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The Mobilization of Science in National Defense*

FRANK B. JEWETT†, FELLOW, I.R.E.

THERE is perhaps no audience before which the role of science and engineering in modern warfare can more appropriately be discussed than one composed of members of the Institute of Radio Engineers. You are primarily communication engineers and of all the branches of applied science, that which has to do with the rapid transmission of intelligence is perhaps most vital to the successful use of the modern fighting instrumentalities. Rapid movement of troops and supplies over far-flung lines of action on sea and land and in the air are possible only on the basis of very effective systems of radio communication. In fact, more and more are means of communication assuming the function of a unifying influence which pervades the other arms of the military organization. They co-ordinate the movement of naval and aerial fleets. They enable infantry, tank columns, and formations of planes to operate as a single effective unit. They shrink as nothing else can, a 2000-mile battle line to the compass of a single sector.

The telephone and telegraph and particularly the radiotelephone and -telegraph are, in effect, the keystone of the whole military arch. You members of the Institute of Radio Engineers are, therefore, exponents of a very vital department of technology, and I am particularly grateful to you for affording me the opportunity to speak here at this time to discuss the mobilization of science in the war program.

Further, it is not merely in the fields we ordinarily think of as communication that men who have devoted their lives to the problems of radio development are in a position to render great service.

One of the striking things connected with the development of new military tools, both offensive and defensive, is the astounding extent to which the fundamental phenomena on which electrical communication is based are employed. In some cases it is application of established techniques in entirely new fields. More frequently it is the pushing of our frontiers of knowledge farther out, and then applying that knowledge to the problems of war in three-dimensional space. Basically, every military problem hinges on the rapid and exact location of an enemy objective and in transmitting and utilizing the knowledge acquired. This may be for the guidance of a commanding officer; the accurate pointing, fuse setting, and firing of a gun; the release of an aerial bomb, or any one of a hundred similar things. Every single physical phenomenon which can be employed must be examined. Because modern science has changed the conditions of warfare from a slow-moving affair in localized areas to one of great rapidity over incredible distances of land, sea, and air, it is imperative that those phenomena which have given us radio be developed and utilized to the full.

While the initial problem is one of intense research and development, each step forward involves great numbers of skilled technicians in design, manufacture, maintenance, and operation of new implements. It seems clear that the demand for men trained in our art is bound to be enormous, not alone in the laboratory but in the services of supply and in the combat forces as well.

For fifteen years following the first World War there were frequent articles on the probable role of science in future warfare. While this was quite natural in view of the part played by the airplane, the tank, and lethal gas in the titanic struggle of 1914–1918, the articles in the main evoked interest rather than concerted action directed toward full employment of science in preparation for more widespread and more deadly warfare.

Despite the fact that the decade and a half following the war was a period of the most productive activity in fundamental science research and of intense effort to apply old and new knowledge promptly in industry, this *laissez-faire* attitude in the military sector was largely a reflection of man's attitude generally toward war. The weariness of the struggle and the distaste for carnage and destruction, coupled with a naive faith that men had learned finally the lesson of war's futility, gave rise to the era of small appropriations to the military, to disarmament conferences, and to the League of Nations and similar efforts to organize the world for a settlement of international controversies by reasonable methods rather than by recourse to mass murder.

In the United States particularly, the decade of the 1920's saw this carried to the extreme. Warships were taken to sea and sunk or were laid up and the Army was reduced to the status of a moderate-sized police force—a force so small and scattered that no really effective training or development of radically new implements could be had. Appropriations were cut to the irreducible minimum of maintaining a national agency which the country would have liked to abolish entirely had it quite dared. In this atmosphere and under these handicaps it is to the credit of the Army and Navy that they did as well as they did. There was little money to spend on development and less still for research to produce entirely new instruments of war.

When the storm clouds of another world war began to form in the middle 1930's, the volume of articles on

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the place and importance of modern science in warfare increased enormously in both the scientific and lay press. So, too, did discussion of the need for insuring that scientific and technical men should be utilized in the fields of their competence and not inducted indiscriminately into the combat services where men of less specialized training could serve equally well.

So far as lay discussion was concerned, it was largely emotional, frequently ill-informed, and sometimes fantastic. Naturally discussion among technical people was more realistic, but on the whole was mainly related to applying newly acquired knowledge and techniques to the improvement of existing military implements. The idea of organizing scientific research on a huge industrial scale, where the ultimate end of "all out war" was the industry to be served, was slow to emerge.

Probably the most difficult hurdle every industry has had to get over in the effective introduction of scientific research as a powerful tool in its operation, has been to realize that the most profitable research is that which is carried on with the least restraint imposed by current practice. Practice can be adapted to radically new ideas, but radical ideas rarely, if ever, evolve from mere improvements in current practice.

Research in military matters is no exception. War being a very ancient art, military men are on the whole extremely conservative as to new tools. Like doctors, long experience has made them cautious and with possibly a more than ordinary tendency to impose on a research project requirements of current practice which, in fact, hamper rather than help. Against this tendency is the fact that they are quick to adopt the radically new once its utility is demonstrated. War more than any other of man's activities puts a high premium on being in the lead.

As soon as war in Europe on a vast scale was seen to be imminent, the nations there commenced frantically to mobilize and organize their scientific and technical men and resources, and to establish effective liaison between them and the combat services. For more than a year after this movement was in full swing across the Atlantic, our aloofness from the struggle and our ardent desire to keep from being sucked into the tragic maelstrom operated to prevent any effective steps in the direction of mobilizing our vast scientific resources for total war. The military services endeavored to strengthen their scientific branches and here and there enlisted the aid of civilian science. They were hampered by inadequate funds, by the pattern of years of a starved organization imposed by an antiwar philosophy, and by the fact that civilian sciences, both fundamental and applied, were built up on a basis of operation in a slow-moving peace economy. The latter had no machinery for marshaling its forces for war and, in the main, it knew little of war's requirements and frequently preferred to follow the courses it understood and liked.

But about two years ago, it became apparent to a few individuals that the *laissez-faire* approach to the mobilization of science ought to be abandoned in favor of a more direct and forceful organizational approach. At that time there existed certain technical groups and associations which, on the one hand, called for strengthening, and on the other were of suggestive value in the search for a suitable organizational setup. I have already remarked upon the scattered technical groups and laboratories within the Army and Navy which over the years had been doing commendable work, but had been given insufficient funds and encouragement. It was, of course, obvious that as the tension of the emergency increased, the responsibilities placed upon these technical groups would mount with a resultant need to augment their personnel, but it was equally apparent that they could not be expected to carry the full load of scientific development and adaptation.

Civilian participation in one way or another in the solution of military problems has come to be taken for granted. It was first given official recognition in the United States when the National Academy of Sciences was incorporated in 1863 by an Act of Congress. The charter of the Academy requires that whenever called upon by any department of the Government, it shall investigate, examine, experiment, and report upon any subject of science or art, the actual expenses of such investigations, experiments, and reports to be paid from appropriations which may be made for the purpose, but the Academy shall receive no compensation whatever for any services to the Government. The Academy is, therefore, recognized as a continuing official adviser to the Federal Government and it must attempt to answer such questions of a scientific or technical nature as are officially submitted to it by members of Government Departments. A permanent channel of communication was thus created, but power to initiate traffic over it resides with the Government and no auxiliary machinery was created whereby the Academy or any other civilian agency might take the initiative in bringing before the Government matters of scientific importance.

Less than a year prior to the entry of the United States into the first World War, a significant step was taken designed to facilitate the use of the channel of communication between the Government and the National Academy. In 1916 the National Research Council was created by President Wilson, and a little later was to play a part in focusing civilian effort on the military problems then arising. The National Research Council was, and is today, a subsidiary of the National Academy of Sciences and, like the Academy, is largely an advisory body only and awaits the assignment of problems by one or another branch of the Government before it can seriously go to work. Moreover, the Council, like the Academy, is not in possession of free money, a corporate laboratory, and other research facilities and is, therefore, not well constituted to conduct research work on any extensive scale.

We turn our attention, therefore, to another agency contemporaneous with the National Research Council, which was created for the express purpose of establishing co-operative effort between military and civilian groups, and which was provided by Congress with funds necessary to create research facilities and to operate them when once created. This agency is the National Advisory Committee for Aeronautics, commonly known as the NACA. The law which created the Committee provides that it shall "supervise and direct scientific study of the problems of flight, with a view to their practical solution," and also "direct and conduct research and experiment in aeronautics." The Committee is composed of fifteen members, including two representatives each of the War and Navy Departments. Throughout its more than twenty-five years of existence, the NACA has given ample testimony of the fruitfulness of co-operation between military and civilian groups, and moreover has provided a prototype as to an organizational arrangement for effecting such co-operative effort successfully.

When, some two years ago, the group to whom I have already referred became convinced that broader participation by civilian scientists in the whole military program was likely to be essential, they regarded the NACA as typifying the sort of organization they would like to see created. A plan was therefore drawn up envisaging a Committee composed in part of civilian scientists and in part of Army and Navy representatives. On the one hand, the Committee was charged with a broad study of the materials of warfare and, on the other, it would recommend and, if possible, initiate such research as it believed to be in the national interest.

The NACA was created in 1915 by an Act of Congress. The somewhat duplicative plan just referred to was submitted to President Roosevelt about a year and a half ago for such action as he saw fit to take. The proposal appealed to him and he decided to create the Committee by Executive Order. This Order established the Committee as a division under the Office for Emergency Management and confers upon them power to take the initiative in many scientific matters which they believed to have military significance. It also directed the Committee to develop broad and coordinated plans for the conduct of scientific research in the defense program, in collaboration with the War and Navy Departments; to review existing scientific research programs formulated by these Departments, as well as other agencies of the Government; and advise them with respect to the relationship of their proposed activities to the total research program. Moreover, and this is especially important, the Order directs them to initiate and support scientific research on the mechanisms and devices of warfare with the object of improving present ones and creating new ones.

The Order contemplated that the Committee would not operate in the field already assigned to NACA nor in the advisory field of the National Academy of Sciences and National Research Council. Parenthetically it might be noted that in this latter field the Academy and Council are currently engaged on advisory work for the Government for which the out-of-pocket expenses alone are at the rate of much more than $1,000,000 a year. A recent count shows that the present personnel of Academy and Research Council advisory committees runs to about 225. These figures will give an idea of the vital part which these fact-finding groups are playing in the present emergency. But to be a little more specific I might mention that one important committee of the National Academy is advising the Office of Production Management on the availability of strategic materials.

In order to formulate adequate rules for the utilization of materials of whatever sort, accurate knowledge as to their availability, as to new processes suggested for producing them, as to possible substitutes, and a thousand and one other basic questions must be answered. This can only be done by highly trained scientists and engineers. Only after they have answered can the urgent problems or proper utilization be handled. The Academy has assembled a group of the most distinguished men in the United States to give OPM this basic information.

Other examples are to be found in the services which the National Academy of Sciences and National Research Council are giving in advising the military departments on highly confidential matters; in the fact that the Medical Division of the National Research Council is the operating arm of the Medical Research Committee mentioned later, and in the service the Council is furnishing in selecting technical personnel.

Thus, in June, 1940, the National Defense Research Committee, more familiarly known as the NDRC, was born. It was constituted of eight members, two of these being high-ranking men from the Army and Navy respectively, five more being civilians well known for their experience in organizing and directing both fundamental and applied scientific research, and, as an eighth member, the Commissioner of Patents.

The Executive Order creating the NDRC omitted any reference to the biological sciences, and, in particular, to the medical sciences. However, during its first year of operation, experience accumulated to the effect that a broader program of attack would not only be useful but was, in reality, urgently demanded. This realization prompted a second approach to President Roosevelt, with the result that in June of last year he created two new functional groups. One of these was the Committee on Medical Research, to explore its indicated territory in the same manner that the NDRC had been exploring the physical sciences. Then, over and above both the NDRC and the Committee on Medical Research, there was placed the Office of Scientific Research and Development, usually referred to as OSRD. This latter office was placed in charge of Dr. Vannevar Bush, who until then had been Chairman of the NDRC. President Conant of Harvard was then made Chairman of the NDRC and Dr. Newton Richards of the Medical School of the University of Pennsylvania was made Chairman of the CMR.

In order to insure complete co-ordination of civilian and military research and development, Dr. Bush, as Director of OSRD, was provided with an advisory council consisting of the Chairmen of NDRC, CMR, and NACA; the Co-ordinator of Naval Research, and the Special Assistant to the Secretary of War performing a somewhat similar function in that service.

The Executive Orders creating these various committees naturally had to leave indeterminate the question of financial support. They are all subsidiary to the Office for Emergency Management and, like this Office, must look to Congress for the necessary operating appropriation. Thus far the appropriations, while not munificent, have been adequate. During its first year of existence the NDRC authorized research projects which totaled about ten million dollars. At the beginning of its second year, it was granted another ten millions and this was recently augmented by several millions more. To be more specific, the OSRD, during its first year of existence, will guide the expenditure of about twenty millions throughout the whole scientific field.

I should now like to take a few minutes of your time to explain the manner in which the expenditure of these funds is initiated and supervised. To begin with, let me point out that the work of the NDRC is divided into four major departments: Division A, of which Professor R. C. Tolman of California Institute of Technology is Chairman, deals with armor, bombs and ordnance, in general; Professor Roger Adams of the University of Illinois heads Division B on chemistry; Division C deals with transportation and communication, and submarine warfare, and I am its Chairman (this Division operates the subsurface-warfare laboratories); finally, Division D, which deals with instruments and numerous miscellaneous projects difficult to catalog, is headed by President Compton of Massachusetts Institute of Technology. It is in this Division that the microwave laboratory is organized.

To expedite discussions, surveys, and the general handling of the work, a further breakdown has been found desirable, the result being that each Division comprises several so-called Sections. Division B on chemistry, under Professor Adams, is divided into thirty-one Sections—which stands to date as a sort of record.

The work of a Section is entrusted to a Section Chairman, who in turn calls to his aid certain individuals who become permanent members of his Sectional Committee and who are known technically as Members. Then there are others who may be asked to render advice and assistance from time to time and hence are called Consultants. Members and Consultants are officially appointed by the Chairman of the NDRC and are designated only after official clearance by the Army and Navy Intelligence and the FBI. Full consideration, therefore, is given to the basic requirements of the military services as regards the confidential handling of their problems. Because of its peculiar interest to you, I would note that the Section dealing with communication problems is under the direction of Dr. Jolliffe, who is a Vice Chairman of Division C.

Neither the five civilian members of the NDRC itself nor any of the Section Chairmen, Members, or Consultants are paid from public funds. Without exception, they are loaned to the Government by their employing organizations and frequently the loan is complete, the work being so voluminous and detailed as to require a man's full time. Thus, when I tell you that about 500 of the leading scientists of the country are encompassed in the present NDRC organization, you will see that the Federal Government and even the forgotten taxpayer are getting a lot of valuable consulting talent free of charge.

So far as I have now outlined it the functioning of the NDRC requires no public money except a very small amount for paid office assistants together with the traveling expenses of Members and Consultants. For the most part Members and Consultants do not carry on the research and development projects which the NDRC decides to promote—their duties are advisory and administrative. They formulate the problems which they believe it important to have undertaken, and then arrange with various scientific institutions to carry on the work. It is this last step which brings in the need for considerable sums of money. For instance, a project assigned to a particular university or industrial laboratory may require the full time of several of its staff together with that of numerous younger men hired specifically for the work in hand.

The number of such projects now approved and, for the most part, contracted out to universities and industrial research laboratories stands around 600 while the number of contracting institutions is over 100; and when it is stated that the total value of the projects thus far determined upon is upwards of twenty million dollars, you will realize at once that the monetary resources of the scientific world would not be adequate to conduct the program on a gratuitous basis. The contracts vary all the way from those involving a few thousand dollars to those calling for two to three hundred thousand dollars per month. I have no doubt but that many of you here today are working either full or part time on one or more of these NDRC contracts.

The question is frequently asked as to how many technical people have been drawn into the civilian defense effort which the NDRC directs, but obviously this is quite difficult to estimate, let alone to enumerate in detail. I have already mentioned that there are about 500 scientists in the NDRC organization serving as Members, Consultants, etc. It seems likely that somewhere between two and three thousand scientists are at work on defense projects as employees of contractors with about an equal number of less highly skilled individuals assisting them as laboratory assistants, technicians, etc. Then, if the situation which I know to exist at the Bell Telephone Laboratories is to be taken as a criterion, we must add to this scientific group another very considerable array of technical people who call themselves engineers as opposed to physicists and chemists—an array which if enumerated would no doubt total four to five thousand.

Recent figures from the Bell Telephone Laboratories might be of interest as perhaps typifying the situation found in a number of industrial laboratories which are fulfilling defense contracts, some for the NDRC and some directly for the Army and Navy. A rough count shows that about 600 of our technical staff are now engaged directly on a full-time basis on defense projects. When I say that they are "engaged directly" on defense projects, I am excluding those who by circumstances arising out of the defense program have been forced to devote themselves to such problems as the finding of substitute materials and the engineering of emergency telephone projects.

Another aspect of the NDRC plan of operation which I should like to stress is its "no-profit" feature. This applies alike to contractors and to employees of contractors. Perhaps this point can be brought out most clearly by reference to a specific situation. The University of California is acting as a contractor to the NDRC on a large project which involves an annual expenditure of around one million dollars. Certain members of the California faculty are employed on a full-time basis on the project and in switching from teaching to defense work have incurred no change in rates of pay. The University has also hired from other faculties certain individuals to augment the defense staff and they likewise, have gone over without changes of salary, although a payment is made to compensate for the cost of moving in the case of both single and married men. It is also stipulated explicitly that the university, as contractor, will derive no monetary profit from the work and the same requirement is exacted of industrial laboratories and other types of contractors.

The "no-profit no-loss" proposition has involved the adoption of certain more or less arbitrary but seemingly equitable rules of accounting. Thus, a university is usually allowed an overhead payment amounting to 50 per cent of the salaries which it pays to its members employed on a defense project. Similarly, an industrial laboratory, by virtue of the fact that it has to operate with commercial capital and is subjected to a variety of forms of taxation from which the university is exempt as well as other expenses, is allowed an overhead of 100 per cent of the salary item.

I suppose it depends upon one's point of view as to whether the effort I have just outlined appears large or small. On the one hand, it seems fairly certain that it is only a beginning and must expand further. On the other hand, it is certainly large already when contrasted with any civilian effort which was able to assert itself during the last war. And looking back to the situation which existed a quarter of a century ago, it is difficult to understand why the then available civilian agencies were not unleashed to an extent commensurate with their obvious capabilities. True, the National Research Council was created to assist with the solution of defense problems, but it was, as I have pointed out, in the position of a doctor waiting for clients; it could not adopt the attitude of an aggressive salesman and initiate attacks on what it regarded to be important military problems. Hence we can declare that as regards organization notable progress has been made.

As to future expansion of our civilian-defense effort, it is becoming increasingly essential to bear in mind the potential shortage of trained personnel. Without insinuating anything as to guilt, the chemists declare that this is a physicist's war. With about equal justice one might say that it is a mathematician's war. The visible supply of both physicists and mathematicians has dwindled to near the vanishing point, consistent with the maintenance of anything like adequate teaching staffs in our universities. If this civilian defense effort is to expand, and such indeed now seems imperative, the limiting factor, therefore, may be a shortage of highly trained individuals and not a shortage of financial aid.

This leads me to state a few general observations concerning the past and future of our work. It is quite apparent that to date the burden of NDRC contracts bears much more heavily upon some institutions than upon others. At the outset this has necessarily been the case. While serious attention has at all times been given to the subdivision of projects so that they could be farmed out as widely as possible, a limit is frequently reached beyond which it isn't practicable to go in the matter of division. And in many cases, no division at all could be entertained, a situation that has given rise to a few large contractors, of which I cited the University of California as an example.

