Thomas.
147—A High-Precision Magnetic-Field Measuring Instrument—R. W. Kane, E. C. Levinthal and E. H. Rodgers.
151—A Sweep Frequency Method for Measuring the Transmission-Amplitude Characteristic of a Television Transmitter—J. Ruston.

621.317(083.74) 2227
Standards for Electrical Measurement—F. B. Silsbee. (*Elec. Eng.*, vol. 70, pp. 202–206; March, 1951.) A paper presented at the 1951 AIEE Winter General Meeting, New York, N. Y., giving an account of some of the methods in use at the National Bureau of Standards for accurate electrical measurements. A block diagram illustrates the various steps in referring such measurements to the fundamental standards of length, mass and time.

621.317.31 2228
Logarithmic Amplification of Weak Currents using Diodes—M. Brière, A. Rogozinski and J. Weill. (*Jour. Phys. Radium*, vol. 12, pp. 144–146; February, 1951.) The logarithmic relation which exists between diode current and anode voltage for negative values of the latter, and which has been used as a basis of measurements, is investigated at very low values. An experimental circuit is described using an under-run multigrid electrometer tube connected as a diode and fed from a source such as an ionization chamber or photocell. The logarithmic portion of the I/V curve may have a current range of 1:10^6, its lower limit depending on the tube used and being as low as 10^{-14} A in some cases. Applications to various measurements are indicated.

621.317.331 2229
Measurement of Very High Resistances at High Alternating Voltages—H. Petersen. (*Elektrotech. Z.*, vol. 71, pp. 577–580; November 1, 1950.) A development of the Schering loss-measurement bridge in which the parallel combination of C and R in the fourth arm is replaced by a potential divider comprising a very high capacitance in series with a variable resistance. This makes it possible to deal with very high resistances having very low parallel capacitances. The very high capacitance is obtained from a network of three capacitances. The variable resistance is used for phase balancing. Accuracy to within 1 per cent was easily obtained with resistances of 10,000 MΩ at 50 kv.

621.317.335.3† 2230
The Use of Special Waveforms in the Study of Linear Dielectric Phenomena—E. Laverick. (*Jour. Brit. IRE*, vol. 11, pp. 81–92; March, 1951.) A survey of the experimental techniques for investigating dielectric phenomena and of the theories suggested in explanation of these phenomena. Most techniques involve the use of sinusoidal signals, but the use of pulsed signals has some advantages. When pulsed signals are used in bridge measurements, with cathode-ray tube display, differences between the properties of a capacitor, including some dielectric, and those of networks intended to simulate such a capacitor, may be easily distinguished.

621.317.336:621.315.212 2231
Pulse Testing of Coaxial Cables—A. W. Lebert. (*Bell Lab. Rec.*, vol. 29, pp. 153–157; April, 1951.) A brief description is given of equipment used to locate impedance variations in coaxial cables during production. The types of echo received from different types of irregularity are described.

621.317.353 2232
Harmonic Distortion in Iron-Core Transformers—T. Williams and R. H. Eastop (*Audio Eng.*, vol. 35, pp. 18–20, 33; April, 1951.) Discussion of a simple and inexpensive bridge suitable for routine checks of total distortion. Errors of the method, and means of extending it to permit measurement of other important performance parameters, are indicated.

621.317.41 2233
Instrument for Production Testing of the Permeability of Magnetic Circuits—M. Andrieux and M. Fraize. (*Onde Élect.*, vol. 31, pp. 65–69; February, 1951.) The principle of the method is the measurement of the no-load secondary voltage of a transformer with constant-current primary feed. The transformer is clamped over the specimen by a simple lever movement. Field strength is adjustable between 2 and 100 millioersted.

621.317.755:534.321.7.08 2234
Precise Calibration of Tuning Forks—C. C. J. Addink. (*Philips Tech. Rev.*, vol. 12, pp. 228–232; February, 1951.) The adoption of the new international standard of concert pitch based on A_3=440 cps emphasizes the importance of accurate tuning standards. A cro method is described in which the frequency of the fork is matched with that of an RC oscillator connected to a synchronous clock.

621.317.755:621.392.5 2235
Experimental Testing of Electrical Networks by Means of the Unit Function Response—J. van Slooten. (*Philips Tech. Rev.*, vol. 12, pp. 233–239; February, 1951.) Pulses of dc are applied to the impedance or network under test by means of a multivibrator which also supplies the timebase voltage for oscilloscopic observation of the response. Several examples, e.g., damped oscillatory circuit, band-pass filter) are discussed particularly. The method is useful where speed is more important than high accuracy.

621.396.6+621.317.7+621.38.001.8 2236
Physical Society's Exhibition 1951—A. B. Wood. (*Nature* (London), vol. 167, pp. 701–704; May 5, 1951.) A brief survey of the apparatus on show at this exhibition, held from April 6th to the 11th. For other accounts see *Wireless Eng.*, vol. 28, pp. 156–161; May, 1951; *Wireless World*, vol. 57, pp. 189–192; May, 1951; *Engineer* (London), vol. 191, pp. 442–445, 473–475, and 505–506; April 6–20, 1951; *Engineering* (London), vol. 171, pp. 409–411, 425–426, and 457–459; April 6–20, 1951.

621.396.615.029.426/.51 2237
A Precision Decade Oscillator for 20 Cycles to 200 Kilocycles—C. M. Edwards. (Proc. I.R.E., vol. 39, pp. 277–278; March, 1951.) Circuit details of a RC-coupled test oscillator with frequency accuracy to within 0.1 per cent from 100 cps to 100 kc and to within 0.5 per cent outside this range. Three ranges are provided by capacitance changes by factors of 10, decade arrangements of resistors giving 100-cps and 10-cps steps respectively, with a linear potentiometer for continuous variations from 0 to 10 cps. On the highest range 100 kc is added to 100 times the combined dial readings. Good tracking over the wide frequency range is effected by the use of trimmers and a wide-band amplifier.