In the assignment of the early contracts, it has been natural, in fact essential, to lean heavily upon those institutions, both academic and industrial, which for one reason or another have been peculiarly fitted to transfer quickly from peacetime to wartime problems. This has been done with a view to conserving time. But the stages of the program to follow will doubtless involve a broader survey of the situation to find locations where new problems can be lodged with a minimum of interference to essential defense work and teaching now in progress. In this survey a guiding principle will be to utilize men and facilities *in situ* whenever possible, thus preserving the "going value" of groups who are accustomed to working together. In the face of crises, the human tendency is usually to do the reverse, it being so easy for central agencies to ignore established but not well-known organizations, and attempt to cope with an emergency by calling workers from right and left to some new location. As a matter of fact, this tendency was beginning to make an appearance even as long as two years ago when the fundamental plan of the NDRC was under discussion. Had the tide then setting in been allowed to run on for some months unimpeded, the result inevitably would have been a literal army of uprooted scientists in Washington and other central points, sitting around idly waiting for vast amounts of research equipment which had been placed on order, but was not much nearer materialization than that, to be installed in hastily constructed laboratories. This would have been the easy and disastrous way. Fortunately the creation of the NDRC came in time to stem such a tide.

Another present problem, and it is the last with which I shall trouble you, is one which by its existence supplies evidence that real progress has already been made in some of the research programs thus far initiated. It has to do with shortening the time gap between proven laboratory research results and the stage where mass production can be undertaken. Some of the laboratory results already achieved hold such promise that every day which intervenes before their widespread utilization becomes a serious matter. Obviously the problems to be met here cover a wide range of equipment and materials—as wide as that marked out by the scientific results themselves—and since they involve large-scale manufacture, the whole plan must be carefully worked out with other official agencies, particularly the Office of Production Management and the armed services. I am sure, however, that we are prepared to meet and solve these problems, and rather than be concerned with the difficulty of making progress along this avenue, I think all who are guiding the work of the NDRC would exclaim to the ranks of scientists and technicians, "Bring on your results, the more the better, and we will guarantee them a speedy passage to the firing line!"

In the foregoing, I have attempted merely to sketch the setup of organized civilian research and development created for the war emergency. Obviously, it is only a part of the total effort which is being mobilized. It would be unfair to thousands of scientists and engineers to infer that the main results were dependent on the work of these agencies.

The scientific departments of the armed services are being greatly enlarged; industrial laboratories are turning more and more of their efforts to direct and indirect war work and engineers everywhere are active. Fundamental and applied science are on the march.

CBS International Broadcast Facilities*

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Summary—*This paper describes the present significance of international broadcasting; its growth and present status in both the Eastern and Western hemispheres; factors governing service to Columbia's new Latin American international network consisting of sixty-four stations located in eighteen different countries; the many problems attendant upon successful relaying of programs to these many points; facilities for this service, including new studios, frequency-modulation program-relay circuits, and two complete 50-kilowatt transmitting plants located at Brentwood, Long Island, New York; features of design and operating performance characteristics of the transmitting apparatus, including thirteen directive antenna arrays and their associated transmission lines. A typical international radio relay receiving-station installation and the importance of properly engineering such facilities, will also be briefly discussed.*

Introduction

RADIO broadcasting means the dissemination of radio communications intended to be received by the public, directly or by the intermediary of relay stations. In the broadest sense, this applies both to short-wave and medium-wave broadcasting. The chief difference between the two lies in the public involved. Whereas medium-wave broadcasting is intended to be received by a public located in the country originating the broadcast, short-wave broadcasts are designed for the public of one or more other countries than that of origin.

The Columbia Broadcasting System is, at the present time, constructing two new 50-kilowatt international broadcast stations and thirteen directive antenna arrays near Brentwood, Long Island, a sparsely populated location, approximately 37 miles east of the New York studios.

Before discussing the purpose and technical aspects of this modern short-wave transmitting plant, it would be well to review briefly the history and present-day significance of international broadcasting.

History and Significance

Broadcasting by short-wave began experimentally during 1924. In the United States, this service was then known as "experimental relay broadcasting." Considerable activity took place in other countries at about the same time, notably in Holland, England, and Germany. The development of this service moved along slowly until the early 30's, when it became more active in both England and Germany. At about this time, the Empire Broadcasting Service of the British

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Broadcasting Corporation was inaugurated.[1] It was not, however, until about 1935 that the importance of international broadcasting became fully recognized by the various countries using it and the race for frequencies and high-power facilities began. During 1936 and 1937, the number of stations tripled, the total number being more than three hundred. Today there are more than one hundred stations of this class in South America alone. In 1937, England, Germany, Italy, the United States, and a little later, other countries including Japan, began transmitting a large number of foreign-language programs utilizing Spanish, Portuguese, French, German, and English languages for the most part. Many of the European transmissions were directed toward the Americas, particularly Latin American countries. It is not the purpose of this paper to discuss propaganda broadcasts or any other subject in this catagory, but as a result of recent history, the significance of international broadcasting has been well established.

During 1940, executives of the Columbia Broadcasting System visited eighteen Latin American countries and made arrangements for sixty-four or more broadcast stations in these countries to become associated with a new CBS international network. It is significant to note that this message was carried to, and left with, the various countries visited.

> The solidarity and, to a great extent, the security of the Western hemisphere will depend upon the amount of sympathetic understanding prevailing among the peoples of all the American nations.
>
> That is why we are now building new radio facilities; facilities which will be devoted entirely to the development of a closer friendship among the twenty-one neighbor republics of America; disseminating information, music, education, and entertainment through the magic of short-wave radio.

This journey was undertaken to determine, on the spot, what could be done to further good-neighbor policy with South and Central America and the West Indies. The investigation demonstrated conclusively that transmitting North American programs to Latin America by short waves was not enough since most persons in those countries listen to their local station broadcasts just as they do in the United States.

For this reason, CBS has contracted with medium-wave outlets in twenty countries to carry regular day-by-day broadcasts of specially built programs. The new network already consists of thirty-nine medium-wave and twenty-five short-wave stations, the latter to serve interior points.

While the primary purpose of the new far-flung network is to promote better relations with Latin America, the commercial radio possibilities of these countries will also be developed, thus promoting an exchange of goods as well as an exchange of ideas.[2,3] In the United States, international broadcasting is a commercial radio service and, in this respect, is unlike similar service from other countries which is, in most cases, government controlled.

CBS International Broadcasting

CBS has been transmitting short-wave programs since 1930. During the first few years this operation consisted of experiments of a technical nature. Network programs were transmitted on irregular schedules, using composite, comparatively low-powered single-frequency equipment and a nondirectional antenna. In 1932, W2XE, the former call letters of WCBX, known to many radio experimenters and amateurs, installed a new 1000-watt station, and in 1937, a 10,000-watt station, which, combined with a few directional antennas, greatly improved service.

Technical developments continued and program experiments commenced in earnest. The new station was not capable of competing favorably with the more powerful and very extensive facilities used by others, particularly those of foreign countries. During the past few years, in addition to station WCBX, located at Wayne, New Jersey, CBS has also programmed an affiliated 10-kilowatt international station, WCAB, formerly W3XAU, located near Philadelphia. These two stations will soon be replaced by the two 50-kilowatt stations now under construction. The new station call letters are WCBX and WCRC.

Engineering and economic studies, made to improve CBS short-wave facilities, began several years ago and have continued on to this date. They have now reached the stage where a large number of engineers are devoting full time to the subject. Facilities are being provided to improve greatly the service to Latin America and Europe. In addition to short-wave *broadcasting*, it is necessary that the new facilities be capable of *relaying* programs from New York to Mexico City, Buenos Aires, Rio de Janeiro, Santiago, Bogota, Lima, Havana, and other distant cities. This requirement has a great deal to do with planning, for instance, with the number and arrangement of directive antenna arrays.

In general, it has been necessary to select an adequate transmitting site and location; to have a sufficient number of transmitters of adequate power; to have available for use, one or more frequencies in each of the bands assigned to international broadcasting, 6 to 6.2, 9.5 to 9.7, 11.7 to 11.9, 15.1 to 15.35, 17.75 to 17.85, and 21.45 to 21.75 megacycles, by world radio allocation agreements as consummated at the most recent Telecommunications Conference held at Cairo, Egypt, in 1938. Stations WCBX and WCRC will operate on one or more frequencies in each of the bands. It was also necessary to decide upon the design of the transmitting equipment which, from a continuity and dependability of operation standpoint, must be arranged with a maximum degree of flexibility and capable of rapid changes in operating frequency. As

[1] "The Empire Short-Wave Station—Daventry" and "Receiving the Empire Station," British Broadcasting Corporation publications, 1939.

[2] Philip L. Barbour, "Open questions in inter-American broadcasting," *Annals Amer. Acad. Pol. and Soc. Sci.*, vol. 213, pp. 116–124; January, 1941.

[3] William S. Paley, "Radio turns south," *Fortune*, vol. 23, pp. 77–79, 108, 111–112; April, 1941.

mentioned previously, the necessary number and type of directive antenna arrays had to be selected to fulfill transmission requirements best.

WCBX-WCRC New Facilities

In addition to the thirty CBS studios now located in New York City, new studios are being constructed to serve the new international stations. The most modern studio construction practices known to the broadcast art will be utilized. The audio facilities will be designed and operated in accordance with standard CBS practice.[4]

From the new studios, programs will be sent to the WABC master control, located on the twenty-third floor of the Columbia Building. From this point, they will be transmitted to three 330- to 340-megacycle frequency-modulation radio relay transmitters located on the roof of the sixty-two story Salmon Tower Building. These transmitters will excite unidirectional antennas, each having a gain of 10 decibels or more in the direction of Brentwood, Long Island, New York.

Similar antennas, for receiving purposes, will be used at Brentwood. Special receiving, amplifying, and other control equipment, will be used to demodulate the signals and transmit them to the main transmitter building located about one mile from the receiving site. Due regard has been given to the proper location of both transmitting and receiving equipment for optimum results. This proposed operation is experimental in nature and will allow CBS engineers to pioneer in this high-frequency relay broadcast field. The performance of this system must be stable, completely reliable, and suitable for continuous operation over long periods of time.

[4] H. A. Chinn, "Broadcast studio audio-frequency systems design," Proc. I.R.E., vol. 27, pp. 83–87; February, 1939.

The Brentwood Installation

Through special arrangements with the Mackay Radio and Telegraph Company, the site of their Brentwood main transmitting plant will be used, where there are now already in operation twenty-two medium- and high-powered radiotelegraph transmitters. Mackay is now using many directive antenna arrays on their 1200-acre site which, for short-wave transmission, is excellent from the standpoint of topography, accessibility, and availability of public-utility services. It is removed from populous centers, airports, and airways.

A new fireproof, single-story wing, 40×60 feet, with basement, is now being added to the existing Mackay transmitter building, to house the new equipment.

Primary power supply is available from two different sources over alternate routes to the Mackay-CBS substation, from which three underground, 2300-volt cables run to the transmitter building, a distance of 0.66 mile. The three power feeders have a combined capacity of 1800 kilovolt-amperes.

Audio, measuring, and monitoring facilities have been designed by Columbia's engineering staff and include the very latest methods of satisfying the requirements of this project. The basic principles that must be considered in the functional design of a modern two-channel transmitting plant's audio and monitoring system will be used. Because of the nature of this service, the frequency- and modulation-monitoring apparatus arrangement, Fig. 1, is more complex than that usually found at standard broadcast stations.

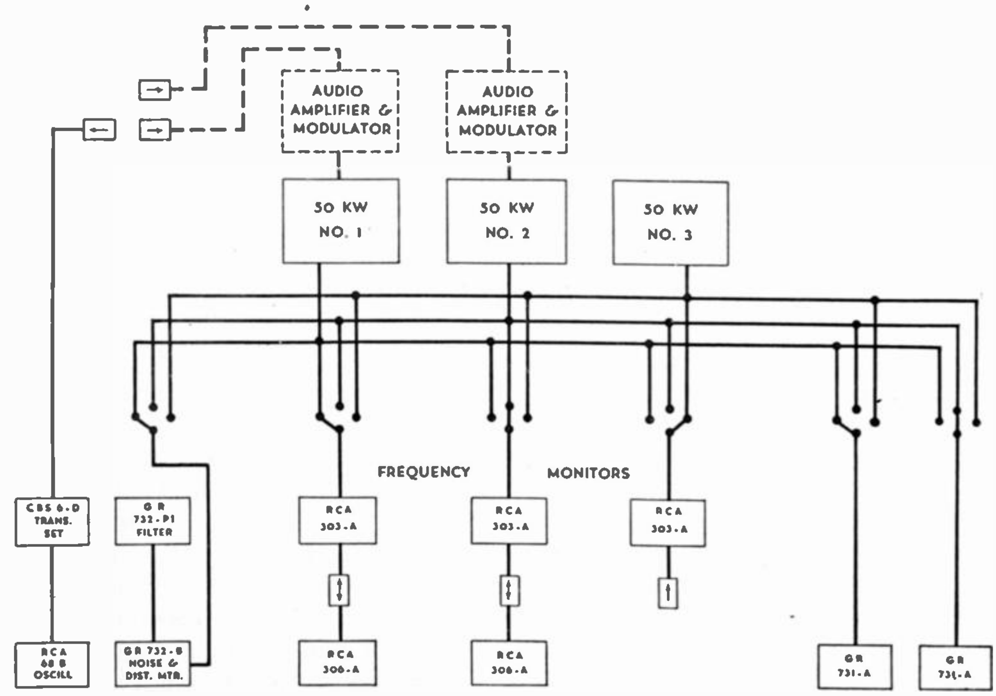


Fig. 1—Block diagram of the WCBX-WCRC monitoring facilities.

Compression of volume range, modulation "peak-chopping," high-frequency pre-emphasis, and variable low- and high-pass filters, will be available to obtain optimum results. The degree of their use will depend upon transmission conditions and other variable factors.

Transmitters

Two custom-built, 50-kilowatt international-broadcast-station equipments of the latest design, conceived three years ago, are now being manufactured for this installation by the Federal Telegraph Company. These facilities are being constructed in accordance with specifications originated by the engineering department of CBS. Each of the two transmitters will be capable of full output power to the transmission line, at 100 per cent modulation, over the entire frequency range of 6 to 22 megacycles. It has been possible only recently to obtain such powers in practice at the higher radio frequencies.

One of the major requirements of this service is the ability to shift instantaneously from one operating frequency to another. These transmitters are designed so that this can be accomplished in a simple, positive, and reliable manner. There are several methods of accomplishing this operation.[5] CBS engineers chose the method to be described after carefully weighing the advantages and disadvantages of various systems.

In order to accomplish an instantaneous change in frequency, there are provided three complete radio-frequency sections from the crystal-oscillator unit to the 50-kilowatt power-amplifier output. Fig. 2 is a block diagram illustrating the arrangement of all major apparatus units. This system allows the technicians who operate the apparatus to preset the operating frequency of one radio-frequency section while the other two radio-frequency sections are being operated simultaneously.

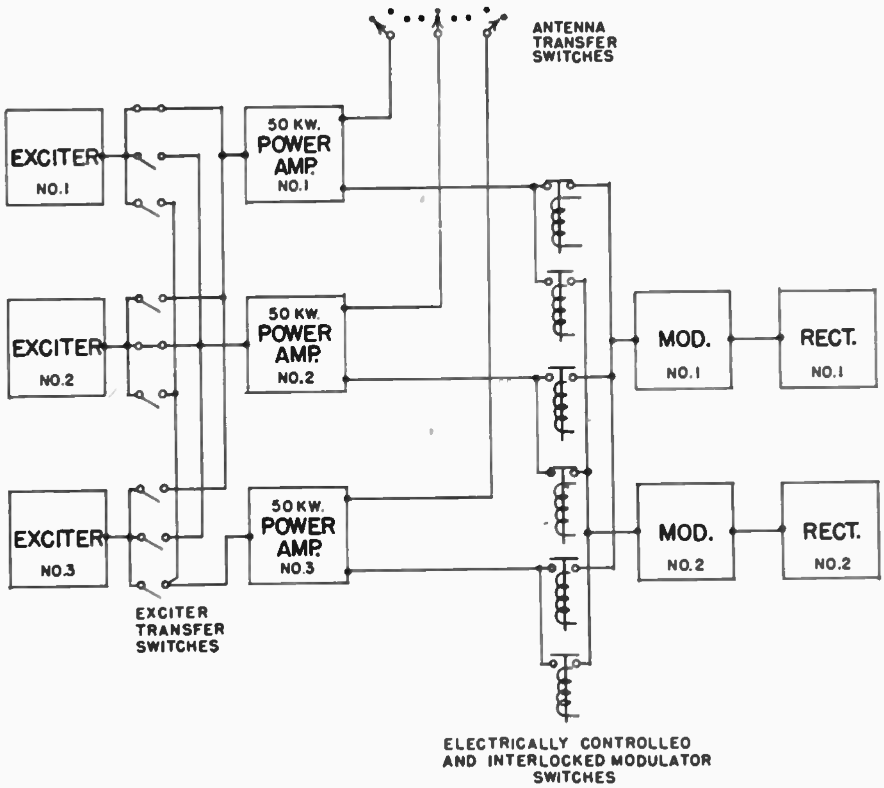


Fig. 2—Block diagram of the WCBX-WCRC power amplifier and modulator selector system.

Each transmitter will be capable of operating on any one of a total of twelve frequencies. Initially, nine crystals will be provided for the frequency control of each radio-frequency section, a total of twenty-seven crystals being required for the specific frequencies assigned to WCBX and WCRC, 6060, 6120, 6170, 9650, 11,830, 15,270, 17,830, 21,520, and 21,570 kilocycles.

Actually, the apparatus for these two stations will consist of two and one-half transmitters. All of the radio-frequency equipment with associated power supply and control facilities will be provided in triplicate, and the high-level class AB modulators and high-voltage power supplies in duplicate. Thus the two stations may be expanded by the addition of a third modulation and power-supply unit which, with accessories, will give CBS a third complete 50-kilowat transmitter, should a third station be required at some future date. The equipment will be installed to accommodate this probable future expansion.

The entire equipment is alternating-current-operated, utilizing specially designed water-cooled tubes, automatically regulated power supplies, and with all circuits fully protected automatically. The apparatus is arranged so that complete accessibility to the interior of the transmitter units is provided for ease of maintenance, thus insuring maximum continuity of service. The operating personnel is safeguarded in every respect.

Performance characteristics will be in accordance with the most modern and best practices known to the art of broadcasting. They conform, in every respect, with the standards of good engineering practice promulgated by the Federal Communications Commission.

TABLE I
Transmitter Performance Specifications

Carrier frequency range	6 to 22 megacycles
Carrier power 6 to 22 megacycles	50 kilowatts
Modulation capability	100 per cent
Audio-frequency response	
40 to 10,000 cycles per second (1000 cycles per second reference)	±0.5 decibel
Audio-frequency distortion	
Root-mean-square total harmonics—100 per cent modulation—50 to 7500 cycles per second	Less than 5 per cent
Carrier noise level	
Root-mean-square total, unweighted (100 per cent modulation reference) 100 to 5000 cycles per second	−60 decibels
Below 100 and above 5000 cycles per second	−50 decibels
Carrier shift	
0 to 100 per cent modulation	Less than 3 per cent
Carrier frequency stability	Within ±0.0025 per cent

Circuits are conventional in design for the most part. There are a few noteworthy departures, including the line-type tank-circuit arrangement of the power amplifiers, the method of matching the power-amplifier outputs to the transmission lines, and the arrangement for multifrequency operation.

A water-cooled "resonating frame" type of line output circuit will be used with each of the three 50-kilowatt power amplifiers. It consists of a copper pipe from each anode parallel to each other for a lineal distance of

[5] R. J. Rockwell and H. Lepple, "A push-button-tuned 50-kw. broadcast transmitter," *Elec. Eng.*, vol. 60, pp. 55–57; January, 1941.

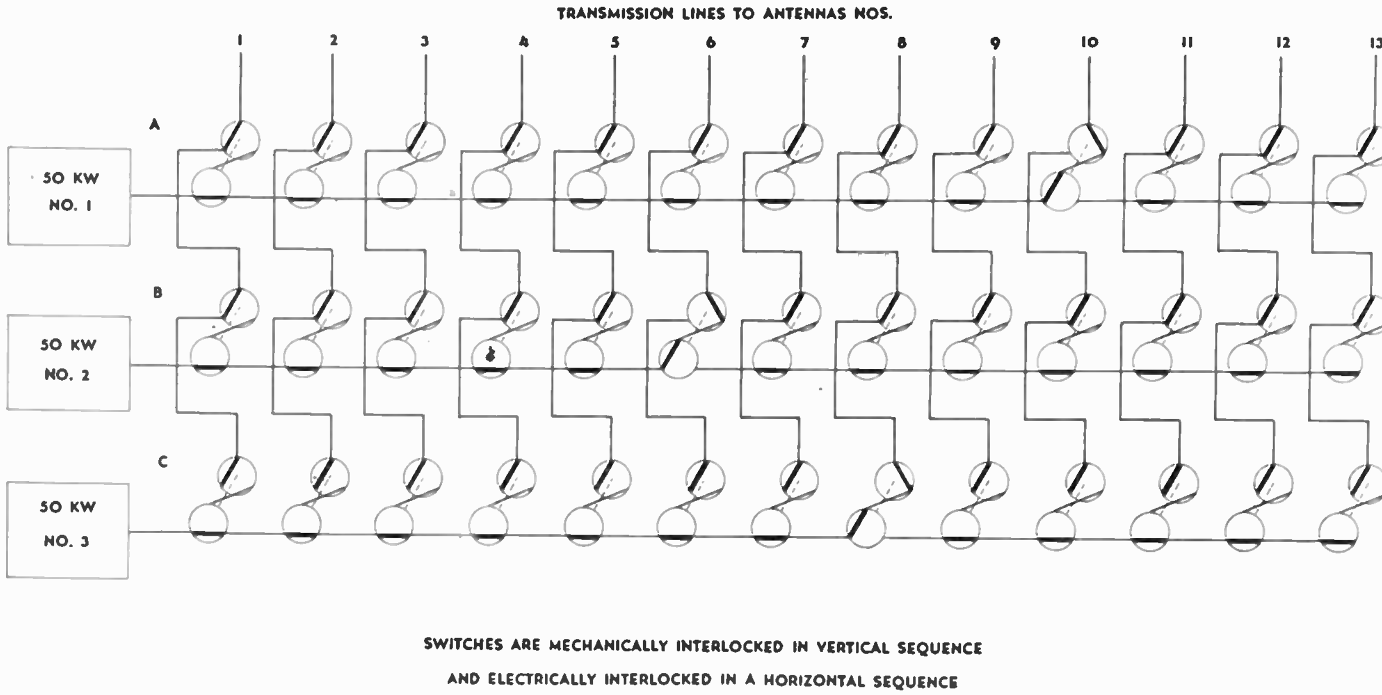


Fig. 3—The WCBX-WCRC antenna-switching system.

about 35 feet with a center-to-center separation of 12 inches. This length is required for 6-megacycle operation. The piping will extend directly below the tubes through a hole in the floor to the basement and there extend horizontally in a shielded interlocked compartment.

Inductive coupling will be used between the output circuit of the final stage and the line to the antenna-switching system. Mechanically this will consist of a transmission-line (or frame) loop mounted in a horizontal plane directly above, and running the full length of the tank-circuit frame. This coupling loop will be electrically grounded directly at its center.

Variation of coupling will be accomplished by mechanically varying the horizontal distance between the two conductors forming this loop. This movement will carry them from a point directly above the individual lines of the tank frame, toward each other until they are but 2 or 3 inches apart. Thus the coupling is decreased, both by moving the coupling-loop conductors away from the tank-frame conductors and by decreasing the area within the coupling loop. The distance between the horizontal plane in which the tank-frame conductors are located and that in which the coupling-loop conductors are located will remain constant.

The movement of these conductors will be manual by means of a large handwheel crank located on the front panel of the power-amplifier unit and mechanically coupled with the mechanism controlling the position of the coupling-loop conductors.

Tuning the tank frame to a particular frequency will be accomplished by varying its length by means of a short-circuiting bar, the position of which may be continuously varied along the full length of the tank frame. This short-circuiting bar will

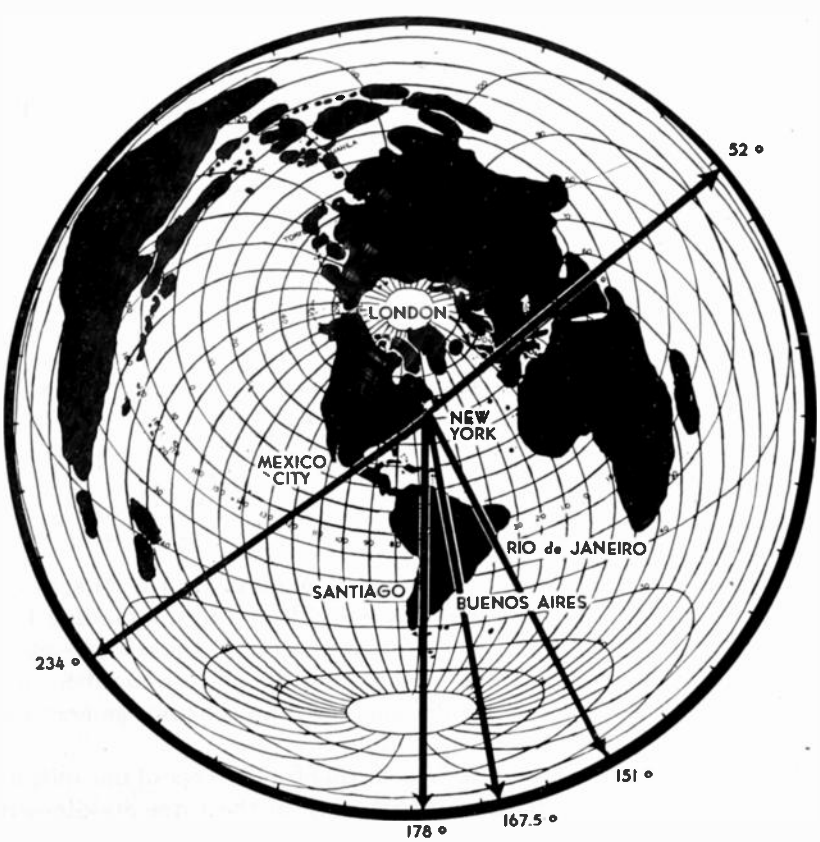


Fig. 4—An azimuth chart centered on New York City.

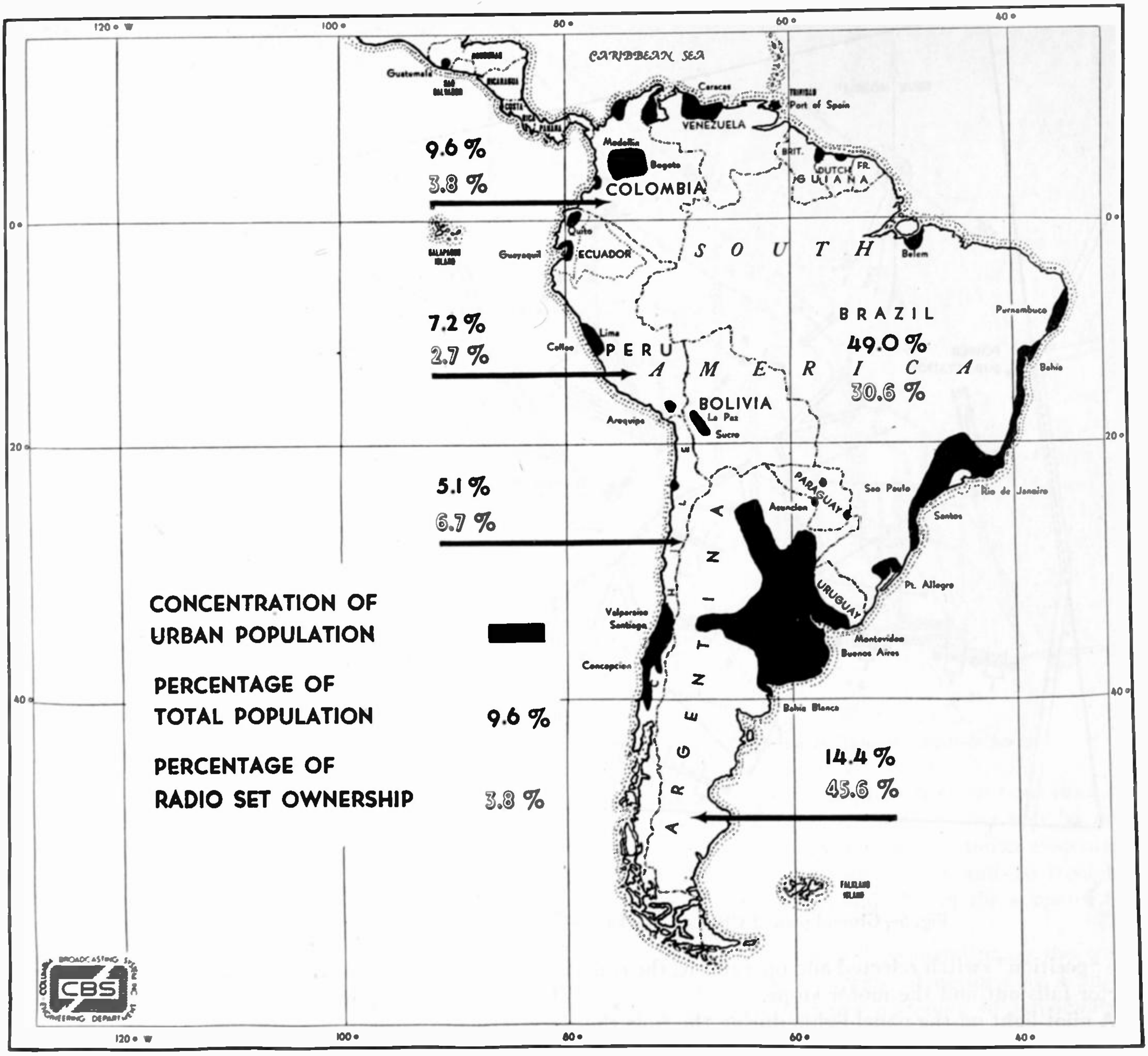


Fig. 5—Population density and radio-set ownership map of South America.

consist of suitable sliding contacts, arranged to grip the line with sufficient pressure, with the short-circuiting conductor between them. This arrangement will be carried on standoff insulators mounted on a traveling carriage moving on tracks below the line.

A large threaded shaft or worm approximately 2 inches in diameter will be located at the center of and below the line, supported by bearings spaced approximately 4 feet on centers. This worm extends the full length of the line and the carriage (with short-circuiting bar) is attached to it by a nut (split on one side to pass the bearing supports) of sufficient length to ride over the receded bearings. Thus the position of the carriage can be controlled by rotation of the worm.

At the end of the line, away from the power-amplifier unit is located a 3-phase, reversible, 2-speed motor, which drives the worm by a V-belt coupling. At the end of the line near the power-amplifier unit a flexible shaft is attached to the worm and this is used to drive a counter, on the front panel, so that the exact position of the carriage can be read on the counter.

To select any one of the six frequency bands the carriage will be run at high speed as follows: A 6-position rotary selector switch on the power-amplifier panel is set to the position desired and a motor-starting button pressed. Six "position" switches located along the carriage track may be placed at any location to determine the operating positions for the six frequencies. The rotary selector switch, in selecting one of these switches, determines the direction in which the motor must turn and pressing the motor-starting button closes the contactor to run the motor (at high speed) in that direction. When the carriage arrives at

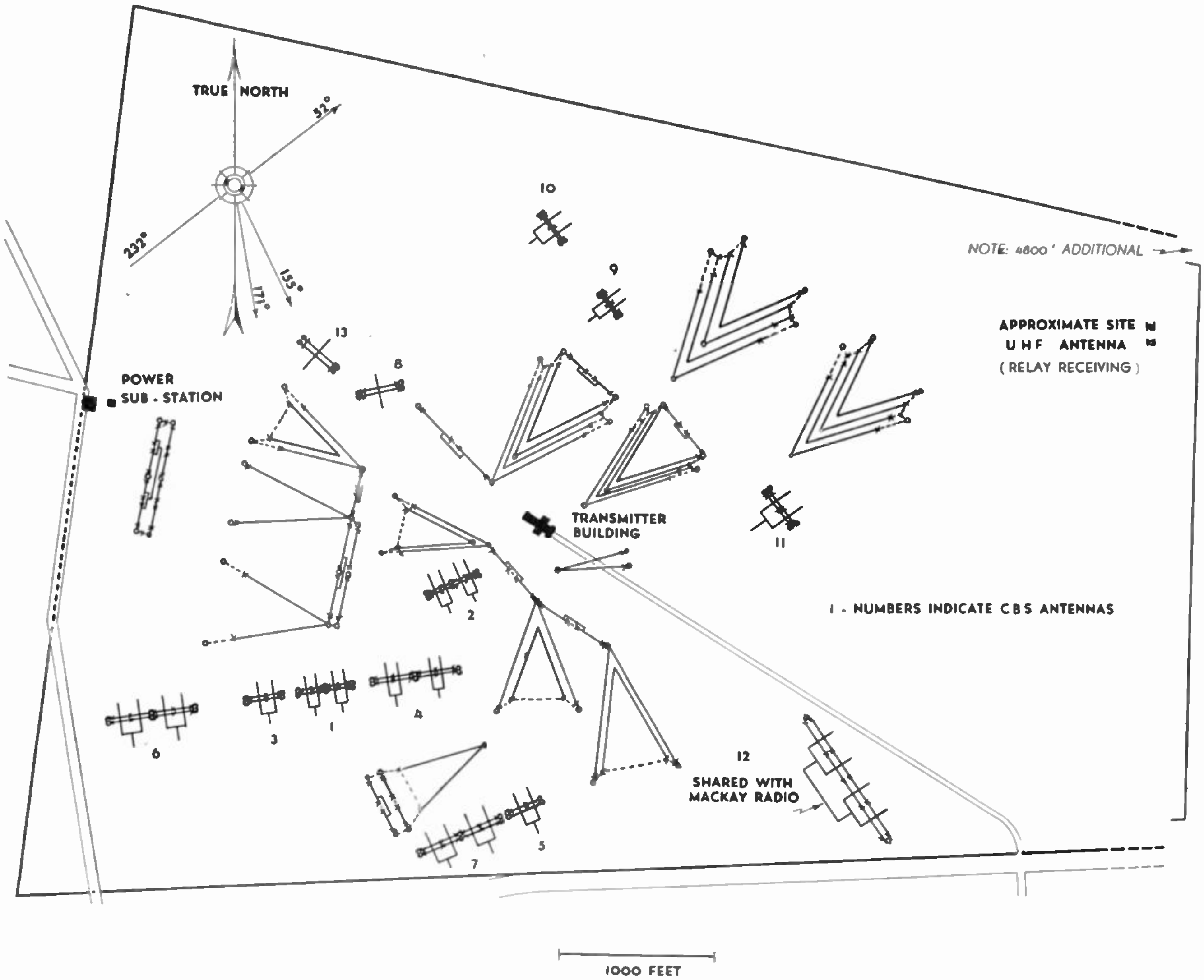


Fig. 6—Ground plan of CBS and Mackay antenna arrays, Brentwood, Long Island, N. Y.

the "position" switch selected and operates it, the contactor falls out and the motor stops.

A pilot light on the panel lights during the time the motor is running to show the operator the change is being accomplished. An interlock relay prevents 12-kilovolt plate voltage being applied to the amplifier during the process.

Safety limit switches are located at each end of the line to cut the motor and prevent damage in case one of the "position" switches fails to stop the travel. These limit switches have associated pilot lights on the power-amplifier panel to inform the operator of the miscarriage. Pressing the start button will bring the carriage back from the end of the line to a selected position without the necessity of going into the basement to run the mechanism by hand.

Vernier adjustment of the carriage position is accomplished by a nonlocking, spring-return, single-pole, double-throw, manual switch on the power-amplifier panel which operates contactors to run the carriage in either direction at slow speed (actually half speed); this adjustment may be made with power on. The manual slow-speed control of the motor is independent of the high-speed position-selecting control except that interlocking contacts prevent their being operated at the same time.

A second pair of pipe lines will also connect to the power-amplifier anodes and run parallel to the pipes just described, but will be enclosed in a separately shielded compartment. This line circuit will be short-circuited at the proper point to resonate it with the fundamental frequency. A fifth pipe will run between this short-circuited pair to provide a path to ground for the even-order harmonics and thus result in more efficient operation of the power amplifier. The short-circuiting bar for adjusting the length of the harmonic-attenuation line has an identical control system to that of the output tank-circuit line. The rotary selector switch and starting button are common to both sets of lines so that one operation serves for both setting the output tank and the harmonic lines.

Voltage regulators, power transformers, modulation transformers, reactors, and other associated equipment will be located in a basement directly beneath the apparatus with which they are associated.

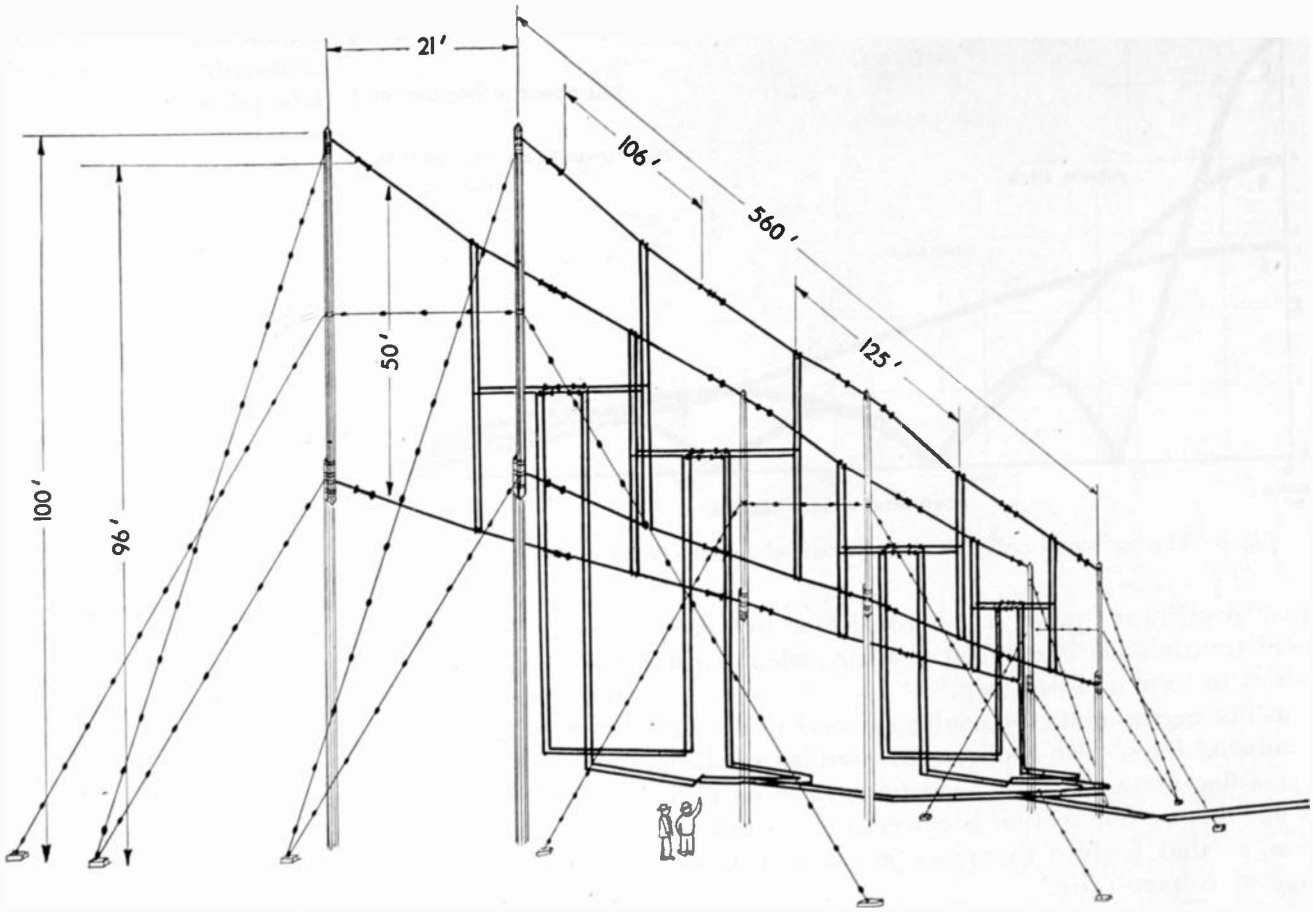


Fig. 7—WCBX-WCRC antenna No. 7 (9650 to 11,830 kilocycles) 4-section horizontal broadside array.