621.317 2238
Die Messung von elektrischen Schwingungen aller Art nach Frequenz und Amplitude (The Measurement of Electrical Oscillations of All Frequencies and Amplitudes). [Book Review]—H. Laporte. Publishers: Verlag Wilhelm Knapp, Halle/Sa., 1949, 111 pp., DM 4.20. (*Optik*, vol. 8, p. 80; January and February, 1951.) This is the first volume in a series of "Handbooks of Practical Physics for Scientists and Engineers," and is particularly valuable for demonstrating the evolution of the methods of measurement from ordinary current and voltage measurements at low frequencies to power or energy measurements at centimeter wavelengths and to the counting of quanta for X rays.

621.317.31/.32 2239
Die Messung von elektrischen Spannungen und Strömen aller Art vom Gleichstrom bis zur Hochfrequenz (The Measurement of Electrical Voltages and Currents from Direct Current up to High Frequency). [Book Review]—H. Laporte. Publishers: Verlag Wilhelm

Knapp, Halle/Sa., 1950, 149 pp., DM 5.20. *Optik*, vol. 8, p. 80; January and February, 1951.) Volume 2 of the series "Handbooks of Practical Physics," mainly for the beginner. Both well known and less usual methods of measurement are discussed; theory is kept to the minimum, while many numerical data are included. One chapter deals with auxiliary apparatus such as potentiometers and scale-reading magnifiers.

OTHER APPLICATIONS OF RADIO AND ELECTRONICS

537.226.1:541.124 **2240**

A Dielectric-Constant Method of Following the Nonstationary State in Polymerization: Part 1—The Theory of the Method—C. M. Burrell, T. G. Majury, and H. W. Melville. (*Proc. Roy. Soc. A*, vol. 205, pp. 309–322; February 22, 1951.) A very sensitive means has been developed for recording small amounts of chemical change occurring in short periods, using the change of dielectric constant accompanying reaction to vary the capacitance of an element in a bridge incorporating a signal generator of special design. Operation is at 40 to 60 mc.

621-526 **2241**

Transducers—Sensing Elements for Servos—Stovall. (*See* 2285.)

621.316.7.076.7 **2242**

On the Regulation of Industrial Processes—H. J. Roosdorp. (*Philips Tech. Rev.*, vol. 12, pp. 221–227; February, 1951.) A general introductory discussion on the automatic control of closed circuits. The advantages of working from an electrical analogue are indicated.

621.317.083.4:551.508.11 **2243**

A New Code Transmitting Radiosonde—H. D. Brailsford. (*Jour. Met.*, vol. 6, pp. 360–362; October, 1949.) The system uses a special disk on which Morse letters are recorded, so that the position of a pickup on the disk is known from the letters transmitted. Three pickups are provided, with angular separations of about 90°, the pickup arms being controlled respectively by an aneroid pressure cell, a bimetal temperature element, and a hair hygrometer. The Morse letters are confined to a sector of about 85° on the record, so that the transmitted signal consists of three code groups followed by a pause. Design problems are discussed.

621.365.54† **2244**

Induction Heating of a Hollow Metal Sphere—A. Colombani. (*Jour. Phys. Radium*, vol. 12, pp. 26–30; January, 1951.) Formulas are derived giving the energy absorption as a function of thickness for a thin spherical metal shell in an alternating field; a maximum is exhibited for a particular value of the thickness. The calculation is made without using spherical functions, by introducing the concept of magnetic potentials.

621.38.001.8 **2245**

1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

39—Some Biological Applications of Random Nets—A. Rapoport.
69—The Rotating Beam Method for Investigating Electron Lenses—D. E. George, R. G. E. Hutter and M. Cooperstein.
82—Automotive Electronic Test Equipment—R. J. L. Butterer and T. S. Bolton.
83—The Vibratron—a New Transducer—J. Ohman and P. M. Erlandson.
84—Electronic Relays in Automatic Process Control Systems—R. W. Greenwood.
114—X-Ray Liquid Level Gage—J. E. Jacobs and R. F. Wilson.
144—Timing Unit and Pulse Deflector Generator for 145-Inch Synchro-Cyclotron—E. M. Williams, C. H. Grace and L. W. Johnson.
145—Design and Construction of a Billion-Volt Linear Electron Accelerator—M. Chodorow, E. L. Ginzton, J. Jasberg, R. Kyhl, R. Neal, and P. Pearson.
157—Telemetry and the Guided-Missile Program—C. H. Hoeppner.
158—F.M./F.M. Telemetry—M. V. Kiebert, Jr.
159—Techniques and Applications of F.M./F.M. Telemetry—W. J. Mayo-Wells.
160—The Case for P.W.M./F.M. Telemetry—J. R. Kauke.
161—P.T.M. Telemetry—A. H. Nelson.
185—Simulation—its Place in System Design—H. H. Goode.
186—Detailed Simulation of a Three-Axis Guided Missile System (Typhoon)—A. W. Vance.
187—The Application of the Simulator to the Design of Automatic Control Systems—L. Botwin.
188—Real Time Simulation of Feedback Control Systems—A. C. Hall.
189—Digital Computers in Simulated Control Systems—J. W. Forrester.

621.38.001.8 **2246**

An Electronic Instrument for the Measurement of the Damping Capacity of Materials—A. D. N. Smith. (*Jour. Sci. Instr.*, vol. 28, pp. 106–108; April, 1951.) The instrument is designed for investigating the internal friction of materials vibrating at frequencies from about 50 cps to 10 kc. The vibrations are detected by means of a pickup, and the time for the vibration amplitude to decay freely to half its initial value, is measured by means of a circuit which transmits two pulses to a standard electronic timing instrument.

621.38.001.8:373.62:656.7.07 **2247**

Electronic Flight Simulator—(*Wireless World*, vol. 57, pp. 130–131; April, 1951.) The equipment described is a model of the nose of an aircraft in which all the controls are electrically connected to a computer unit and to an instructor's control desk. The flight instruments, engine indicators and devices simulating engine noise and other flight conditions, are controlled via the computer. Aircrews can gain experience of the aircraft controls with fewer flying hours and under simulated fault conditions which could not be deliberately contrived in the air.

621.38.001.8:545.81 **2248**

Electronic Colorimetry—D. W. Thomasson. (*Electronic Eng.* (London), vol. 23, pp. 91–93; March, 1951.) Photocell methods of color measurement are outlined. A new type of photocell with Ag-O-Cs and Sb-Cs layers deposited on opposite sides of an internal partition may solve the problem of obtaining constant sensitivity over the visual wavelength range.