Transmission Lines

One of the major considerations is the switching facilities to be used for interconnecting any of the three 50-kilowatt-amplifier output lines with any desired combination of the thirteen transmission lines. Thirty-nine specially designed switches are required for this purpose. Fig. 3 illustrates the system to be used. These switches, manually operated, will be interlocked mechanically and electrically, in order to insure proper operation and protection to apparatus. As the voltage on the lines will be high during peaks of modulation (14,000 volts, root-mean-square) special insulators with properly designed fittings must be used. This is also true of the transmission-line and antenna insulators, all of which have been designed for operation at 400 kilowatts peak power, at 22 megacycles, with a liberal safety factor included. These switches are so arranged as not to unbalance the impedance of the lines, and thus reduce to a minimum loading difficulties, reflection losses, and undesired radiation. Voltage-breakdown tests have been made to determine the comparative merits of various insulator designs when operated at high voltages under practical operating conditions.[6]

More than 100,000 feet of copper wire will be used for the open 2-wire balanced transmission lines. Each of the lines will have a characteristic impedance of about 550 ohms. It is interesting to note that 20 tons of No. 0 B & S gauge copper wire will be required for the transmission lines and antenna elements, supported from 536 wooden poles and 10 steel towers. This gives one a general idea of the scope of the antenna system.

Special networks will be installed on the transmission lines for the purpose of performing a variety of services, including the matching of impedances, the control of phase relationships, the division of power, filter action, the filtering of harmonic frequencies, and the simultaneous transmission of two frequencies over one transmission line.

Some of the functions of these networks could be carried out using lumped inductance and capacitance, but it has been found more practical to utilize networks made of sections of transmission line of the same construction as the feeders themselves. The latter are preferable mechanically and economically, not only because they are more rugged and stable when exposed to the elements, but also because their performance may be calculated with a greater accuracy. The parameters on which their electrical properties depend are linear dimensions which may be measured on the job, in feet and inches, more simply and more accurately than the inductance of a coil or the capacitance of a condenser could be measured under similar circumstances.

Some of the networks that will be used are known

[6] Andrew Alford and Sidney Pickles, "Radio frequency high voltage phenomena," *Elec. Eng.*, vol. 59, pp. 129–136; March, 1940.

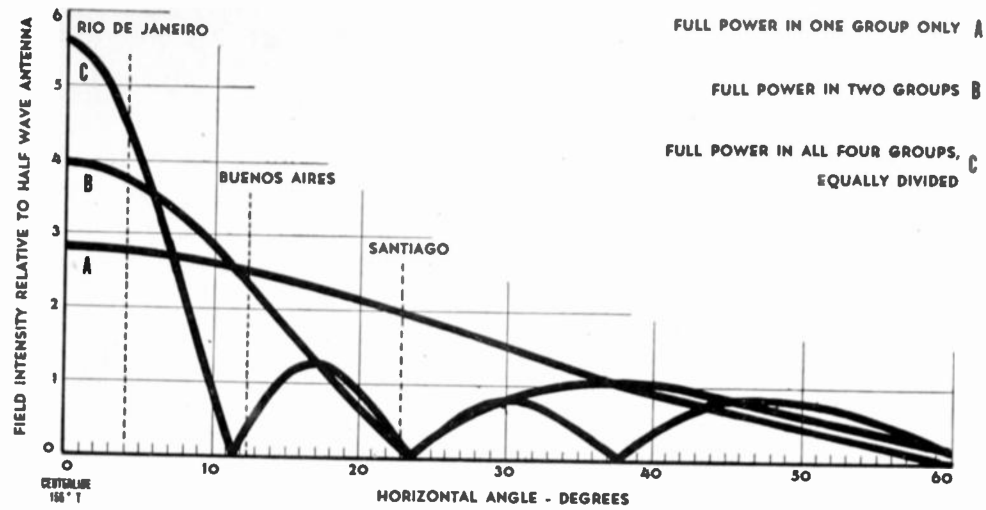


Fig. 8—The horizontal radiation characteristic of antenna No. 7 (9650 kilocycles).

as the "re-entrant" type, which consist of two sections of transmission line joined at their ends in such a way as to form a closed loop.[7]

It will be necessary to use conjugate sections on the transmission lines. Two sections are conjugate when the standing-wave (E_{max}/E_{min}) voltage ratio created on a flat line by one section is corrected by a second section, so that a given frequency is passed without change of voltage ratio.

A further and more important use of conjugate sections is to employ them in two pairs, the first pair passes frequency F_1 without introducing a ratio, but is so designed as to introduce a predetermined ratio for frequency F_2 for the purpose of matching the line to the load. The other pair passes frequency F_2 without change of line ratio, but matches impedances for frequency F_1. Thus, the line will be matched to the load for two frequencies simultaneously and permits one antenna to be fed with either one of the two frequencies, or by the two simultaneously, if a suitable line input network is employed to isolate the lines from each transmitter properly.

One of the antennas for transmission to Europe will be used simultaneously by CBS and Mackay, the former using 6120 kilocycles and the latter 6935 kilocycles. The first is a modulated 50 kilowatt carrier and the second a 50-kilowatt continuous-wave carrier.

A re-entrant 2-stage conjugate filter will be used to isolate the two transmitter output circuits and to maintain proper impedance relationships between the power-amplifier outputs and the line that feeds the antenna array.[7,8] A network of this type consists of four filters. Two on one side of the network are designed to block frequency 6935 kilocycles. The other two filters on the opposite side of the network block frequency 6170 kilocycles. The first two filters are conjugate at frequency 6170 kilocycles while the other two are conjugate at frequency 6935 kilocycles.

These networks will be installed near the transmitter building in order that only a single long transmission line will be required to carry the two frequencies to the antenna. This feeder is about 3800 feet long. The economic advantages are obvious as this plan eliminates the requirement of two separate long transmission lines and two separate antenna arrays.

Several of these networks have been successfully used by Mackay at Brentwood. Their use has been entirely trouble-free and excellent constancy of adjustment has been obtained with a minimum of maintenance attention.

Experience has shown that a 5 per cent separation between frequencies of two transmitters is sufficient for satisfactory operation of these networks. The degree of filtering obtainable under these conditions is such that the attenuation of the undesired frequency amounts to about 40 to 50 decibels. The power loss is not more than 0.2 to 0.3 decibel.

Directive Antenna Arrays

The engineering, mechanical, and economic considerations affecting the choice of directional antenna design were given detailed study by a group of engineers. After giving due attention to all service requirements, including direction, distance, and areas to be served, many plans were considered and one of these adopted.

Fig. 4, an azimuth chart centered on New York City, indicates the true bearings to the various worldwide areas proposed to be served. Fig. 5 shows the

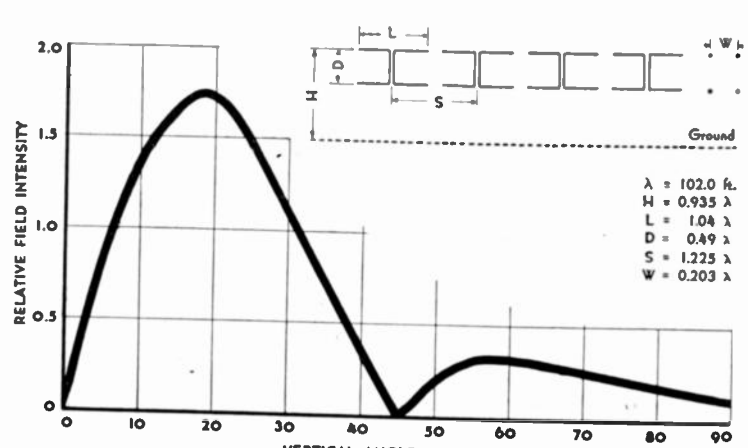


Fig. 9—The vertical radiation characteristic of antenna No. 7 (9650 kilocycles).

[7] Andrew Alford, "High frequency transmission line networks," *Elec. Comm.*, vol. 17, pp. 301–310; January, 1939.

[8] Andrew Alford, "Coupled networks in radio-frequency circuits," Proc. I.R.E., vol. 29, pp. 55–70; February, 1941.

concentration of urban population and receiving sets in South America.

These, and other factors, resulted in the decision to erect, initially at least, 13 unidirectional arrays, 30 antenna-array—frequency combinations, in accordance with Table II.

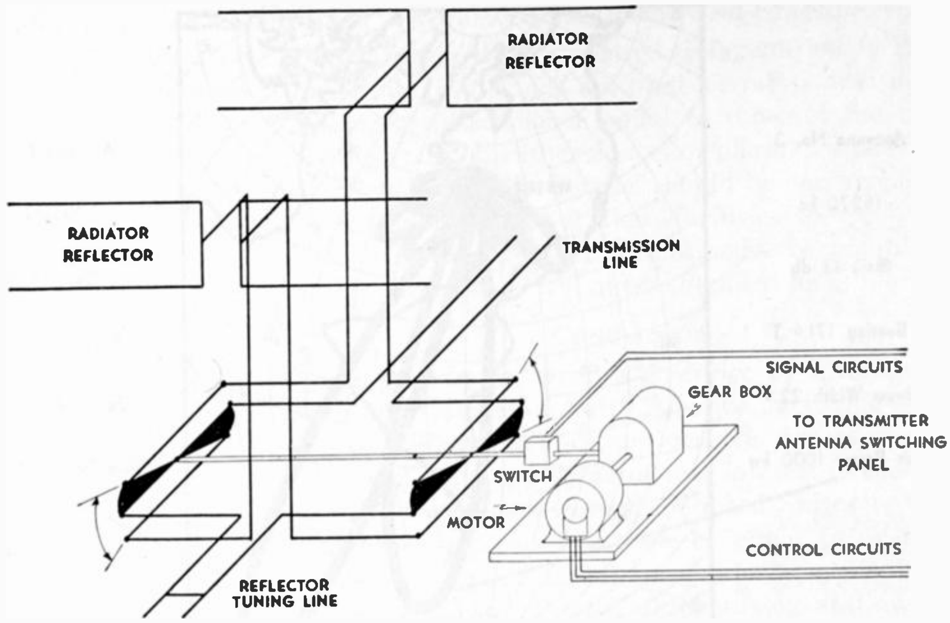
The radiation characteristics of a directive antenna array of this, and other horizontally polarized types, depends upon the topography, arrangement, physical dimensions, number of elements, distance between the elements, distance between the radiator and the reflector, height of the elements above ground, the phase and distribution of the current, the magnitude of power in each of the elements, and the operating frequency.[9]

The Brentwood antennas will consist of stacked horizontal broadside arrays, with parasitically excited reflectors. They comprise rows of 2, 4, or 8, 0.5 λ to 0.64 λ elements, placed side by side, in two rows stacked one above the other, with a vertical separation between rows of 0.50 to 0.64 λ. The reflector is 0.20 to 0.22 λ from the radiator. The height above ground of the bottom row of elements depends upon the frequency for which the antenna is designed and is usually more than 0.5 λ. Fig. 6 shows the arrangement of CBS and Mackay antennas on the Brentwood site ground plan.

Fig. 7, is a drawing of a typical array, antenna number 7, designed for operation on 9650 or 11,830 kilocycles, having a calculated gain of 15 decibels at the lower and 16 decibels at the higher frequency. Fig. 8 indicates the horizontal and Fig. 9 the vertical radiation characteristics of this array.

Field tests, with small-scale models, give results which corroborate the antenna-design calculations and thus, it is believed that anticipated performance will be realized in practice.

Reflectors are used to obtain an additional gain of almost 3 decibels in the forward or desired direction of radiation. This is equivalent to doubling the carrier power of the transmitter, with the additional advantage of reducing backward radiation, which, on the higher frequencies, sometimes results in impairing the quality of reception due to echo effect. The signal, when radiated both forward and backward, arrives at the receiving antenna over two different great-circle paths of different lengths, thus producing this phenomenon. Echo sometimes arises, even when unidirectional radiation takes place, because of the signal arriving at the receiver once, and a second time, approximately $\frac{1}{7}$ of a second later, after it has traveled



(SHOWN AS APPLIED TO A SINGLE SECTION ARRAY. TWO OF THESE SWITCHES ARE REQUIRED ON EACH 2 SECTION REVERSIBLE ARRAY)

Fig. 10—WCBX-WCRC remote-control radiator-reflector reversing system used on antennas Nos. 9, 10, and 11 for transmission to Europe or Mexico—Central America.

[9] G. C. Southworth, "Certain factors affecting the gain of directive antennas," Proc. I.R.E., vol. 18, pp. 1502–1536; September, 1930.

TABLE II

Directional Antennas to South America and West Indies

Antenna Number‡	Frequency Kilocycles	Direction True (E of N)	Beam Width (6 decibels down)	Vertical Angle (maximum radius)	Gain†	General Direction
		Degrees	Degrees	Degrees	Decibels	
1.	17830 21520 21570	171*	14 12	14 12	15 16	Argentina-West Coast South America
2.	17830 21520 21570	155*	14 12	14 12	15 16	Brazil-East Coast South America
3.	11830 15270	171*	30 22	18 14	11.5 13	Argentina-West Coast South America
4.	15270 17830	171*	14 12	17 14	15 16	Argentina-West Coast South America
5.	11830 15270	155*	30 22	18 14	11.5 13	Brazil-East Coast South America
6.	9650 11830	171*	14 12	18 16	15 16	Argentina-West Coast South America
7.	9650 11830	155*	14 12	18 16	15 16	Brazil-East Coast South America
8.	6060 6120 6170	166	41	18	10	South America
Directional Antennas to Europe or Mexico and Central America						
9.	17830 21520 21570	52* or 232*	28 24	14 12	12.5 13	Europe or Mexico and Central America
10.	11830 15270	52* or 232*	30 22	18 14	11.5 13	Europe or Mexico and Central America
11.	9650 11830	52* or 232*	28 22	18 15	12 13	Europe or Mexico and Central America
12.	6060 6120 6170	54	14	18	15	Central Europe
13.	Same	220	41	18	10	Mexico and Central America

* Adjustable ± 10 degrees.
† Reference antenna 0.50λ horizontal dipole in free space.
‡ 30 antenna-array—frequency combinations.

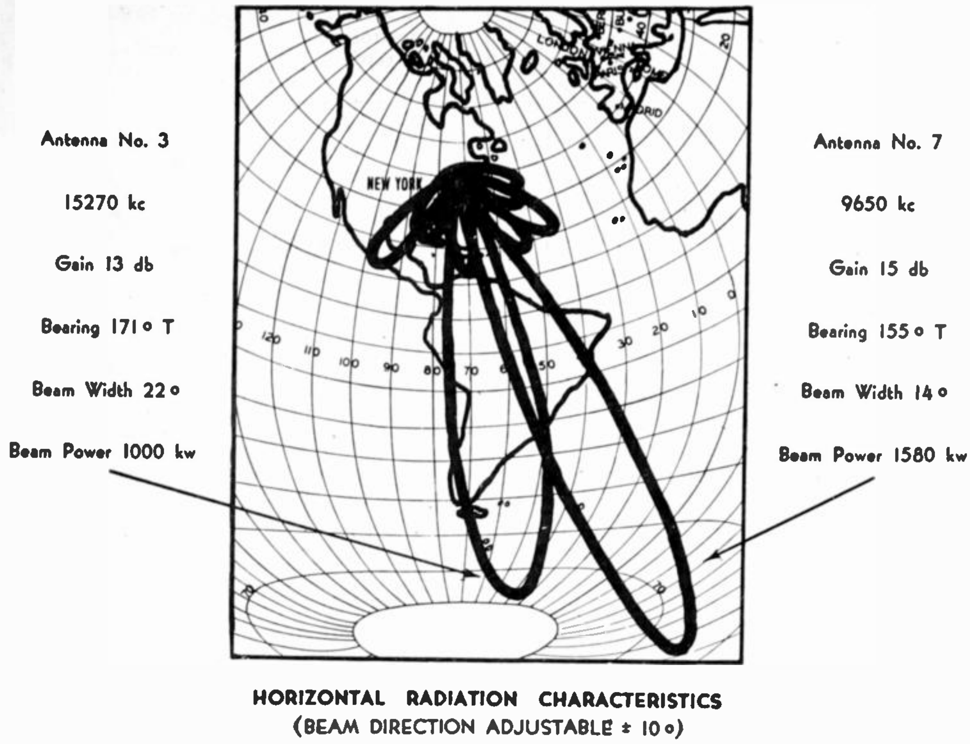


Fig. 11—Simultaneous transmission to Latin America from WCBX and WCRC.

all the way around the world and been received again.

Three of the antennas, numbers 9, 10, 11, may be reversed 180 degrees by remote control, and used for transmission to Europe or to Mexico and Central America. This is accomplished by interchanging the transmission-line and reflector-line matching stub with the radiator and reflector, using two double-pole, double-throw switches, a switch for each section of the antenna. Two switches will be required for each of these reversible arrays. Fig. 10 indicates some of the details of this arrangement.

Figs. 11 and 12 show typical simultaneous transmission to various points of the world and represent typical combinations of antenna arrays as they will be used in practice. These are merely horizontal polar diagrams applied to an azimuth map centered on New York. The contours do not indicate coverage nor absolute field-intensity values but show the directions of maximum radiation.

The tuning and adjusting of the directive antenna arrays, with their associated transmission lines, is a complex task that requires the services of expert engineers who are experienced in this field and thoroughly familiar with the theory and measuring technique involved. Proof-of-performance data, based on field-intensity measurements, will be obtained at the Brentwood site, using as a reference antenna a 0.50 λ horizontal dipole located at various heights above ground. The array and reference antenna will be fed the same amount of power while rapid comparisons in performance are observed at the distantly located relay receiving stations. Empirical observations will also be made and these data evaluated. This subject is beyond the scope of this paper and will be treated in a future paper, based on the results of this work which will take many months to complete.

Operating Conditions

The best transmitting and receiving apparatus is of limited usefulness unless a number of frequencies are available for this service, at least one or more in each band. In general, the lower frequencies are good for night transmissions over paths of complete darkness, the higher frequencies for daytime transmission, and

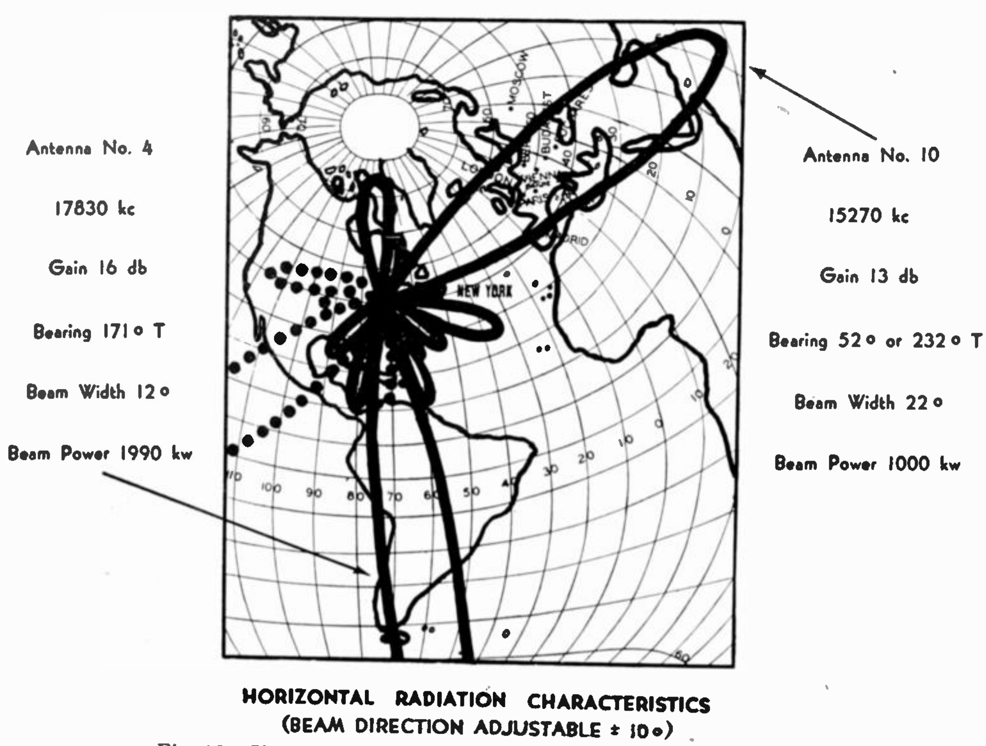


Fig. 12—Simultaneous transmission to Europe (or Mexico) and the West Coast of South America.

the intermediate frequencies, 15- and 11-megacycle bands, for transitionary periods of time; i.e., when the transmission path is partly in darkness and partly in daylight. Because several variable factors greatly influence the propagation characteristics of short waves, it is necessary to use the frequency best suited for an existing condition of transmission and upon the proper choice of frequency depends to a large degree the success or failure of a short-wave broadcast or relay.

The frequencies selected for daily operation, i.e., the station operating schedule, are determined by exhaustive study of (1) the United States National Bureau of Standards radio wave propagation data,[10] (2) field-intensity-measurement data, (3) professional reception reports such as those compiled by the British Broadcasting Corporation receiving station at Tatsfield, England, (4) frequency measurements made by the Union Internationale de Radiodiffusion Control Center, formerly located at Brussels and more recently located at Berne, Switzerland, (5) reports from CBS representatives abroad, and (6) correspondence from short-wave-station listeners.

The Union Internationale de Radiodiffusion Control Center frequency measurements are very useful for predicting sources of interference from other short-wave stations. They indicate, quite accurately, the number and identity of stations operating in each of the frequency bands. The 6- and 9-megacycle bands are exceedingly crowded at present resulting in considerable chaos and interference. It is hoped that with the conclusion of present unsettled conditions, world radio conferences will again convene, and this situation be improved. The recent inter-American radio conference held at Santiago, Chile, made noteworthy progress in this direction.

[10] T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer, "Characteristics of the ionosphere at Washington, D. C.," monthly reports published in the Proc. I.R.E., vols. 25–29; 1937–1941.

International Receiving Station

It is necessary that the receiving-station facilities, the signals from which are used for rebroadcasting, be capable of performance equal to those of the transmitting station. Either space- or phase-diversity unidirectional antenna systems should be employed, and the entire receiving-station facilities properly engineered. A great deal of information has been published on this subject and will not be detailed here.[11,12,13]

Conclusion

The present and proposed service by international broadcast stations of North America, including expansion of existing facilities and construction of new stations, will undoubtedly accelerate interest in this service.[14] Transmissions from the United States to Latin American countries will soon be equal to or better than those now received from other countries. The new WCBX and WCRC transmitting stations will increase the intensity of CBS signals to Latin America and Europe, based on a conservative estimate, by at least 20 decibels. This is equivalent to a hundredfold increase in the power of the existing facilities.

Acknowledgment

Sincere thanks and appreciation are extended to Mr. Andrew Alford and associates of the Mackay Radio and Telegraph Company, and to my associates in the CBS General Engineering Department, for their cooperation and assistance in obtaining much of the material presented.

[11] A. A. Oswald, "The Manahawkin musa," *Bell Lab. Rec.*, vol. 8, pp. 130–134; January, 1940.

[12] J. B. Moore, "Recent developments in diversity receiving equipment," *RCA Rev.*, vol. 2, pp. 94–116; July, 1937.

[13] H. T. Friis and C. B. Feldman, "A multiple unit steerable antenna for short-wave reception," Proc. I.R.E., vol. 25, pp. 814–917; July, 1937; *Bell Sys. Tech. Jour.*, vol. 16, pp. 337–419; July, 1937.

[14] Raymond F. Guy, "NBC's international broadcasting system," *RCA Rev.*, vol. 6, pp. 12–35; July, 1941.

The Velocity of Radio Waves Over Short Paths*

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J. E. BAILEY†, STUDENT, I.R.E., AND C. O. MARSH†, ASSOCIATE, I.R.E.

Summary—*The velocity of radio waves was measured directly in the following manner. Two radio stations were set up on frequencies of 3492.5 and 2398 kilocycles, respectively. One station was fixed while the other was portable. The fixed station sent out pulses which were received at the portable station. A thyratron control set off return pulses which came back to the base station. At the base station the two pulses appeared upon a cathode-ray oscilloscope with a sweep of 22,800 inches per second. The separation of these pulses gave the time for the pulses to travel twice the distance between the stations plus the time required to pass through the receiving apparatus. By taking the portable station to two positions one 0.73 kilometer from the base and the other 3.67 kilometers, it was possible to eliminate the time lag in the receiver and so to find the exact time of propagation. Each station was in sight of the other. The average of 180 measurements was* 2.985×10^{10} *centimeters per second.*

* Decimal classification: R111.1. Original manuscript received by the Institute, July 17, 1941.
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THE VELOCITY of radio waves in air is always assumed to be the same as the velocity of light. Exact measurements over long distances are subject to the uncertainty that the real path of the waves cannot be determined. If, however, the path of the wave remains in the line of sight, it is reasonable to assume that it will follow the straight line connecting the two points. The distance between the two points can be measured but the time interval becomes so small that ordinary measuring devices cannot be used. However, very short intervals of time (1 microsecond) may be measured upon a cathode-ray oscilloscope with a fast sweep.

In the actual experiment two radio stations were set up on frequencies of 3492.5 and 2398 kilocycles, respectively. The fixed station sent out 60 pulses per second, each pulse lasting for 8 microseconds. These pulses were received at certain distances on a portable receiver so arranged that a thyratron control set off return pulses from a transmitter in the portable station. Thus the portable station was made to send out pulses in exact synchronism with the base transmitter. This relayed pulse was received at the base station upon the screen of the oscilloscope. The original pulse appeared upon the same screen so that the distance between the two pulses, as seen upon the screen, gave the time taken for the radio waves to travel twice the distance between the stations as well as the time consumed in passing through the equipment. For example, if T_1 represents the time for the pulse to make the round trip over base line b_1, and T_2 is the time to make the round trip over base line b_2, then

$$T_1 = T_{b_1} + T_e$$
$$T_2 = T_{b_2} + T_e \qquad (1)$$

where T_e is the time for the pulse to pass through the equipment and T_{b_1}, T_{b_2} are the times for the double transit of the two base lines b_1 and b_2. From these values, the velocity becomes

$$V = \frac{D_2 - D_1}{T_2 - T_1} \qquad (2)$$

in which $D_2 = 2b_2$ and $D_1 = 2b_1$.

The alternating-current supply for the base-station pulser comes from a phase-shifting mechanism which places the pulse upon any portion of the oscilloscope sweep. In this way both the initial and received pulse may be placed side by side on the screen of the oscilloscope. The base-station receiver is of the video response type; it will pass a band of frequencies 2 megacycles wide without attenuation. Such a frequency response is necessary in order to preserve the waveform of very short pulses.

The portable station was built into a panel delivery truck which served as the operating room. A power extension cord could be plugged into a receptacle in the side of the truck and any house outlet. A ground rod was always used to provide a good electrical connection to the earth. The portable receiver is also of the video type with television pentode amplifier tubes and a vacuum-tube peak voltmeter to measure the output voltage of the receiver. Voltage-regulator tubes are employed to eliminate the effects of line-voltage fluctuations.

The voltage necessary to fire the thyratron must be measured accurately each time an observation is made because the corresponding voltage values along the wave fronts will depend upon the amplification levels. The voltage peak will appear earlier on the wave front which has the higher value. For every voltage value on one base line, there is a corresponding voltage value for any other base line. Only by the use of corresponding values of voltages can accurate results be obtained.

The observations consisted of the measurement of the separation of the direct and relayed pulses on the oscilloscope for various values of voltage injected to the thyratron. This was done over several base lines of different lengths. The velocity of the sweep on the oscilloscope was determined by putting a signal of known frequency on the vertical deflecting plates while the sweep voltage was on the horizontal plates. The pattern on the oscilloscope screen gives the number of cycles of known frequency per centimeter and this gives the velocity of the sweep. The velocity was found

TABLE I

Base Line b_1 = 0.73 kilometer										
Volts	Separation of Pulses in Centimeters									
5	4.9	5.0	4.9	4.8	4.8	4.9	5.0	4.8	4.8	4.8
7	4.6	4.7	4.7	4.6	4.6	4.6	4.7	4.6	4.6	4.6
9	4.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.4	4.4
11	4.3	4.3	4.4	4.3	4.4	4.3	4.4	4.4	4.3	4.3
13	4.2	4.2	4.2	4.2	4.3	4.2	4.2	4.2	4.2	4.2
15	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
17	3.8	3.9	3.9	3.9	3.9	4.0	4.0	3.8	3.9	3.9
Base Line b_1 = 3.67 kilometers										
5	7.5	7.3	7.6	7.5	7.0	6.8	6.7	6.8	7.2	8.2
7	6.6	6.5	6.6	6.1	5.8	6.1	5.7	5.9	6.0	6.3
9	5.8	5.7	5.7	5.6	5.6	5.6	5.5	5.6	5.6	5.6
11	5.6	5.5	5.4	5.4	5.5	5.5	5.5	5.4	5.5	5.5
13	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.4	5.4
15	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.3	5.2
17	5.0	4.9	5.0	5.0	5.0	5.0	5.1	5.0	5.0	5.0

to be 22,800 inches per second or 1 centimeter equivalent to 17.25 microseconds. The latter number multiplied by the separation on the screen will give the value for T_1 on the base line b_1. The value T_2 is obtained by using the separation of the pulses for the identical voltage value on the second base line b_2. Five to seven different voltages were used on each base line. The separation for each voltage was the average of ten trials. The distance between the two pulses is measured by placing a caliper on the screen of the oscilloscope and opening the jaws until they are coincident with the vertical wave fronts of the two pulses.

In this method, the assumption is made that the T_e of (1) is constant over a wide range of signal levels and distances. This assumption was substantiated by varying the length of the receiving antenna at the portable station. In this way a wide range of input signal strengths was obtained. Provided the gain of the receiver was adjusted so that the output voltage remained the same, no change in the separation of the pulses occurred.

The characteristics of the thyratron tubes used also influence the results. There is a time delay of several microseconds between the application of the ionizing potential to the grid and the actual breakdown of the tube. This delay depends upon the type of gas used in the tube, the bulb temperature, and the increase in voltage after the ionizing potential has been reached.

Tubes filled with argon were found to be most satisfactory for this investigation. The characteristics of two tubes of the same type are not identical and data obtained with one tube should not be compared with data from another.

The entire apparatus contains almost 60 vacuum tubes and a large change in the characteristics of any one of them will affect the accuracy of the measurement. However, modern tubes retain their characteristics for a long time and no trouble has been experienced in this respect. The general method is not particularly accurate at present but it is subject to many refinements.

A typical set of data is given in Table I. From this table the values for 15 volts give

$$v = \frac{2(3.67 - 0.73) \times 10^5}{17.25 \times 10^{-6} (5.21 - 4.07)}$$
$$= 2.985 \times 10^{10} \text{ centimeters per second.}$$

Eighteen similar sets of measurements were made or 180 for each station. The most probable average was very close to the velocity of light.

Directional Characteristics of Tropical Storm Static*

STEPHAN P. SASHOFF†, MEMBER, I.R.E., AND WILLMAR K. ROBERTS†, STUDENT, I.R.E.

Summary—*This paper discusses tabulated data of static recorded during the hurricane seasons of 1938 and 1939. It shows that static arriving at three recording stations totalized over long periods of time seems to come from certain well-defined points on the compass and indicates that the directional distribution of static, for the summer months at least, may be associated with areas very active in producing atmospherics. The paper discusses records obtained on the tropical disturbance of August, 1939, which, although mild in intensity, was of considerable interest since its center passed only 100 miles from the recording station at Gainesville, Florida. The results indicate that (a) only certain portions of the storm may be regarded as important sources of static, (b) the relative position of each static-producing area remains fairly well fixed with respect to the storm center, and (c) as far as can be determined, no static emanates from the eye of the storm.*

Introduction

A METHOD OF recording the direction of arrival of atmospherics and of triangulating for the apparent position of the source based on data obtained during the summer of 1937 has been described previously.[1] During the summers of 1938 and 1939 similar observations were made on 10 kilocycles, and additional information was secured on the characteristics of the incoming static, particularly on static which appeared to have its origin in tropical disturbances. While tabulating and statistically analyzing the data obtained during these periods, two significant facts stood out: First, that the angular distribution of the incoming static totalized over long periods of time seems to favor certain points on the compass; and second, that static reasonably identified as coming from a tropical disturbance reaches a peak at points related to the reported positions of the storm.

Distribution of Static over Long Periods of Time

Tabulation of static arriving at each recording station was made by segregating the crashes into 10-degree angles in eighteen groups. Each group was designated by the direction of the center of the group angle. The crashes falling in each group angle for a single observation period of three minutes duration were first added, and then the totals for all periods and all angle groups for the corresponding summer were obtained.

The distribution of static for the three recording stations at Gainesville and Pensacola, Florida, and Rio Piedras, Puerto Rico, from data obtained during the summer of 1938 is shown on Fig. 1. This figure shows the static bidirectional. It should be noted, however, that past experience has shown that for the three recording stations used in making the records practically all of the static originates in the third and fourth quadrants. Keeping this fact in mind, it can be seen that:

1. The Gainesville station shows two main peaks; one at 140 degrees and the other at 240 degrees from the true north. The minimum points are at 100 and 190 degrees.
2. The distribution for the Pensacola station also exhibits two maxima at 135 and 225 degrees. The minima are at 90 and 175 degrees.
3. The Rio Piedras station on the other hand shows two main peaks without a definite minimum between these but with a small additional peak at 230 degrees. There is a wide angle of static-free area extending from 90 to 155 degrees and from 115 to 270 degrees.
4. The distribution of static for all three stations shows that the directions from which a considerable number of crashes arrive are invariably pointing to areas of high mean annual days with thunderstorms as indicated on the climatic map of North America, published by the Blue Hill Observatory of Harvard University.

* Decimal classification: R114. Original manuscript received by the Institute, May 13, 1941; revised manuscript received, November 5, 1941. Presented, U.R.S.I.–I.R.E. Meeting, Washington, D. C., April 26, 1940.

† University of Florida, Gainesville, Fla.

[1] S. P. Sashoff and Joseph Weil, "Static emanating from six tropical storms and its use in locating the position of the disturbance," Proc. I.R.E., vol. 27, pp. 696–700; November, 1939.

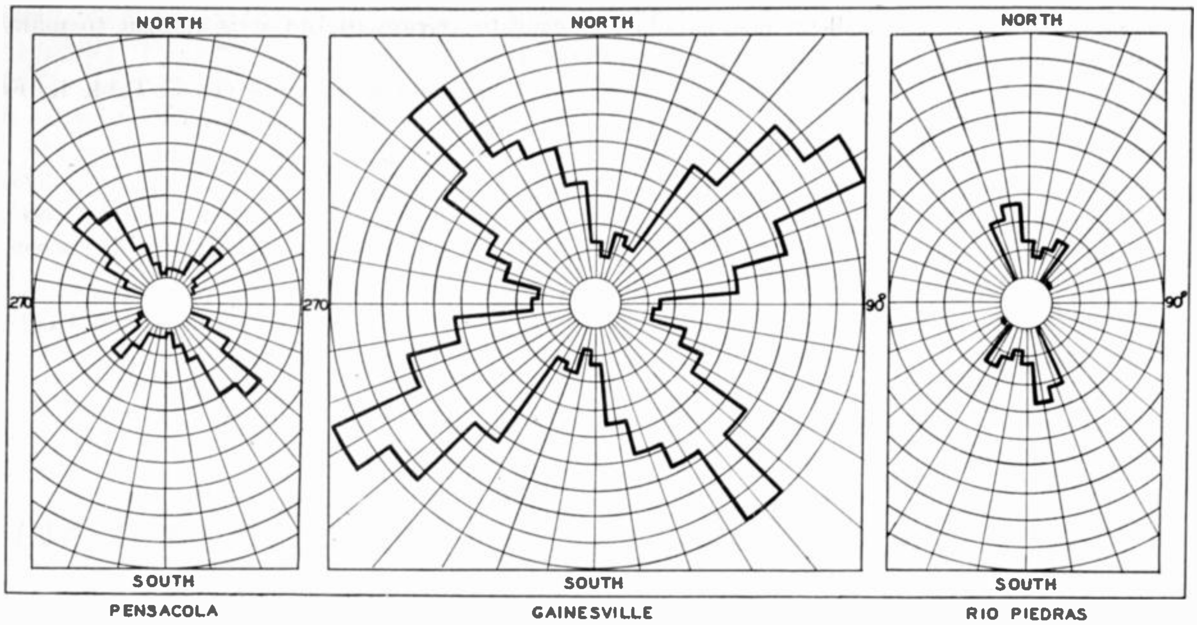

Fig. 1—Directional distribution of static received at Gainesville and Pensacola, Florida, and at Rio Piedras, Puerto Rico during the summers of 1938 and 1939.

The distribution of the static would indicate that, for the summer months at least, certain areas are very active in producing atmospherics and that the direction of arrival of the latter at the recording station makes it possible to locate these areas. Thus the three recording stations have peaks triangulating at a point near the border of Venezuela and Brazil at longitude 64 degrees west and latitude 5 degrees north. Of course, this is only an apparent position of the disturbing area since other active centers are located on the islands of Haiti and Cuba. These are localities of numerous thunderstorms and fall in the direction of the Gainesville station. The fact that the peaks do triangulate over a small area, however, would indicate that this must be the center of a static source of unusual activity.

It may be noted that the number of recorded crashes at Gainesville is three times the number recorded at Pensacola and nearly five times the number recorded at Rio Piedras. On first thought it would seem that Gainesville is located in the center of a large static-producing area. If this were true, however, a more even distribution might be expected. The most feasible explanation, supported by further checks, is that the disparity in the number of recorded crashes is due in a large extent to the lower sensitivity of the receiving amplifiers at Pensacola and Rio Piedras. The manner in which the record film is processed will also contribute greatly towards revealing the presence of all crashes appearing on the end of the cathode-ray tube.

The above results indicate that the method employed gives acceptable procedure for locating static-producing areas. Furthermore, if the tabulation of the recorded crashes is made over short periods of time, the locations of thunderstorms may be established. This agrees with results obtained independently by Henderson who used synchronous crashes from unidirectional recorders.

Distribution of Static in the Direction of a Known Storm

Static arriving at the recording stations from the direction of a tropical storm was found to be only a small portion of the static which was received. It would follow, then, that if the totaling of the crashes is made over large enough angles, the unwanted crashes will completely mask those coming from the storm. At first an effort was made to differentiate between the useful and useless static by concentrating on synchronous crashes only; i.e., on crashes which could be identified as occurring at the same instant at all the stations. Unfortunately, this method was found impracticable since the number of crashes so identified was very small (only a fraction of 1 per cent for all stations), and triangulation by means of such meager data could not be relied upon. The meagerness of the synchronous crashes may be due to one of the following: (a) Low sensitivity of the amplifiers at one or more stations, (b) Local static at some station masking the desired crash, or (c) The distance from the storm of one or two of the stations is such that only the most violent crashes were recorded. It was found, however, that although only a few synchronous crashes were recorded, considerable amount of static arrives at each station from the direction of the storm. Therefore, unless most of the latter static is due to local disturbances in line with the direction of the storm, some method could be found to identify the storm static.

Consequently, the crashes were plotted on a scale broad enough that sufficient delineation between crashes only 1 degree apart could be obtained. The results were highly encouraging.

Tropical Storm of August, 1939

The tropical storm of August 8 to 20, 1939, has been described by Tannehill[2] as follows:

"The first definite evidence of this disturbance was on August 8. . . . The disturbance moved west-northwestward during the next 3 days, crossing the Bahamas late on the 10th and early on the 11th. The center reached the east coast of Florida in the late afternoon of the 11th. Its progressive movement had increased gradually from about 10 miles an hour on the 8th to approximately 15 miles an hour on the 10th and 11th. Ship reports do not indicate that it was of more than moderate intensity in the Atlantic. The highest wind noted on shipboard was force 10 . . .

"On the east coast the lowest pressure and highest wind were recorded at Fort Pierce, 991.2 millibars (29.27 inches) and 54 miles per hour.