621.38.001.8:623.8 **2249**

Electronics in Naval Architecture: Some Applications to Research Problems—(*Engineer* (London), vol. 191, p. 295; March 2, 1951.) Long summary of a paper read before the North-East Coast Institution of Engineers and Shipbuilders by L. C. Burrill and A. G. Boggis, January, 1951. Replacement of mechanical by electrical devices is considered. Problems mentioned include measurement of (a) resonance vibrations of ships' hulls, (b) moment of inertia of swinging propeller, (c) small thicknesses, and (d) metacentric height.

621.383.001.8:535.61-15:778.37 **2250**

Use of Image-Converter Tube for High-Speed Shutter Action—A. W. Hogan. (Proc. I.R.E., vol. 39, pp. 268–270; March, 1951.) "The equipment described provides a means for obtaining high-speed photographs while utilizing a continuous light source. The device may be pulsed once for "one-shot" exposures, or repetitively for motion pictures or stroboscope applications. The heart of the equipment is an image-converter tube such as the 1P25. Images are impressed on the photocathode and the tube is pulsed electrically for a duration equal to the exposure time desired. The image will then appear on the fluorescent screen and may be viewed directly or photographed."

621.384:539.185 **2251**

A 200-kV Neutron Generator: Part 1—G. Carlson. (*Ark. Mat. Astr. Fys.*, vol. 2, pp. 277–287; December 28, 1950.) Description of apparatus constructed at the Institute of Physics at Uppsala.

621.384:539.185 **2252**

A 200-kV Neutron Generator: Part 2—I. Bartholdson and G. Carlson. (*Ark. Mat. Astr. Fys.*, vol. 2, pp. 289–293; December 28, 1950.) The adjustment of the generator and some preliminary measurements are described. Part 1: 2251 above.

621.384.611.2† **2253**

Synchro-Cyclotron for Liverpool University—(*Engineer* (London), vol. 191, p. 425; March 30, 1951.) Brief note of model under construction, designed to accelerate protons to about 400 mev.

621.384.612.1† **2254**

Design of Acceleration Chamber and Dees for the 225-cm Cyclotron at the Nobel Institute for Physics, Stockholm—H. Atterling. (*Ark. Mat. Astr. Fys.*, vol. 2, pp. 559–570; February 20, 1951.)

621.384.612.2†:621.396.615 **2255**

Pulser for Cyclotron Oscillator—W. H. Henry and J. D. Keys. (*Canad. Jour. Phys.*, vol. 29, pp. 137–141; March, 1951.) The pulser for the rf oscillator of the McGill synchrocyclotron is described.

621.385.833 **2256**

Approximation to Rotationally Symmetrical Potential Fields with Cylindrical Equipotential Surfaces by means of an Analytical Function—F. Lenz. (*Ann. Phys.*, (Lpz), vol. 8, pp. 124–128; November 10, 1950.) An analytical expression is derived for the exponentially decreasing field at a great distance from the center of a lens with cylindrical equipotentials. For magnetic lenses, the formula gives the field as a function of the pole-piece dimensions. The closeness of the approximation is assessed by comparing the analytical results with the field distribution calculated numerically.

621.385.833 **2257**

Second Session of the German Electron-Microscopy Society, 14th-16th April 1950—(*Optik*, vol. 7, pp. 185–335; October/December, 1950.) The text is given of some forty papers presented at the meeting, covering electronoptical aspects and applications of electron microscopes.

621.387.4† **2258**

Symposium of Papers on Radiation Monitoring Apparatus—(*Proc. IEE* (London), vol. 98, part II, pp. 173–255; April, 1951.) Full text of and discussion on the following papers:

Nuclear Particle and Radiation Detectors: Part 1—Ion Chambers and Ion-Chamber Instruments—D. Taylor and J. Sharpe.
A Counting-Rate Meter of High Accuracy—E. H. Cooke-Yarborough and E. W. Pulsford.
An Accurate Logarithmic Counting-Rate Meter covering a Wide Range—E. H. Cooke-Yarborough and E. W. Pulsford.
Nuclear Particle and Radiation Detectors:

Part 2—Counters and Counting Systems—J. Sharpe and D. Taylor.
The Development of End-Window Geiger-Müller Counter Tubes—R. O. Jenkins.
A Survey Equipment using Low-Voltage Halogen-Quenched Geiger-Müller Counters—E. Franklin and W. R. Loosemore.
Scintillation Counting Equipments—R. B. Owen and E. A. Sayle.

621.387.4† 2259
Improved CO_2-Filled Geiger-Müller Counters—J. Labeyrie. (*Jour. Phys. Radium*, vol. 12, pp. 146–148; February, 1951.)

621.387.424† 2260
Time Delays in Low-Voltage Halogen-Quenched Geiger-Müller Counters—W. R. Loosemore and J. Sharpe. (*Nature* (London), vol. 167, pp. 600–601; April 14, 1951.) An interim note on an investigation in progress at Harwell.

777.2:621.383 2261
Half-Tone Cuts Produced Electronically—G. Washington, Jr. (*Proc. Radio Club Amer.*, vol. 28, no. 1, pp. 3–10; 1951.) Illustrated description of a method of producing half-tone blocks on plastic-sheet material. The picture is scanned by a photocell, the current in which is used to control the amplitude of vibration of a red-hot stylus which jabs into the plastic sheet 350 times per second. After washing, the plate is ready for direct printing. The time required for making a 5 inch×7 inch block is about 12 minutes.

621.385.38 2262
The Industrial Applications of Gasfilled Triodes (Thyratrons). [Book Review]—Walker. (*See* 2306.)

PROPAGATION OF WAVES

621.396.11 2263
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:
48—Selective Fading of Microwaves—A. B. Crawford and W. C. Jakes, Jr.
49—Propagation Studies at Microwave Frequencies by means of Very Short Pulses—O. E. DeLange.
50—Low-Frequency Ionosphere Soundings with Atmospherics—W. J. Kessler and W. F. Zetrouer, II.
51—The Effect on Propagation of an Elevated Atmospheric Layer of Nonstandard Refractive Index—L. H. Doherty.

621.396.11:551.510.535:523.3 2264
Moon Echoes and Transmission through the Ionosphere—F. J. Kerr and C. A. Shain. (Proc. I.R.E., vol. 39, pp. 230–242; March, 1951.) Moon echoes of pulses with frequencies about 20 mc were studied, mainly to obtain information on ionospheric transmission of radio signals at small angles of elevation. Special transmissions of single pulses or groups of pulses were made from the hf broadcasting station at Shepparton, Victoria, Australia, and receivers were used at two distant stations in Australia and three in America. Preliminary results have been reported previously [2030 of 1949 (Kerr et al)]. The observations extended over about a year, echoes were received in 24 out of 30 experiments. Comparison of the results with those to be expected from orthodox ray theory for a horizontally stratified ionosphere indicates that (a) observed echo intensities were well below the theoretical values, (b) minimum moon altitudes at which echoes were first detected were unexpectedly large. The close correlation of these anomalies with f_0F_2 values suggests that they may be explained by irregularities in the F_2 region. Another possible explanation of the discrepancies is inadequacy of the ray theory for very oblique incidence. Discussion of the two types of fading observed with moon echoes shows that for the frequencies used, the moon is a "rough" reflector.

RECEPTION

621.396.621 2265
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:
2—Cross-Correlation and the Optimum Signal-to-Noise Ratio for Periodic Systems—M. Leifer and N. Marchand.
3—Detection of Repetitive Signals In Noise by Correlation—Y. W. Lee and L. G. Kraft.
31—Echo Distortion in the F.M. Transmission of Frequency-Division Multiplex—W. J. Albersheim and J. P. Schafer.
128—Semi-Automatic Fabrication of Audio and Video Equipment—W. H. Hannahs, R. Bahr, Jr., and J. Caffiaux.
131—Radio Receiver Subminiaturization Techniques—G. Shapiro.
170—A Practical Speech Silencer for Radio Receivers—R. C. Jones.
176—Internal Television Receiver Interference—B. Amos and W. Heiser.

621.396.621 2266
The LD-R1 Single Sideband Radio Receiver—G. Rodwin. (*Bell Lab. Rec.*, vol., 29, pp. 169–172; April, 1951.) A single-sideband receiver for radiotelephony in the frequency range 4 to 23 mc. Up to four speech channels can be provided with one carrier. A double-superheterodyne circuit is used, with optional crystal or variable-frequency first oscillator. The frequency of the second oscillator is automatically controlled to synchronize the second IF output with a locally generated demodulating frequency.

621.396.621:621.396.812.3 2267
Experimental Evaluation of Diversity Receiving Systems—J. L. Glaser and S. H. Van Wambeck. (Proc. I.R.E., vol. 39, pp. 252–255; March, 1951.) Apparatus is described which records the total times during which the signal from a diversity receiving system lies within each of seven signal-strength ranges. The use of the data so obtained for comparison of the statistical properties of different systems is discussed.

621.396.621:621.396.812.3 2268
Performance of Diversity Receiving Systems—S. H. Van Wambeck and A. H. Ross. (Proc. I.R.E., vol. 39, pp. 256–264; March, 1951.) Results are reported of investigations carried out continuously over a period of two years on various systems using frequencies in the range 7 to 16 mc over a 900-mile path. Improvement in reception provided by the systems is shown graphically, and the variability in improvement is indicated. A diversity system using three spaced antennas is found to be definitely superior to one using only two antennas which, in turn, is generally more effective than a polarization-diversity system.

STATIONS AND COMMUNICATION SYSTEMS

621.3.018.42(083.71) 2269
A Proposed Numbered Frequency Band Subdivision Plan—C. W. Young. (*TV Eng.*, vol. 2, pp. 24–25, 30; March, 1951.) A scheme is proposed whereby small portions of a band could be referred to simply and clearly.

621.39 2270
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:
1—A Storage Tube as an Amplitude Distribution Analyzer—R. E. Nienburg and T. F. Rogers.
2—Cross-Correlation and the Optimum Signal-to-Noise Ratio for Periodic Systems—M. Leifer and N. Marchand.
3—Detection of Repetitive Signals in Noise by Correlation—Y. W. Lee and L. G. Kraft.
4—Error Reduction in the Determination of Electronic System Parameters—L. S. Schwartz.
5—Coding Processes for Bandwidth Reduction in Picture Transmission—A. E. Laemmel.
22—The Generation of Single-Sideband Suppressed-Carrier Signals by a New Balancing Method—H. M. Swarm.
28—A.M.-F.M. Analogy—H. C. Harris.
29—Survey of Electronic Commutation Methods—R. S. Butts.
30—High-Frequency Radio Communication System utilizing Phase-ModulationTransmission and Single-Sideband Reception—H. F. Meyer and H. Y. Littlefield.
31—Echo Distortion in the F.M. Transmission of Frequency-Division Multiplex—W. J. Albersheim and J. P. Schafer.
52—Master Control Facilities for a Large Studio Center—R. H. Tanner.
54—Performance of Sectionalized Broadcasting Towers—C. E. Smith.
71—Generation of Sidebands due to Gain and Phase Shift Modulations in a Traveling Wave Tube Amplifier—M. Arditi, A. G. Clavier and P. Parzen.
108—Aircraft and Airport Characteristics—L. P. Tabor.
109—Economic Demand—F. B. Lee.
110—Human Engineering—P. M. Fitts.
111—Traffic Control Theory—D. H. Ewing.

621.39.001.11 2271
Adaptation of Message to Transmission Line: Part 1—Quanta of Information—B. Mandelbrot. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1638–1640; April 30, 1951.) Since words, in the ordinary sense, satisfy a privileged statistical system of the form $p_n \sim A(n+n_0)^{-B}$, they constitute natural quanta of information. The transmission of the message is considered from the standpoint of "cost," (a term related to entropy), and of structure.

621.39.001.11 2272
Information and Regression—R. Féron and C. Fourgeaud. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 1636–1638; April 30, 1951.) Quantity of information is investigated by probability-calculus methods.