"In crossing Florida the rate of progression increased to about 18 miles per hour, while the intensity of the disturbance did not change materially. The center passed very close to Lakeland and Tarpon Springs and moved to the extreme northeastern Gulf on the 12th. At the Tampa Airport the highest wind was 62, south-southwest at 4:30 A.M. on the 12th."

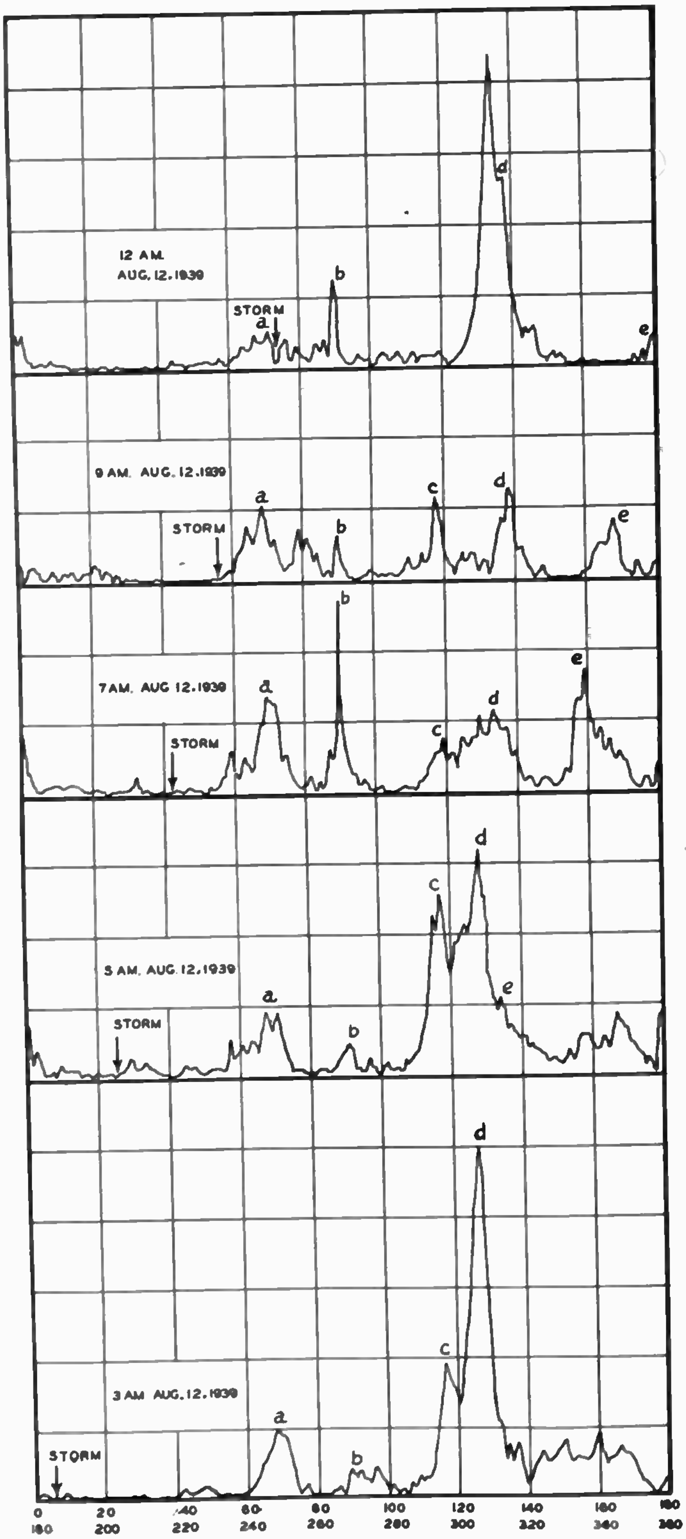

Fig. 2—Distribution of static from tropical storm, August 12, 1939. Peaks *a*, *b*, and *c* correspond to stationary static-producing areas; peaks *d* and *e* are associated with the forward movement of the storm. Note that practically no static emanates from the storm center.

Observations on this storm were made by the Gainesville station and the tabulated static is shown in Fig. 2. Although this storm was not of hurricane force, certain interesting conclusions may be drawn from the static distribution. In this case the 1-degree spread was used for the first time. Thus it was found that static peaks marked *a*, *b*, and *c* persisted during the entire observation period of from 3:00 A.M. till 12:00 NOON; peaks marked *d* shifted at the rate of about 5 degrees every two hours, while those marked *e* shifted between 10 and 20 degrees during the same intervals.

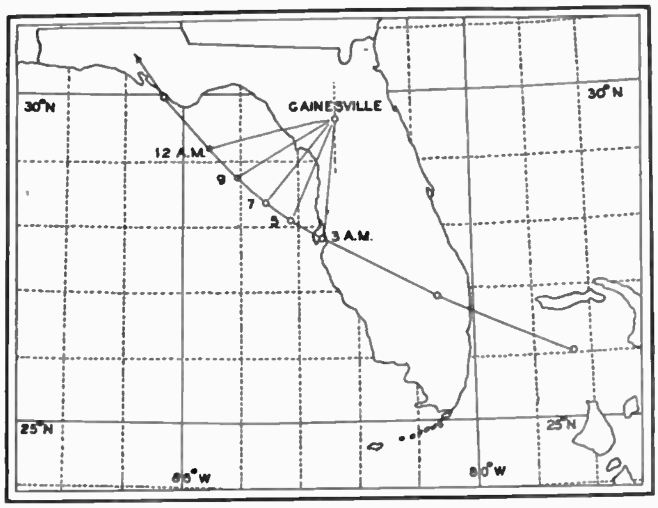

Fig. 3—Path of tropical storm of August 8–20 as it passed through Florida. Points indicated are for 3:00, 5:00, 7:00, 9:00, and 12:00 o'clock noon on August 12th, 1939.

Comparing the position of the peaks of Fig. 2 with the path of the storm of Fig. 3, it appears that static peaks *d* and *e* may be associated with the forward movement of the storm. The location of the disturbing areas in this case, however, is found to be from 200 to 500 miles back of the storm center as reported by the United States Weather Bureau. Another significant fact also seen on Fig. 2 is that practically no static is recorded from the "eye" of the storm.

Acknowledgment

In conclusion the authors wish to thank Dean Joseph Weil for his suggestions and encouragement in the course of the work; Dr. G. W. Kenrick for his cooperation in making the observations at Rio Piedras; and John F. Atkinson and Arthur Luedtke for assisting greatly in the collecting and tabulating of the data.

[2] I. R. Tannehill, "Tropical disturbance of August, 1939," *Monthly Weather Review*, vol. 67, pp. 296–297; August, 1939.

Formulas for the Amplification Factor for Triodes*

BERNARD SALZBERG†, MEMBER, I.R.E.

Summary—*Existing formulas for the amplification factor of the 3-electrode vacuum tube implicitly assume, among other things, that the distance between the grid and anode is large compared to the distance between turns of the grid. Formulas are developed here for the calculation of the amplification factor for plane and cylindrical structures for which this assumption is not permissible. The results given by the new formulas become identical with those obtained from existing formulas when the foregoing assumption is legitimate. A satisfactory experimental verification, made by determining the amplification factor for an ideal scale model of a plane structure immersed in an electrolytic trough, is also presented.*

FORMULAS for the amplification factor of triodes have been available for some time. The original formulas[1–4] were based upon small grid-wire diameters; these were later modified for the important practical case of large grid-wire diameters by Vogdes and Elder.[5] It was implicitly assumed in these derivations that the distance between grid and anode was large compared to the distance between turns of the grid, an assumption which may be unwarranted in in some cases. The object of the present note is the extension of these formulas to the calculation of the amplification factor of plane and cylindrical structures for which this assumption is not valid.

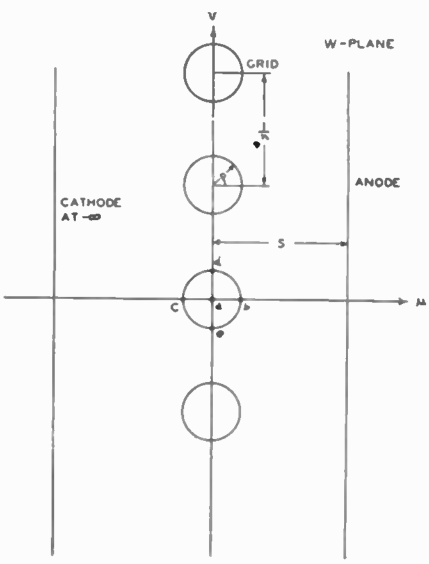

Fig. 1—A section of an ideal plane triode drawn in the w plane.

The problem is treated here as a purely electrostatic one (as was done in the papers referred to), the effects of space charge being neglected. The tube itself is assumed as being quite ideal; that is to say, the effects of wire pitch and support rods and the distortion of the field around the ends are ignored.

Case 1. Plane Structures

First, it is supposed that the tube, a right section of which is shown in Fig. 1, consists of a grid of n parallel wires per inch, placed between two infinite plane electrodes drawn in the w plane. In this figure, the cathode is relegated to minus infinity, which is tantamount to the assumption that the induced charge density is uniform over the cathode surface.

For mathematical convenience, the figure is transferred to the z plane by means of the conformal transformation[6]

$$\epsilon^{2\pi n w} = z \tag{1}$$

where

$$w = u + iv, \quad \text{and} \quad z = x + iy = r\epsilon^{i\theta}.$$

With the relations

$$\begin{aligned} \ln r &= 2\pi n u \\ \theta &= 2\pi n v \end{aligned} \tag{1a}$$

obtained from (1), the section of the tube structure drawn in the w plane maps into the section of the simpler 3-electrode configuration in the z plane, as shown in Fig. 2. Here the plane cathode has become a line at the origin, the plane anode a coaxial cylinder, and the infinite array of right circular cylindrical grid wires has become a cylinder whose right section is represented by the asymmetrical figure b-d-c-e between the cathode and anode. An approximation is now introduced by assuming that the asymmetrical figure b-d-c-e in the z plane is circular. The center and diameter of this circle may be taken in various ways, each leading to a slightly different end result, but for our purpose we assume, as has been done before,[5] that the center P of this assumed circle is equidistant from the points b and c. Then

$$OP = Oa + \tfrac{1}{2}(d_2 - d_1) = \cosh 2\pi n\rho = r_G.$$

This locates the center of the assumed circle. Its radius is

$$cP = \tfrac{1}{2}(d_1 + d_2) = \sinh 2\pi n\rho = a_G.$$

* Decimal classification: R262.4. Original manuscript received by the Institute, July 21, 1941; revised manuscript received, October 20, 1941. The mathematical analysis given in this paper was developed in Part I of a thesis submitted by the author to the Faculty of the Graduate School of the Polytechnic Institute of Brooklyn for the M.E.E. degree, June, 1933.

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[1] W. Schottky, "Über hochvakuum Verstarker," *Archiv. für Elektrotech.*, vol. 8, pp. 1–31; July, 1919.

[2] M. Abraham, "Berechnung des Durchgriffs von Verstarkerrohren," *Archiv. für Elektrotech.*, vol. 8, pp. 42–45; July, 1919.

[3] M. V. Laue, "Über die Wirkungsweise der Verstarkerrohren," *Ann. der Phys.*, vol. 59, pp. 465–492; August, 1919.

[4] R. W. King, "Calculation of the constants of the three-electrode thermionic vacuum tube," *Phys. Rev.*, vol. 15, pp. 256–268; April, 1920.

[5] F. B. Vogdes and F. R. Elder, "Formulas for the amplification constant for three element tubes in which the diameter of grid wires islarge compared to the spacing," *Phys. Rev.*, vol. 24, pp. 683–689; December, 1924.

[6] For such transformations see any standard book dealing with this subject, for example, J. H. Jeans, "The Mathematical Theory of Electricity and Magnetism," Macmillan Company, New York, N. Y., 1925.

When this circular figure is transferred back to the w plane, the resulting grid wires are no longer circular. The lateral diameter remains the same, but the diameter along the grid axis is decreased. The amplification factor calculated on this basis, therefore, is somewhat lower than the actual value. The magnitude of the approximation thus introduced can be estimated by comparing the position of the grid potential line obtained (on the basis of this simplification) from the formulas which follow, or from the equivalent graphical 2-plane mapping with the actual grid.[7]

These alterations are included in Fig. 3, which represents a structure consisting of a filamentary cathode of radius $r_K \rightarrow 0$, a coaxial cylindrical anode of radius $r_A = \epsilon^{2\pi ns}$, and a cylindrical grid which is parallel to the cathode and separated from it by a distance $r_G = \cosh 2\pi n\rho$. When the structure is one for which $s \gg \rho$ then a solution of this subsidiary electrostatic problem may be obtained by the method of images in a simple way.

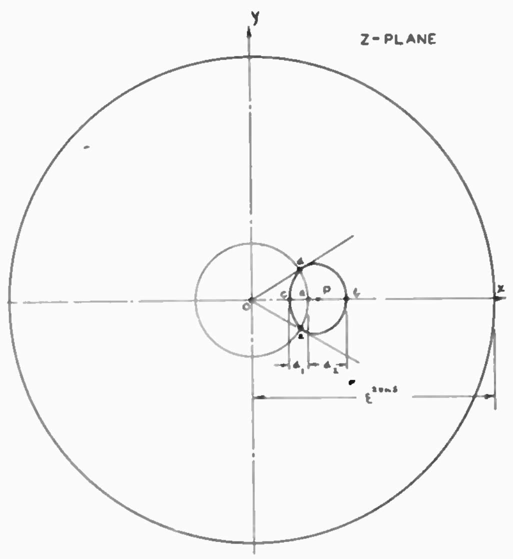

Fig. 2—The structure of Fig. 1, transformed to the z plane.

The anode is an equipotential surface; therefore, the line charge at the axis of the grid must be accompanied by an image charge at a distance $r_A^2/r_G = \epsilon^{4\pi ns}/\cosh 2\pi n\rho$ from the cathode along the straight line joining the cathode and grid, as shown in Fig. 3. Only by the introduction of this fictitious charge can the anode surface be made to remain equipotential.

The total potential distribution within the tube thus consists of two partial potential distributions: (a) the concentric field associated with the charges on the cathode and anode, of values Q_1 and $Q_3 = -Q_1$ per unit length, respectively; and (b) the field between the grid with a line charge Q_2 per unit length at its center, and its image with a charge $Q_4 = -Q_2$ per unit length. The total potential at any point P, situated at a distance r_{nP} from the nth charge, is thus

$$V_P = 2k_e\left(Q_1 \ln r_{1P} + Q_2 \ln \frac{r_{4P}}{r_{2P}}\right) + C \qquad (2)$$

where $k_e = 1/4\pi\Delta$, Δ being the absolute dielectric constant[8] and C an arbitrary constant. The various electrode potentials are obtained by allowing the point P to coincide with the electrode in question, thus assigning definite values to the distances r_{1P}, r_{2P}, and r_{4P} in (2). Thus, for the anode potential,

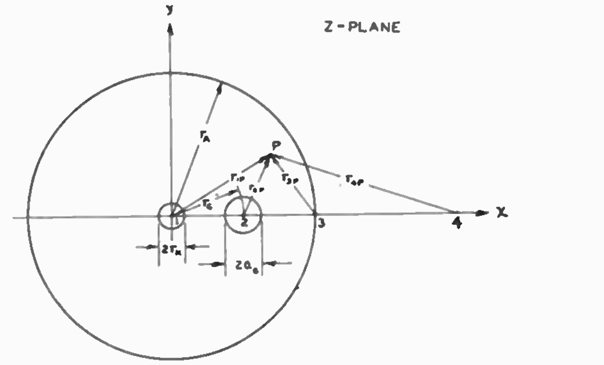

Fig. 3—The configuration of the electrostatic problem.

$$V_A = 2k_e\left[Q_1 \ln r_A + Q_2 \ln\left(\frac{\dfrac{r_A^2}{r_G} - r_A}{r_A - r_G}\right)\right] + C \qquad (3)$$

and similarly for the grid and cathode potentials:

$$V_G = 2k_e\left[Q_1 \ln r_G + Q_2 \ln\left(\frac{\dfrac{r_A^2}{r_G} - r_G}{a_G}\right)\right] + C \qquad (4)$$

$$V_K = 2k_e\left[Q_1 \ln r_K + Q_2 \ln\left(\frac{\dfrac{r_A^2}{r_G}}{r_G}\right)\right] + C. \qquad (5)$$

Hence,

$$\begin{aligned}(V_A - V_K) = V_{AK} &= 2k_e\left[Q_1 \ln \frac{r_A}{r_K} + Q_2 \ln \frac{r_G}{r_A}\right]\\ (V_G - V_K) = V_{GK} &= 2k_e\left[Q_1 \ln \frac{r_G}{r_K} + Q_2 \ln \frac{r_G}{a_G}\left(1 - \frac{r_G^2}{r_A^2}\right)\right].\end{aligned} \qquad (6)$$

Actually, the two electrode potential differences V_{AK} and V_{GK} are specified and the two charges Q_1 and Q_2 are unknown. The two simultaneous equations of condition (6), which make the problem determinate, are therefore to be solved for Q_1 and Q_2, the charges on the cathode and grid surfaces, respectively. These values are

$$\begin{aligned}Q_1 &= \frac{2k_e}{D}\cdot\left[V_{AK}\cdot\ln\frac{r_G}{a_G}\left(1 - \frac{r_G^2}{r_A^2}\right) - V_{GK}\cdot\ln\frac{r_G}{r_A}\right]\\ Q_2 &= \frac{2k_e}{D}\cdot\left[V_{GK}\cdot\ln\frac{r_A}{r_K} - V_{AK}\cdot\ln\frac{r_G}{r_K}\right]\end{aligned} \qquad (7)$$

[7] A more rigorous, although less tractable treatment of the problem of large wires is suggested by J. C. Maxwell, "Electricity and Magnetism," third edition, section 206, Macmillan Company, New York, N. Y., 1904. I hope to discuss the particular problem of large grid wires at greater length at a later date.

[8] E. Weber, "A proposal to abolish the absolute electrical unit systems," *Trans. A.I.E.E.* (*Elec. Eng.*, September, 1932), vol. 51, pp. 728–742; 1932.

where

$$D = 4k_e^2\left[\ln\frac{r_A}{r_K}\cdot\ln\frac{r_G}{a_G}\left(1-\frac{r_G^2}{r_A^2}\right)-\ln\frac{r_G}{r_K}\cdot\ln\frac{r_G}{r_A}\right].$$

The amplification factor may be defined, subject to the original assumption that the induced charge density over the cathode surface is uniform, as

$$\mu = \frac{\dfrac{\partial Q_1}{\partial V_{GK}}}{\dfrac{\partial Q_1}{\partial V_{AK}}} \tag{8}$$

that is to say, the grid-cathode potential difference is μ times as effective in altering the induced charge at the cathode as is the anode-cathode potential difference.

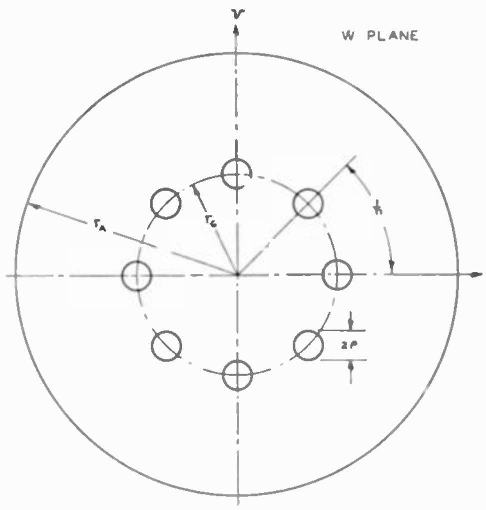

Fig. 4—A section of an ideal cylindrical triode, drawn in the w plane.