621.39.001.11 2273
Definition of Information—E. Reich. (Proc. I.R.E., vol. 39, p. 290; March, 1951.) The uniqueness of the definition of the rate R of information transfer is examined, since it is conceivable that a different definition of information might lead to different criteria for communication-link design. The basic postulate here proposed for R to satisfy is that R is invariant under any transformation of x and y that merely amounts to a relabelling of the message symbols. If R is given by the formula proposed by Shannon (1361 and 1649 of 1949), the postulate is satisfied. An expression representing a certain class of possible definitions is considered which involves (a) the conditional probability that x was transmitted if y was received, and (b) a function $F(u, v)$ of two real variables to be chosen in such a way that the fundamental postulate is satisfied. With the usual continuity assumption, the only possible choice for the function F leads to Shannon's expression for R. Details of the derivation are to be published in a mathematical journal.

621.39.001.11:621.396.933.4 2274
Application of the Information Theory to System Design—W. G. Tuller. (*Elec. Eng.*, vol. 70, pp. 124–126; February, 1951.) An assessment of the facilities required to transmit certain standard messages from a traffic control center to aircraft. Any surplus channel capacity can be used for checking messages and for improving operation at low signal-noise ratios.

621.391.32 2275
Subterranean Communication by Electric Waves—H. P. Williams. (*Jour. Brit. IRE*, vol. 11, pp. 101–111; March, 1951.) Communication through ground over distances of several hundred yards is possible using frequencies of the order of 1 kc. The electrostatic field must be used; various electrode systems for setting up such a field are described and analyzed. Electrode spacings of the order of a mile may be desirable. The terminal equipment can be made compact and easily portable.

621.396:628.1/.2 2276
Electronics in a Large Public Utility—The Sydney Metropolitan Water, Sewerage and Drainage Board—H. A. Stowe. (*Proc. IRE* (Australia), vol. 12, pp. 69–76; March, 1951.) The development of the use of radio communications by the Sydney Water Board is outlined, and systems in actual use are described, including cableway signalling, flood warning, and shaft-cage signalling.

621.396.44+621.397.24 2277
Television and Sound by Wire—R. I. Kinross. (*Wireless World*, vol. 57, pp. 126–129; April, 1951.) Describes a system being installed in Montreal for the simultaneous distribution of sound and television programs by wire. Two television and eight sound programs modulate separate carriers, the vision carrier frequencies being 16 mc and 28 mc and the sound carriers 180 to 320 kc at 20 kc spacing. Trunk coaxial feeders, with repeaters at one-mile intervals, are used to feed subscriber cables, the total area covered having a radius of about 5 miles.

621.396.6 2278
Equipment for 450 Mc/s—L. P. Morris. (*FM-TV*, vol. 11, pp. 26–28; March, 1951.) Equipment is described for adapting standard 152-mc communication transmitters and receivers for operation in the new 450 to 460-mc band. The conversion is performed by frequency tripling at the transmitter, and heterodyning at the receiver.

621.396.931 2279
Operational Study of a Highway Mobile Telephone System—L. A. Dorff. (*Elec. Eng.*, vol. 70, pp. 236–241; March, 1951.) Paper presented at the 1951 AIEE Winter General Meeting, New York. The United States system for communication between telephone subscribers and vehicles on the highways operates in the 30 to 44-mc band; the country is divided into seven zones and each zone is allocated one frequency in this band for base stations and one for all vehicles. Each zone is divided into overlapping areas containing a base transmitter and receivers. An account is given of trials to devise operating procedure to minimize the effect of interference between areas, and increase the traffic-handling capacity of the system.

621.396.97:621.396.66 2280
Automatic Program Monitor—J. Moir. (*FM-TV*, vol. 11, pp. 42–45; March, 1951.) See 1491 of July (Rantzen, Peachey and Gunn-Russell).

621.396.97:621.396/.397].8 2281
The Variation with Frequency of the Signal Range of F.M. and Television Broadcasting Stations—K. A. Norton and E. W. Allen. (*Jour. Brit.* IRE, vol. 11, pp. 93–100; March, 1951.) The factors limiting the range of broadcast transmissions in the vhf and uhf bands are discussed. The two main types of noise, viz. receiver noise and cosmic noise, are also discussed. Curves are given showing the effective range of a transmitter when various types of receiving antenna are used. Above 100 mc, range is limited by receiver noise, which in present receivers is much greater than the theoretically attainable minimum.

621.396.97+621.397](410) 2282
Sound and Vision Broadcasting in Great Britain—(*Nature* (London), vol. 167, pp. 617–619; April 21, 1951.) Summary of the Report of the Broadcasting Committee, 1949, published by H. M. Stationery Office, 1951, at 6s. 6d.

621.396 2283
Drahtloser Überseeverkehr. (Radio Oversea Communication) [Book Review]—P. Kotowski and H. Sobotka. Publishers: S. Hirzel, Leipzig, 2nd edn 1950, 271 pp., DM 14.80. (*Elektrotechnik Berlin*, vol. 5, p. 141; March, 1951.) Strongly recommended to a wide circle of readers.

SUBSIDIARY APPARATUS

621–526+621.396.68 2284
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951. Summaries are given of the following papers:

62—Network Synthesis applied to Feedback Control—J. G. Truxal.
65—Electrical-Mechanical Equivalent Network Synthesis—A. A. Gerlach.
130—Power Supplies for Television Receivers—A. M. Levine and S. Moskowitz.

621–526 2285
Transducers—Sensing Elements for Servos—J. R. Stovall. (*Elec. Mfg.*, vol. 45, pp. 88–92, 184; April, 1950.) Seventeen types of sensing elements are enumerated for converting position, motion or pressure into electrical signals for servo operation. Some practical applications for measurement, recording, and control are described.

621.319.45.025:621.314.64 2286
Variation with Frequency of the Dynamic Characteristic *i(V)* of the System Al-Al_2O_3-Electrolyte—W. C. van Geel and B. C. Bouma. (*Philips Res. Rep.*, vol. 5, pp. 461–475; December, 1950.) A tentative explanation is advanced of the phenomena described in 1254 of June (Dekker & van Geel). It is assumed that the oxide layer contains an excess of Al in the vicinity of the Al layer; in this region it is an excess semiconductor. The other part of the oxide layer is the barrier, whose thickness changes with the direction of the applied voltage, giving rise to the loop observed in the characteristic. The variation of thickness is due to electrolysis in the Al_2O_3 layer. A possible alternative assumption is that the oxide layer in the vicinity of the electrolyte contains a surplus of oxygen, corresponding to a defect semiconductor.