Performing the indicated partial differentiations of the first of equations (7), we obtain

$$\mu = \frac{\ln\dfrac{r_A}{r_G}}{\ln\left[\dfrac{r_G}{a_G}\left(1-\dfrac{r_G^2}{r_A^2}\right)\right]}. \tag{9}$$

As it stands, this is a formula for the amplification factor for a triode consisting of a thin cylindrical cathode of radius r_K, a coaxial anode of radius r_A, and a single cylindrical grid wire of radius a_G, parallel to the cathode and spaced a distance r_G from it.[9]

Now, if the values of r_A, r_G, and a_G previously given be substituted in (9), we obtain a formula for the amplification factor for the plane structure shown in Fig. 1. Thus,

$$\mu = \frac{2\pi ns - \ln\cosh 2\pi n\rho}{-\ln\tanh 2\pi n\rho + \ln(1-\epsilon^{-4\pi ns}\cdot\cosh^2 2\pi n\rho)}. \tag{10}$$

This is similar to an expression previously derived,[5] except for an additional term $\ln(1-\epsilon^{-4\pi ns}\cdot\cosh^2 2\pi n\rho)$ present in the denominator. For the usual cases, where the distance between grid and anode is large compared to the distance between turns of the grid, the term $\epsilon^{-4\pi ns}\cdot\cosh^2 2\pi n\rho$ is negligible compared to unity, so that μ is given quite accurately by the older formula

$$\mu = \frac{2\pi ns - \ln\cosh 2\pi n\rho}{-\ln\tanh 2\pi n\rho}. \tag{11}$$

Case 2. Cylindrical Structures

For this case it is supposed that the tube consists of a grid of n wires per inch parallel to a filamentary cathode at the origin and disposed along the circumference of a circle of radius r_G and a coaxial anode of radius r_A, drawn in the w plane, as shown in Fig. 4. To avoid complication by end effects, it is again assumed that the structure is infinite in extent. The combination of filamentary cathode and vertical strut grid is chosen in order that the induced charge density may once more be taken as uniform over the cathode surface. (The structure utilizing a helical grid, more frequently encountered in practice than the longitudinal type under discussion here, has been treated elsewhere on the basis of the assumption that the grid may be represented by an infinite array of toroidal rings: with certain further assumptions as to the structural configuration, the final results become identical in form to those derived for the longitudinal type.)[10]

The solution of the problem thus set forth may be made to depend, in a number of different ways, upon the solution of the reduced electrostatic problem given in Case 1. For example, the use of the conformal transformation $w=z^{1/2\pi n r_G}$, together with the appropriate approximation as to the shape of the resulting grid figure, will convert the configuration of Fig. 4 to one of a similar form, for which the total number of turns is not $2\pi n r_G$, but 1. Another method makes use of the conformal transformation $\epsilon^{z/r_G}=w$ together with the approximation of the resulting grid figures as circular.[5] This converts the cylindrical structure of Fig. 4 to an equivalent plane structure which may then be treated as indicated in Case 1.

Using the transformation $w=z^{1/2\pi n r_G}$, and relocating the charge at the grid wire, as before, we find for the "transformed" distances

$$r_A' = r_A^{2\pi n r_G}$$
$$r_G' = \tfrac{1}{2}\left[(r_G+\rho)^{2\pi n r_G} + (r_G-\rho)^{2\pi n r_G}\right]$$
$$a_G' = \tfrac{1}{2}\left[(r_G+\rho)^{2\pi n r_G} - (r_G-\rho)^{2\pi n r_G}\right].$$

If it is assumed that $\rho/r_G \ll 1$, these become

$$r_A' = r_A^{2\pi n r_G}$$
$$r_G' = r_G^{2\pi n r_G}\cosh 2\pi n\rho$$
$$a_G' = r_G^{2\pi n r_G}\sinh 2\pi n\rho.$$

[9] A similar result for this special case is given by I. Langmuir and K. T. Compton, "Electrical discharges in gases. Part II, Fundamental phenomenon in electrical discharges," *Rev. Mod. Phys.*, vol. 3, p. 211; April, 1931.

[10] G. J. Elias, Balth. van der Pol, and B. D. Tellegen, "Das elektrostatische Feld einer Triode," *Ann. der Phys.*, vol. 78, pp. 370–406; December, 1925.

The substitution of these distances in (9) provides a formula for the amplification factor for the cylindrical structure shown in Fig. 4. We find that this is exactly similar to (10) except that for the distance s, we must use, instead of the actual grid-plate spacing,

$$s = r_G \cdot \ln \frac{r_A}{r_G}. \qquad (12)$$

The special case of the inverted cylindrical tube, in which the cathode and anode interchange roles, is amenable to like treatment. It turns out that for this case we may again use (10), provided that

$$s = r_G \cdot \ln \frac{r_G}{r_A} \qquad (13)$$

where r_G and r_A are now the radii of the grid and anode considered as the outer and inner cylinders, respectively.

Experimental Confirmation

The foregoing results were based, as stated at the outset, upon electrostatic solutions of idealized structures in which the effects of the space charges were ignored. The propriety of applying formulas derived on such grounds to the design of actual tubes has been discussed elsewhere.[11]

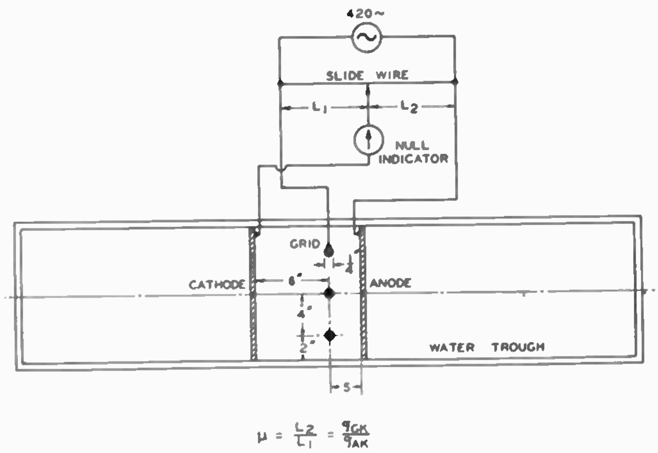

Fig. 5—The experimental setup for the determination of the amplification factor by means of the electrolytic trough.

To obtain proper experimental confirmation of the final formulas it was decided to simulate the theoretical conditions as closely as possible. Instead of resorting to measurements of experimental tubes whose structures merely approximated the assumed ones, measurements were made on a scale model of a plane structure in an electrolytic trough.[12] The field conditions in the trough are exactly analogous, by virtue of LaPlace's equation, to the field conditions in the assumed electrostatic case, the capacitances of the latter being replaced by the corresponding conductances in the trough. The model itself was constructed, as shown in Fig. 5, so that it artificially simulated the infinite structure of Fig. 1: this was experimentally possible because the perpendicular field lines midway between the grid wires could be replaced by insulators. To avoid end leakage, the electrolyte was confined within the model by means of insulating end plates. The cathode and anode were made movable, so that a number of observations could be conveniently made on the same model. Also, to avoid error caused by any possible bowing of the grid rods, the depth of the electrolyte was kept small. The actual connections and the details of the model are indicated in Fig. 5.

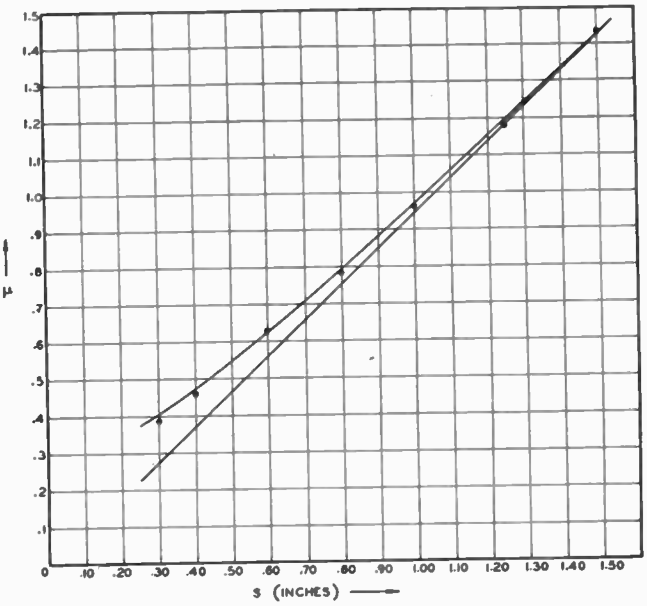

Fig. 6—A comparison of the theoretical curves and the experimental values. The lower curve is given by equation (11). The upper curve is given by equation (10). The points indicate the experimental values.

The theoretical and experimental results are compared in Fig. 6, in which the amplification factor is plotted as a function of the grid-anode spacing. A rather satisfactory experimental confirmation of the theoretical results is obtained in the region $s > 0.250$. In the region $s < 0.250$ the theoretical results do not apply because of the initial assumption that $s \gg \rho$.

Conclusions

Formulas have been developed for the amplification factor for plane and cylindrical triodes which are not based upon the assumption that the spacing between grid and anode must be greater than the distance between turns of the grid. The formula for the amplification factor is

$$\mu = \frac{2\pi n s - \ln \cosh 2\pi n \rho}{-\ln \tanh 2\pi n \rho + \ln (1 - \epsilon^{-4\pi n s} \cdot \cosh^2 2\pi n \rho)}$$

where 2ρ is the grid-wire diameter and n represents the grid turns per unit length. For plane structures s is the grid-anode spacing. For cylindrical structures in which

[11] See, for example, E. L. Chaffee "Theory of Thermionic Vacuum Tubes," McGraw-Hill Book Company, New York, N. Y., 1933, p. 173 et seq.

[12] Similar measurements have also been described by H. Barkhausen and J. von Bruck, "The distribution of the electric field in electron tubes, determined in the electrolytic trough," *Elek. Zeit.*, vol. 54, pp. 175–177; February, 1933.

grid and anode enclose the cathode, $s = r_G \cdot \ln(r_A/r_G)$. For cylindrical structures in which the cathode surrounds grid and anode, $s = r_G \cdot \ln(r_G/r_A)$.

The theory (and its experimental verification) indicates that the assumption regarding the grid-anode spacing which is implicit in existing formulas, is reasonable except when this spacing is quite small.

ACKNOWLEDGMENT

By way of acknowledgment, it is a real pleasure to thank Professor Ernst Weber, Research Professor of Electrical Engineering, Polytechnic Institute of Brooklyn, Brooklyn, N. Y., for the helpful criticisms which he so kindly supplied during the course of this work.

Some Simplified Methods of Determining the Optical Characteristics of Electron Lenses*

KARL SPANGENBERG†, ASSOCIATE, I.R.E., AND LESTER M. FIELD†, STUDENT, I.R.E.

Summary—*Some new methods of calculating lens characteristics are proposed which are relatively simpler and more accurate than those previously suggested. The first is an extension of Salinger's method of joined circular segments applied to paraxial rays in fields with a rotational symmetry. This requires as information only the axial potential and derivatives thereof. This method is the computational equivalent of the original graphical method. A second method makes use of the action function which is approximated from the potential function. Electron paths are taken as normal to the lines of constant action. A third method replaces the convergent and divergent parts of the usual lens with equivalent thin lenses and then calculates the focal lengths by means of combination formulas applied to the two thin lenses. All calculating methods are, however, sufficiently long in application and indeterminate in accuracy that experimental methods of finding lens characteristics are preferred.*

A new experimental method makes use of a demountable vacuum tube. Lens characteristics are determined from angular magnifications measured from the shadows cast by object screens illuminated by a point source of electrons. No moving screens are required nor is it necessary to generate rays parallel to the axis. By observing magnifications for all voltage ratios for two positions of the object screen enough data are available to determine the four cardinal focal distances for all voltage ratios. The results are considered more accurate and cover a greater range of voltage ratios than those reported by previous investigators. A graphical method has been developed for determining the spherical-aberration characteristics of the lens from the curvature of the object-screen images observed on the fluorescent screen.

Results are presented in a new and simplified form in addition to the standard form showing the variation of focal distances with voltage ratio. The new form gives associated object and image distances and corresponding magnification for any voltage ratio. The relation between the four useful variables is thus given on one chart for each lens. In effect this new form is a graphical presentation of the complete solution of the lens equation which shows clearly the relation between the four associated variables and gives quantitative results which can be applied directly. The new form reveals a number of properties of lens strength and magnification which have not been previously recognized.

I. Methods of Calculating Electron Paths

A. Previous Methods

A NUMBER of methods for calculating the characteristics of electron lenses from the potential field have been proposed. All of these calculate the principal rays of the lens, that is, the rays entering the lens parallel to the axis from the right and from the left, and then determine the location of the focal points and principal planes from these rays. When the four cardinal values of the lens, that is, the location of the two focal points and the two principal planes are known as a function of the voltage ratio, then the operation of the lens is completely determined.

The method of Klemperer and Wright[1] is the trigonometric ray-tracing method of physical optics applied to electrostatic lenses. The electrostatic field is broken up into a succession of thin lenses having a constant ratio of equivalent index of refraction for adjacent lenses. Formulas are given for calculating the effect of every refraction at a lens surface upon the angle of a ray and the point at which it crosses the axis. Lens surfaces are assumed to be spherical and their radius of curvature must be determined either graphically or from the axial potential. The method requires a large number of equivalent thin lenses, at least twenty for an accurate determination, and the results converge slowly as the number of segments taken is increased.

From purely mechanical considerations Maloff and Epstein[2] have proposed several methods based upon a step-by-step solution of the differential equation of the paraxial electron. The methods give the electron path as an exponential of the axial distance in any increment and join the paths in successive increments both in magnitude and slope. The methods are capable of good accuracy but the computations are lengthy. Information necessary for calculation is the axial potential and its derivatives.

Another approximate method based upon the differential equation of the paraxial electron has been proposed by Gans.[3] The axial potential is replaced by a number of straight-line segments which approximate it closely and the differential equation is then solved for the successive regions in which the potential is linear and the gradient is constant. At each boundary between segments there is a jump in the slope of the

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† Electrical Engineering Department, Stanford University, California.

[1] O. Klemperer and W. D. Wright, "Investigations of electron lenses," *Proc. Phys. Soc.*, vol. 51, part II, pp. 296–317; March, 1939.

[2] I. G. Maloff and D. W. Epstein, "Electron Optics in Television," McGraw-Hill Book Company, New York, N. Y., 1938, pp. 81–89.

[3] R. Gans, "Electron paths in electron optics," *Zeit. für Tech. Phys.*, vol. 18, pp. 41–48; February, 1937.

electron path because of the infinite value of the second derivative of potential at the junction of the straight-line segments. The final path as determined by this method consists of a number of curved segments of path connected together, giving a path which is continuous but which has discontinuities in slope at the corners of the segmented approximation to the axial distribution of potential. Such a path cannot represent accurately the true nature of the path within the lens but it can be used to obtain relations between initial and final values with considerable accuracy. The method is relatively easy to apply and gives fair accuracy for as few as six segments in the approximate axial potential curve.

B. Method of Joined Circular Segments

A new method which is the equivalent in simplicity and accuracy of any of the methods described above is based upon an extension of the general method of Salinger.[4] By considering the electron path to be a section of a circle at any point, it follows from equating the centrifugal force of the motion to the centripetal force of the field that the instantaneous radius of curvature is given by $R=2E/\overline{\nabla_n E})$ where E is the potential at the point in question and $\overline{\nabla_n E}$ is the component of the gradient of the field normal to the instantaneous direction of motion. This is a relation which holds for all fields and permits a graphical construction of an electron path to be made by joining segments of circles tangentially.

For application to the case of paraxial electrons in an electron gun a graphical method is not feasible because the radii of curvature are so long that they cannot readily be drawn. However, it is possible to make use of the well-known series expansion for potential along the axis to obtain some simple relations which will give a step-by-step location of the electron as it moves through the field. For electrons close to the axis and making a small angle with it the normal component of the gradient is

$$\overline{\nabla_n E} = \sqrt{(r^2 E_0'')^2 + (E_0'\theta)^2} \qquad (1)$$

in which the subscript zero indicates axial potential, the primes indicate derivatives in the axial direction, θ is the angle which the ray makes with the axis, and r is the radial distance from the axis to the electron path. If the radius of curvature R is determined from the potential E and the normal gradient as given in (1), and the electron be assumed to be swung through a circular arc of angle x such that the displacement Δs is about 1/40 of the distance through the lens, then the axial displacement Δz equals the displacement Δs to within 0.1 per cent. Thus

$$\Delta z = Rx \qquad (2)$$

[4] H. Salinger, "Tracing electron paths in electric fields," *Electronics*, vol. 10, pp. 50–54; October, 1937.

and the radial displacement is given by

$$\Delta r = Rx\left(\theta + \frac{x}{2}\right). \qquad (3)$$

Initial and final values of r and θ for any increment are obviously given by

$$r_f = r_i - \Delta r \qquad (4)$$

$$\theta_f = \theta_f - x \qquad (5)$$

in which the subscripts f and i represent final and initial values.

By means of the above formulas the path through a lens may readily be calculated. The method is quite accurate because the path is made up of short segments of arcs of circles which join tangentially.

C. Action Function Method of Calculating Electron Paths

This method is based upon the principle that electrons will move in paths which are normal to surfaces of constant action where the action a is defined as the integral of the product of the square root of potential and distance

$$a = \int \sqrt{E}\, ds \qquad (6)$$

and is given in general by

$$(\overline{\nabla a})^2 = E \qquad (7)$$

which may be written as

$$\left(\frac{\partial a}{\partial r}\right)^2 + \left(\frac{\partial a}{\partial z}\right)^2 = E \qquad (8)$$

in cylindrical co-ordinates.

The method given here approximates the action function from the known potential and then determines the electron paths through the action field. This is done by writing action as an even-powered series in r because of symmetry

$$a = a_0 + a_2 r^2 + a_4 r^4 + \cdots. \qquad (9)$$

where the a's are functions of axial distance. Taking the gradient of this, squaring, and then equating term for term to the expression for potential gives

$$a_0'^2 = E_0 \qquad (10)$$

and

$$4a_2^2 + 2a_0'a_2' = -E_0''/4 \qquad (11)$$

as relations determining the first two coefficients. The last differential equation cannot readily be solved exactly, but a solution over a small interval in which the coefficients may be considered to remain constant gives

$$a_{2R} = \frac{a_{2L} - \dfrac{E_0''z}{8\sqrt{E_0}}}{1 + \dfrac{2a_{2L}z}{\sqrt{E_0}}} \qquad (12)$$

where a_{2R} is the value of a_2 at the right of the interval and a_{2L} is the value at the left. By means of the above expression it is possible to calculate the value of a_2 as a function of z. When this is known, enough information is available to determine the path of an electron entering the lens parallel to the axis.

At any point in the lens the slope of the electron path M is given by the ratio of the r to the z component of the gradient of the action function. For electrons close to the axis this is

$$M = \frac{2a_2 r}{\sqrt{E_0}} \tag{13}$$

from which

$$\Delta r = (2a_2 r/\sqrt{E_0})\Delta z \tag{14}$$

so that

$$\ln_e \frac{r_2}{r_1} = 2\int_{z_1}^{z_2} \frac{a_2}{\sqrt{E_0}} dz \tag{15}$$

in which r_2 and r_1 are final and initial radial distances, respectively, and z_2 and z_1 are the final and initial axial distances between which the calculations are made. The distances z_1 and z_2 are the points at the ends of the gun field at which the derivatives of potential are inconsiderable. This integral tells at what distance r_2 from the axis an electron will emerge from the lens if it enters at a distance r_1 from the axis.

The above integral is readily evaluated numerically. When the initial and final radial distances as given by the above integral are known and the initial and final slopes are also known the focal distance and location of the principal plane are easily determined. The principal plane is located by the intersection of the straight-line-path portions through the initial and final points drawn with the initial and final slopes, respectively. The focal distance is the reciprocal of the final slope multiplied by the final radial distance.

The method outlined above requires, as data from which to work, only the axial distribution of potential. The advantages of the method are that the numerical processes involved are relatively simple to apply and that the actual numerical work involved is less than that involved in any of the other methods tested. Essentially there is only one step-by-step formula to apply and the results of this operation are integrated through the lens structure. The only disadvantage of the method is that it is not valid in cases in which the electron crosses the axis within the lens structure. This is not a serious limitation because most of the practical lenses focus well beyond the last electrode.

D. Method of Equivalent Thin Lenses

The usual electron lens has a convergent behavior on the low-potential side and a divergent behavior on the high-potential side, the net lens behavior being convergent. The behavior is convergent when the second derivative of the axial potential is positive and divergent when the second derivative is negative. It is reasonable, therefore, to consider that the lens is made up of two thin lenses, a convergent lens followed by a divergent lens.[5] If the strength and location of these lenses are known the cardinal points of the equivalent thick lens may be determined.