621.352 2287
Some Notes on Unsaturated Standard Cells—F. C. Helmes. (*N. Z. Elect. Jour.*, vol. 23, pp. 300–301; April 25, 1950.) Errors up to 0.5 per cent may be introduced when Weston standard cells are used without suitable precautions. The causes include unequal heating of the two limbs of the cell, hysteresis or temporary changes of emf resulting from abrupt changes of cell temperature, and decrease in emf with age of the cell.

TELEVISION AND PHOTOTELEGRAPHY

621.396/.397].8:621.396.97 2288
The Variation with Frequency of the Signal Range of F.M. and Television Broadcasting Stations—Norton and Allen. (*See* 2281.)

621.396.97+621.397] (410) 2289
Sound and Vision Broadcasting in Great Britain—(*See* 2282.)

621.397.24+621.396.44 2290
Television and Sound by Wire—Kinross. (*See* 2277.)

621.397.24 2291
Local Wire Television Networks—C. N. Nebel. (*Elec. Eng.*, vol. 70, pp. 130–135; February, 1951.) A description, with circuit and performance details, of terminal, repeater, and equalizer equipment developed for local video distribution, existing telephone facilities being used where practicable. A flat response with minimum cross-talk, noise, and losses is obtained by the use of special cables, and by pre-attenuation of the lower frequencies and subsequent equalization.

621.397.5 2292
1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

5—Coding Processes for Bandwidth Reduction in Picture Transmission—A. E. Laemmel.
6—Colorimetry in Television—F. J. Bingley.
7—Subjective Sharpness of Additive Color Pictures—M. W. Baldwin, Jr.
8—Color Multiplexing by Sine-Wave Functions—N. Marchand.
9—Measurement and Control of Color Characteristics of Flying Spot Color Signal Generator—R. Moore, J. Fisher and J. Chatten.
10—Performance of Carrier Synchronizing Circuits for Color Television Receivers—E. M. Creamer, Jr., and M. I. Burgett.
11—A Simple Pattern Generator for Color Television Signals—R. P. Burr, W. R. Stone and R. O. Noyer.
55—Increased Economy and Operating Efficiency of Television Broadcast Stations through Systemic Design—R. A. Isberg.
56—Technical Considerations of Television Recording—G. E. Hamilton.
68—The Design of 90°-Deflection Picture Tubes—H. Grossbohlin.
127—Wide-Angle Deflection Yoke Design—H. Thomas.
128—Semi-Automatic Fabrication of Audio and Video Equipment—W. H. Hannahs, R. Bahr, Jr., and J. Caffiaux.
129—U.H.F. Converter—B. F. Tyson.
148—Parallel Operation of Vacuum Tubes at U.H.F. to obtain High Transmitter Power—W. H. Sayer, Jr., and E. Mehrbach.
149—An Ultra Portable Television Pickup Equipment—L. E. Flory, W. S. Pike, J. E. Dilley and J. M. Morgan.
150—The Technique of Dot Arresting for Television Transmission using Dot Interlace—K. Schlesinger.
151—A Sweep Frequency Method for Measuring the Transmission-Amplitude Characteristic of a Television Transmitter—J. Ruston.
175—Synchroflection: a Horizontal Deflection System possessing Inherent Noise Immunity—W. K. Squires and K. R. Wendt.
176—Internal Television Receiver Interference—B. Amos and W. Heiser.
177—An R.F. Amplifier for the U.H.F. Television Band—B. F. Tyson and J. G. Weissman.
178—Television Line Selector with Automatic Identifier—J. Fisher.
179—Development of a High Stability U.H.F. Television Tuner—M. W. Slate, J. P. Van Duyne and E. G. Mannerberg.

621.397.5 2293

Image Gradation, Graininess and Sharpness in Television and Motion Picture Systems: Part 1—Image Structure and Transfer Characteristics—O. H. Schade. (*Jour. Soc. Mot. Pic. & Telev. Eng.*, vol. 56, pp. 137–177; February, 1951.) The physical quality of motion-picture and television images is determined by the transfer characteristic, the signal/noise ratio, and the resolution. A detailed analysis is given of the transfer characteristics of television camera tubes and motion-picture film. Means are described for improving the fidelity of reproduction; practical examples are given in illustration. The signal/noise ratio and resolution will be discussed in parts 2 and 3.

621.397.6 2294

The Genlock—A New Tool for Better TV Programming—J. H. Roe. (*Jour. Soc. Mot. Pic. & Telev. Eng.*, vol. 56, pp. 232–234; February, 1951.) Long abstract of paper published in full in *Proc. Nat. Electronics Conference, Chicago*, vol. 6, pp. 178–184; 1950. The unit described enables a local synchronizing-pulse generator to be locked in phase with a distant one. This makes possible the use of "lap dissolves," and superpositions involving pictures from two distinct program sources.

621.397.62 2295

Matching of the Frame Output Stage to the Deflection Coils in Television Receivers: Part 2—High Impedance Deflection Coils—P. D. van der Knaap and J. Jager. (*Philips Tech. Commun.* (Australia), No. 1, pp. 9–13; 1951.) Design requirements are analyzed. In the case of high-impedance deflection coils, a choke is used in the anode circuit of the output valve, with the deflection coils connected in parallel through a coupling capacitor. A comparison is made with the low-impedance case using a transformer, discussed in part 1 (1793 of August).

621.397.621.2 2296

Television Image Reproduction by use of Velocity-Modulation Principles—M. A. Honnell and M. D. Prince. (Proc. I.R.E., vol. 39, pp. 265–268; March, 1951.) The video signal (obtained in the usual manner) is not applied to the grid of the viewing tube, but is superimposed on the horizontal-deflection voltage. The resulting brightness is proportional to the derivative of the signal. The system may have some application in the reproduction of printed material and line drawings, and for radar. The resolution of an ordinary television picture may be improved by the use of a suitable amount of velocity modulation combined with grid modulation.

621.397.7:534.861.1 2297

Television Studio Acoustics—M. Rettinger. (*Audio Eng.*, vol. 35, pp. 13–14, 47; April, 1951.) Discussion of methods of acoustic treatment of television studios to ensure optimum sound quality.

TRANSMISSION

621.396.61 2298

1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

24—Stabilized Variable-Frequency Transmitter Exciter for Military H.F. Equipment—J. Bush.
26—Crystal Control of a 4-kw, 1,036-mc Transmitter—J. W. Clark, R. W. Kane, W. G. Abraham, N. P. Hiestand, and S. F. Varian.
148—Parallel Operation of Vacuum Tubes at U.H.F. to obtain High Transmitter Power—W. H. Sayer, Jr., and E. Mehrbach.
190—Low-Distortion Frequency-Modulation Modulators—A. R. Vallarino and C. Greenwald.

621.396.61 2299

Air-Cooled Variometer for Mobile S. W. Transmitter—W. Schirp. (*Elektrotech. Z.*, vol. 72, pp. 171–173; March 15, 1951.) Constructional details are given for the output-stage variometer of a 20-kw mobile transmitter, particular attention being paid to the air-cooling and roller-contact arrangements. The wavelength range is 12.5 to 100 m. Only the windings in circuit at the highest frequencies need to be cooled.

621.396.61:621.396.933 2300

Design of a Loran Transmitter—R. H. Myers. (*Elec. Commun.*, vol. 28, pp. 31–45; March, 1951.) Problems encountered in the design of a new type of transmitter are discussed and the equipment described. The main objectives were (a) to narrow the radiated frequency spectrum, (b) to increase the peak output to 1 mw, and (c) to fix the phase of the carrier with respect to the pulse envelope in order to enable cycle-matching technique to be used. Theoretical considerations showed that a cosine-squared shape of pulse was suitable. Pulse shaping was achieved by grid modulation in the penultimate stage. By deriving the modulation voltage from the master oscillator used for generating the rf driving voltage, phase locking between the two was obtained.

TUBES AND THERMIONICS

537.581:539.16 2301

Effect of Radioactivity on the Thermoelectronic Emission from Cathodes—J. Debiesse, G. Neyret, J. Challansonnet, and J. Amoignon. (*Compt. Rend. Acad. Sci.* (Paris), vol. 232, pp. 2015–2016; May 28, 1951.) When a cathode emits β or γ radiations [see 1522 of July (Debiesse, Challansonnet, and Neyret)], a strong disturbance of the electrostatic field at the emission centers is produced. The effect of these disturbances on the thermoelectronic emission was studied, using cathode bases of Ni with 5 per cent Co, coated with Ba/Sr carbonates. Lower currents were observed from the radioactive cathodes than from similar, but inert, cathodes. Working from a simplified form of a known empirical formula for saturation current, the work function is found to be 1.5-2 v for the radioactive cathodes and of the order of 1 v for the inert cathodes. Further experiments were made with pure w cathodes, the radioactive specimens again giving lower emission currents.

621.314.632+621.383]:546.289 2302

***p-n* Junction Rectifier and Photo-Cell**—W. J. Pietenpol. (*Phys. Rev.*, vol. 82, pp. 120–121; April 1, 1951.) Description of two devices made from *p-n* junctions in single-crystal Ge by the process described by Teal, Sparks and Buehler (1682 of August). The first of these is a rectifier which retains its high impedance in the reverse direction to well above 1,000 v, where its value is 117 MΩ. In the forward direction the dc resistance at 1v is 237 Ω. The saturation current increases by a factor of about 10 for a temperature increase from 25° to 60°C. The rectifier can be used slightly above the af range. The second device is a photocell which responds to light of wavelength up to 1.9 μ with a quantum efficiency of unity. The sensitivity to a light source of 2,900°K color temperature is about 0.01 ma/millilumen. The dark impedance is of the order of megohms.

621.383.42 2303

The Electron Voltaic Effect—W. Ehrenberg, Chi-Shi Lang and R. West. (*Proc. Phys. Soc.* (London), vol. 64, p. 424; April 1, 1951.) Experiments indicate that photovoltaic cells are sensitive to electron bombardment, the gain (i.e., ratio of circulating current to bombarding current) depending on the voltage of the bombarding electrons.

621.385+621.396.615 2304

1951 IRE National Convention Program—(Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

18—The Effect of Secondary Emission in Power Tubes—Hsiung Hsu.
19—Reflex Resnatron Operation and its Implication for Bandwidth—M. Garbuny and G. E. Sheppard.
20—The Multibeam Electron Coupler—an Improved Spiral-Beam Electron Tube for the Modulation and Control of Power at U.H.F.—C. L. Cuccia.
21—A New Single-Cavity Resonator for a Multianode Magnetron—J. S. Needle, G. Hok, G. R. Brewer and H. W. Welch.
43—A Coaxial Power Triode for 50-kw Output up to 110 mc—R. H. Rheaume.
44—A High-Power Tetrode—C. E. Murdock.
45—The Reflex Resnatron—G. E. Sheppard, M. Garbuny and J. R. Hansen.
46—Transmitting Tube suitable for U.H.F. Television—W. G. Abraham, F. L. Salisbury and S. F. Varian.
47—Frequency-Modulated High Efficiency Klystron Transmitter—M. Chodorow and S. P. Fan.
70—A Miniature Traveling-Wave Tube for the Lower U.H.F. Band—R. Adler.
97—The Plasmatron, a Continuously Controllable Gas Tube—E. O. Johnson and W. M. Webster.
98—Switching Time Limitations in Hydrogen Thyratrons—J. B. Woodford, Jr., and E. M. Williams.
99—A New Type Heater Cathode Tube for Portable Battery-Operated Equipment—G. W. Baker.
100—New Vacuum-Tube Materials—E. B. Fehr and A. P. Haase.
121—A Five-Digit Parallel Coder Tube—J. V. Harrington K. N. Wulfsberg and G. R. Spencer.
192—A *K*-Band Amplifier Klystron—W. G. Abraham, J. W. Clark, D. L. Snow and S. F. Varian.
193—Mode Interactions in Magnetron Oscillators—R. R. Moats.

621.396.822 2305

Theory of the Shot and Johnson Effects—H. Dänzer. (*Ann. Phys.* (Lpz.), vol. 8, pp. 176–186; November 10, 1950.) A unified mathematical treatment of the two effects is developed.

621.385.38 2306

The Industrial Applications of Gasfilled Triodes (Thyratrons) [Book Review]—R. C. Walker. Publishers: Chapman and Hall, London, Eng., 40s. (*Engineering* (London), vol. 171, p. 276; March 9, 1951.) A comprehensive treatment, with clear circuit diagrams and references to original papers.

621.396.615.141/142+621.392.26† 2307

Electromagnetic Problems of Microwave Theory. [Book Review]—Motz. (*See* 2113.)

MISCELLANEOUS

37 2308

1951 IRE National Convention Program—Proc. I.R.E., vol. 39, pp. 292–315; March, 1951.) Summaries are given of the following papers:

58—Educational Requirements for Development Engineers in Electronic and Communication Technology—M. J. Kelly.
59—Making Engineering Education Professional—B. R. Teare, Jr.
60—Using Tests to Select Engineers—W. G. Findley.
61—Orienting the Engineer in Industry—E. W. Butler.

SECTION MEETINGS

Atlanta

"Television from Outside to Inside," by S. R. Smith, Television Technical Institute; June 8, 1951.

Buenos Aires

"Basic Idea of the Microwaves," by J. P. Arnaud; April 20, 1951.

"Social View of Television in the U.S.A.," by Adolfo Flucksmann; May 18, 1951.

"Girocompasses," by C. Rottlander; June 1, 1951.

"Cooling of Transmitting Tubes," by L. A. Pereyra; July 6, 1951.

Chicago

"Basic Concepts of Television Lighting," by R. Blount, General Electric Company; January 19, 1951.

"An Analysis of Color Television," by A. V. Loughren, Hazeltine Electronics Corporation; February 16, 1951.

"Military Airborne Test Instrumentation," by Dr. J. C. Bellamy, Cook Research Laboratories; March 16, 1951.

"Electronic Problems in Alternating Current Network Analyzers," by Dr. J. D. Ryder, Faculty, University of Illinois; April 20, 1951.

"Television With Arrested Dots—Applications for Monochrome and Color," by Dr. Kurt Schlesinger, Motorola, Inc.; May 18, 1951.

"Single-Channel Multi-Station Mobile Telephone System Operation," by R. E. Drechsel, Illinois Bell Telephone Company; June 15, 1951.

Cincinnati

"Atomic Power Plants and Their Instrumentation," by M. A. Schultz, Westinghouse Electric Corporation; January 16, 1951.

"Theater Television," by Ralph Lincoln, Radio Corporation of America; February 20, 1951.

"Electrical Applications of Glass," by Dr. E. M. Guyer, Corning Glass Works; March 13, 1951.

Fifth Annual Television Conference, I. E. Coggeshall keynote speaker; April 14, 1951.

Annual Student Paper Competition by Senior University Students; May 15, 1951.

"Crime Does Pay," by W. F. Hopkins, Attorney; June 19, 1951.

Dayton

"Color Television," by R. B. Dome, General Electric Company; February 8, 1951.

"Electroencephalography," by Dr. A. R. Vonderske, Good Samaritan Hospital; March 8, 1951.

"Kilocycle Kutie Kut-ups," by Ladies Committee program of entertainment; March 16, 1951.

"There is a Better Way," by Dr. L. M. Gilbreth, Society for Advancement of Management; March 27, 1951.

"Laboratories Beyond the Sky," by Dr. M. O'Day, Cambridge Research Laboratories, USAF; April 12, 1951.

"Unity in the Engineering Profession,"—panel discussion of Dayton technical societies and award given by Dayton Section to D. J. Groszewski of University of Dayton; May 11, 1951.

National Conference on Airborne Electronics; May 23, 24 and 25.

Fort Wayne

"Servo-Mechanisms—The Instrument Revolution," by H. P. Rockwell, Rockwell Engineering Company; April 26, 1951.

(Continued on page 70A)

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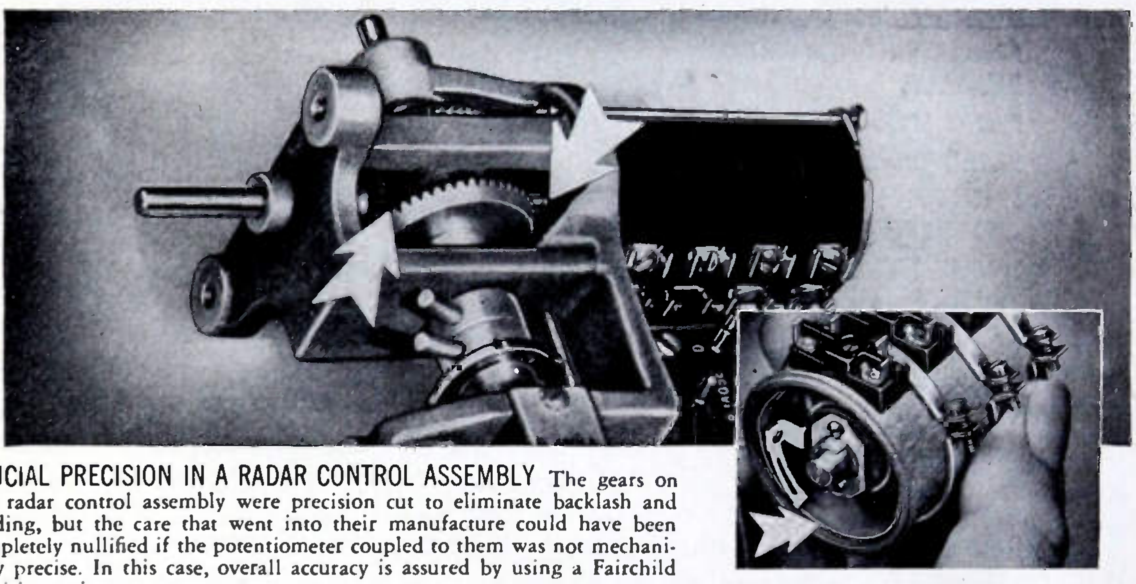

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