The focal lengths of the convergent lens as shown in Fig. 1 are given by

$$\frac{1}{F} = \int_{z_1}^{z_m} \frac{E''}{2\sqrt{2E}} dz \tag{16}$$

and

$$f_1 = F\sqrt{2E_1} \tag{17}$$

$$f_2 = -f_1\sqrt{E_m/E_1} \tag{18}$$

where F is a focal term from which the focal lengths are derived, E_1 is the lowest potential on the lens axis, E_m is the potential at the point at which the second derivative assumes a value of zero, changing sign. The integration of (16) is carried over the region in which the second derivative is positive.

Similarly the focal distances for the divergent component of the lens are given by

$$\frac{1}{F'} = \int_{z_m}^{z_2} \frac{E''dz}{2\sqrt{2E}} \tag{19}$$

and

$$f_1' = F'\sqrt{2E_m} \tag{20}$$

$$f_2' = -f_1'\sqrt{E_2/E_m} \tag{21}$$

where E_2 is the highest value of potential reached on the axis on passing through the lens.

When the focal lengths of the convergent and divergent components of the lens are known the focal characteristics of the entire lens are readily determined, this being a simple problem in the combination of lenses. When the distance between the second focal point of the convergent component and the first focal point of the divergent component is d_{12} then the focal lengths of the entire lens are[6]

$$f_1'' = -f_1f_2/d_{12} \tag{22}$$

$$f_2'' = f_1'f_2'/d_{12}. \tag{23}$$

The location of the first principal plane measured from the first focal point of the convergent component is

$$x_1 = f_1f_2/d_{12} + f_1'' \tag{24}$$

and the location of the second principal plane as measured from the second focal point of the divergent component of the lens is

$$x_2 - f_1'f_2'/d_{12} + f_2''. \tag{25}$$

[5] L. M. Myers, "Electron Optics," D. Van Nostrand Company, New York, N. Y., 1939, p. 131.

[6] S. Rosin and O. H. Clark, "Combinations of optical systems," *Jour. Opt. Soc. Amer.*, vol. 31, pp. 198–201; March, 1941.

The method is extremely rapid in application. Some uncertainty exists as to the exact location of the thin-lens components. The location of the lens components is best taken as being at the center of the area repre-

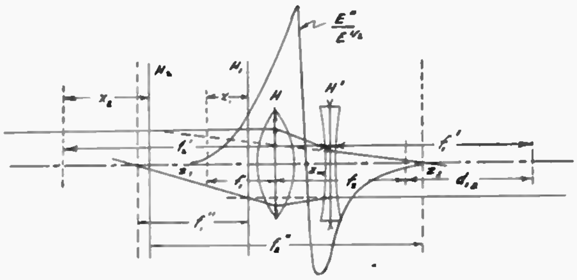

Fig. 1—Thin-lens equivalent of a thick lens: nomenclature.

sented by the integrals of (16) and (19), as shown in Fig. 1.

All of the methods referred to above are subject to some error which is difficult to determine except by more detailed and extensive calculations. In general it may be said that although the methods are satisfactory, experimental methods are preferable, and usually more dependable.

II. Experimental Method

A. Method of Determining Focusing Characteristics

The experimental method used in determining the lens characteristics is based upon observed magnifications of measuring grids placed before and after the lens structure.

A grid of closely spaced parallel wires (for measurement purposes only and not for control of the beams) is placed in the fore part of the lens. This grid casts a shadow upon a fluorescent screen following the lens. In order to avoid the need of a tube having parts which can be moved relative to one another while in a vacuum, another measuring grid is used between the end of the gun and the fluorescent screen. This arrangement is shown schematically in Fig. 2 in which the measuring grid in the fore part of the lens is indicated by a vertical row of crosses. With this arrangement of measuring grids, it is necessary to make observations on the magnifications of two grids, as the voltage ratio of the main lens electrodes is varied, for each of two distances of the lens from a point source of electrons. Hence two complete runs must be made to obtain the data from which the complete lens characteristics can be measured.

The details of the mathematical relations involved can be seen from Fig. 2. The cathode-lens structure gave the effect of a point source of electrons at a known point near the cathode. The location of this point and the constancy of its position under varying conditions of lens voltage ratio were determined by placing two measuring grids in the fore part of the lens and observing the ratio of their magnifications. The constancy of the ratio of magnifications indicated that the location of the point source changed very little with lens voltage ratio and also over the normal range of control-grid voltages used. The location of the point source was very nearly at the control-grid aperture. When these facts were once determined from a

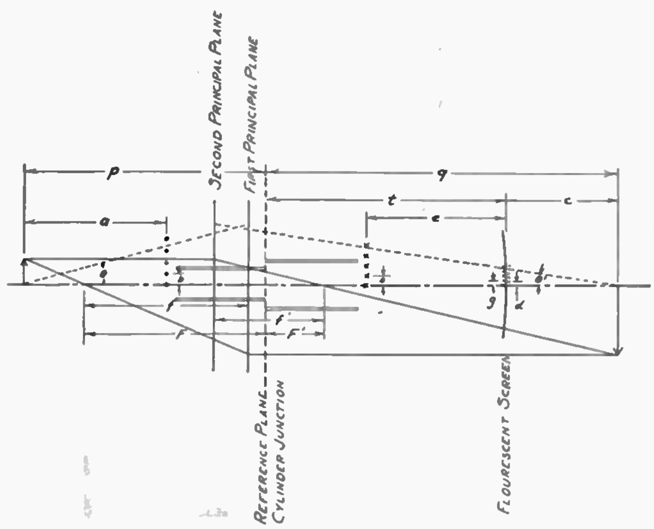

Fig. 2—Experimental determination of lens characteristics.

test run it was no longer necessary to use two measuring grids in the fore part of the lens.

With the point source of electrons available the following general method is applied: The angular magnification of the bundle of rays is determined from screen patterns obtained on the fluorescent screen, such as that shown in Fig. 3. Here the lines in one direction are the shadows of one measuring grid and the lines in the other direction are the shadow of the other measuring grid. When the angular magnification is known then for any given voltage ratio the lateral magnification can be determined from Lagrange's law, which states that the product of the internal magnification and the angular magnification is equal to the square root of the ratio of the final and initial potentials.[7] Image distances at each of the two object distances used are given for various voltage ratios from magnifications of the second grid alone. The object distances are known from physical measurements on the gun assembly. When lateral magnification, object distance, and image distance are known as a function of voltage ratio for two different values of the object distance then the cardinal quantities f, f', F, and F' of the lens may be calculated readily.

The method by which this calculation is made will be briefly indicated. Object and image distances can be expressed in terms of the lateral magnification and focal distances as

$$p = -f/m + F \tag{26}$$

$$q = -mf' + F'. \tag{27}$$

[7] O. Klemperer, "Electron Optics," Cambridge University Press, New York, N. Y., 1939, p. 12.

These two equations involve the four quantities f, f', F, and F' as unknowns. In order to determine them it is necessary to know two sets of associated values of p, q, and m for the same voltage ratio. When subscripts 1 and 2 are used to indicate values of p, q, and m for two different values of p at a given voltage ratio, then there may be obtained from the above relations the following expressions for the cardinal focal distances

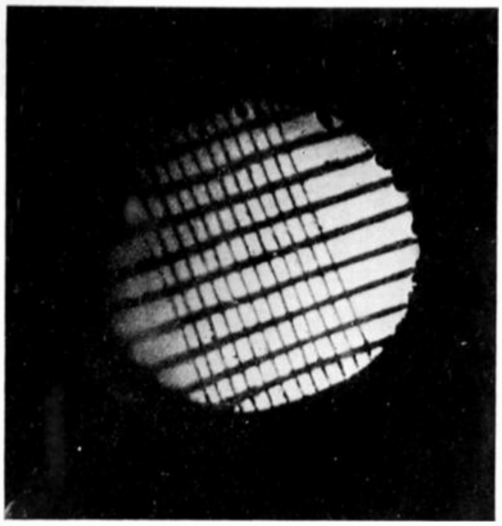

Fig. 3—Shadows of measuring grids on fluorescent screen.

$$f = \frac{p_1 - p_2}{\frac{1}{m_1} - \frac{1}{m_2}} \tag{28}$$

$$f' = \frac{q_1 - q_2}{m_1 - m_2} \tag{29}$$

$$F = \frac{p_1 m_1 - p_2 m_2}{m_1 - m_2} \tag{30}$$

$$F' = \left(\frac{q_1}{m_1} - \frac{q_2}{m_2}\right) \Big/ \left(\frac{1}{m_1} - \frac{1}{m_2}\right). \tag{31}$$

Up to this point the relations are the same as those used by Maloff and Epstein.[2] It is now only necessary to show how the lateral magnification may be deduced from the screen patterns to complete the collection of necessary relations. Referring to Fig. 2 it is seen that the angular magnification is given by

$$m_a = \theta'/\theta. \tag{32}$$

For small angles such as are encountered in the gun the angular magnification in terms of the dimensions is given very closely by

$$\theta'/\theta = ad/bc \tag{33}$$

in which c is the distance beyond the fluorescent screen to the point at which the ray would focus. This distance is determined from the spacings of the grid images as follows:

For focus beyond fluorescent screen

$$c = \frac{e}{1 - \frac{s}{g}} \tag{34}$$

For focus between second measuring grid (crosses) and fluorescent screen

$$-c = \frac{e}{1 + \frac{s}{g}} \tag{35}$$

when the angular magnification is known, then the lateral magnification may be calculated from Lagrange's law as previously indicated.

With the above relations the cardinal quantities are readily calculated. In practice this is most easily done by plotting curves of the various quantities involved against voltage ratio because the same voltage-ratio observations may not have been taken on one run as on the other. There is a small hole in each curve at the point where the beam focus is at the fluorescent screen because the image becomes so small here that it is not possible to measure the spacings of the wires on the images. However, there is no trouble in drawing smooth and continuous curves through these holes if the data are taken with care. It is convenient to plot curves of reciprocal magnification rather than of magnification because the latter becomes infinite when the focus is on the fluorescent screen, whereas the reciprocal magnification is continuous through zero at this point.

B. Determination of Aberration Characteristics

Of all the types of aberrations encountered in electrostatic lenses, the most serious is spherical aberration. This is always present to some degree and is very difficult to reduce and nearly impossible to eliminate completely.

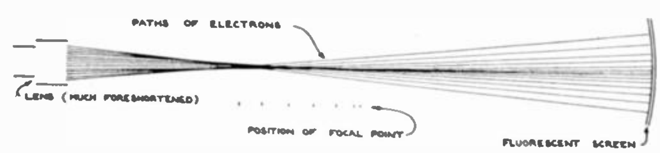

Fig. 4—Graphical method of determining spherical aberration: 1.5 to 1 cylinder lens, $E_2/E_1 = 4.5$.

The screen patterns from which the focusing characteristics were obtained can also be used to determine the spherical aberration. The intersections of the grid-wire images tell how far from the axis any ray, starting off of the axis, will fall in the image. With this information it is possible to determine the spherical aberration by a graphical method. A ray diagram such as that shown in Fig. 4 can be drawn connecting points on the image with corresponding points of emergence at the lens. From this diagram it is possible to determine the variation in the focal point with the original radial distance of the rays. It is also possible to determine the minimum spot for any lens aperture.

III. Results

This paper is concerned primarily with methods and there will be given here only samples of the results as obtained by the methods described.

A. Optical Constants

The focusing characteristics of the lenses tested may be presented in what has become a conventional

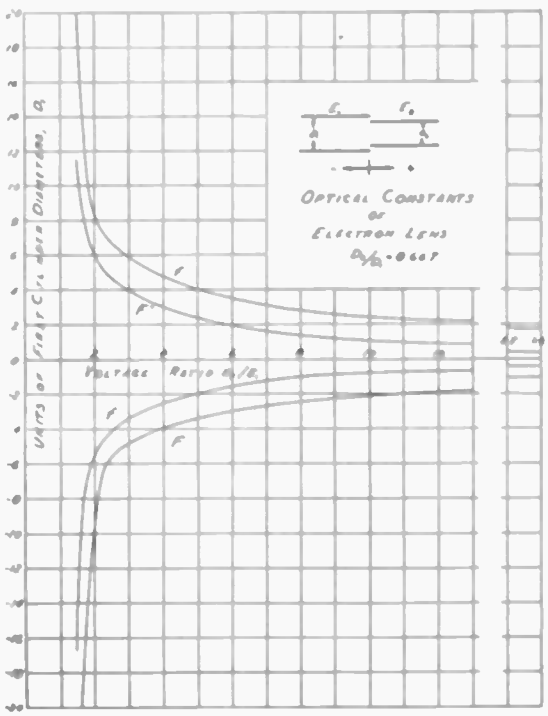

Fig. 5—Optical constants at a two-diameter cylinder lens, $D_2/D_1 = 0.667$.

form. In this form the focal distances and the distances from a reference point in the lens to the focal points are plotted as a function of the voltage ratio. Such a representation is given in Fig. 5 in which the reference point is the cylinder junction. It is seen that the characteristics are readily obtained for an extremely wide range of voltage ratios, roughly 25 to 1.5, or about three times any previously reported.

B. Object-Image Distance Curves

The focal characteristics were also presented in a new form which is believed to have many advantages over the conventional representation. From (26) and (27) it is seen that at any given voltage ratio the object and image distances are parametric with magnification in terms of the focal distances. Since the focal distances themselves are quantities which are used in determining the answer to any lens problem but which do not appear in the answer it seems logical to seek a representation in which these quantities do not appear. Such a representation is shown in Fig. 6. This representation will be referred to as the object-image—distance curves of the lens. The curves give immediately the image distance corresponding to any object distance at a given voltage ratio and show also the

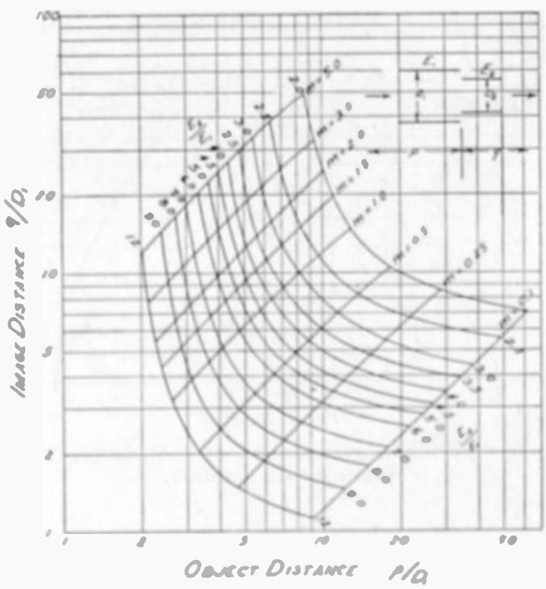

Fig. 6—Object-image—distance curves of a two-diameter cylinder lens, $D_2/D_1 = 0.667$.

corresponding magnification. Essentially this is a graphical representation of the solution of all possible problems associated with the lens.

The object-image—distance curves have several important merits. They give immediately quantitative relations between the controllable variables. They

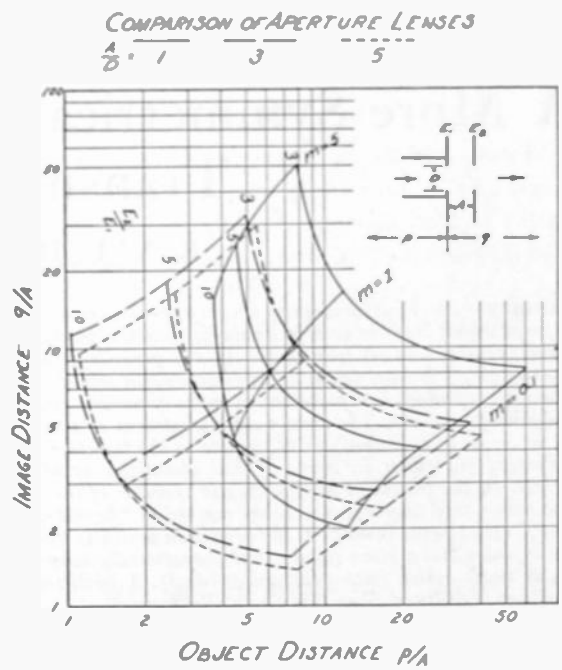

Fig. 7—Comparison of aperture lenses.

make possible a design procedure which is direct and does not depend upon any trial-and-error calculations. They show very clearly the effect of changes in voltage and physical structure. They reveal some universal lens properties which may not have been noted previously. They make possible a quick and comprehensive comparison of the characteristics of different lenses or of lenses of the same type with different dimensions. Such a comparison is shown in Fig. 7 which shows the effect of changing the ratio of aperture diameter to aperture spacing in an aperture lens. In this figure, object distance and image distance are measured from the first aperture, A is the aperture diameter, and D is the axial distance between apertures.

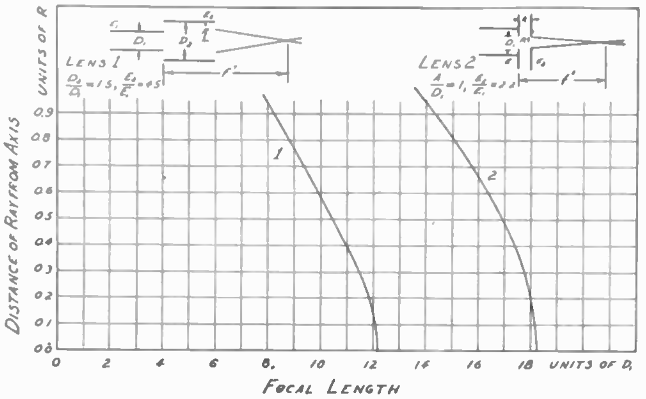

Fig. 8—Spherical aberration of lenses: Variation of focal distance with aperture.

C. Aberration Characteristics

Some typical aberration curves as determined graphically from the screen patterns are shown in Fig. 8. These show the decrease in focal distance as the ray separation from the axis is increased. Such curves are about the same for all lenses. These curves are nearly universal in that the reduction in focal distance is approximately a percentage function of the focal distance itself. A sample curve showing the spread of spot produced by aberration is shown in Fig. 9. This is also nearly a universal curve.

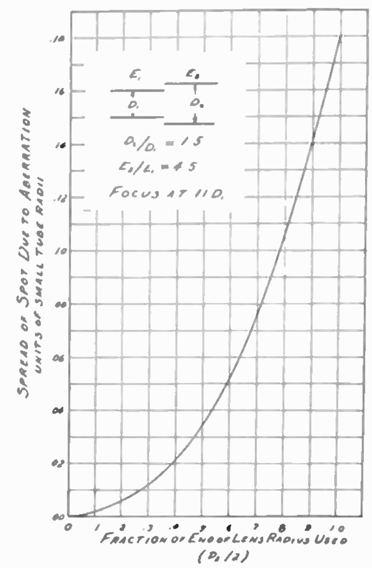
Fig. 9—Aberration curve: Variation of minimum spot size with aperture.

IV. Conclusions

The methods proposed here are improvements on previously proposed methods from the standpoint of simplicity, ease of execution, and accuracy of results. The new representation of lens characteristics tells the whole story of the lens at a glance. The experimental method permits simultaneous determination of focal characteristics and aberration properties.

A More Symmetrical Fourier Analysis Applied to Transmission Problems*

R. V. L. HARTLEY†, FELLOW, I.R.E.

Summary—The Fourier identity is here expressed in a more symmetrical form which leads to certain analogies between the function of the original variable and its transform. Also it permits a function of time, for example, to be analyzed into two independent sets of sinusoidal components, one of which is represented in terms of positive frequencies, and the other of negative. The steady-state treatment of transmission problems in terms of this analysis is similar to the familiar ones and may be carried out either in terms of real quantities or of complex exponentials. In the transient treatment, use is made of the analogies referred to above, and their relation to the method of "paired echoes" is discussed. A restatement is made of the condition which is known to be necessary in order that a given steady-state characteristic may represent a passive or stable active system (actual or ideal). A particular necessary condition is deduced from this as an illustration.

A NEW formulation of the Fourier integral identity is derived and compared with the familiar ones and its properties are discussed. The application of the resulting analysis to transmission problems, steady-state and transient, follows.

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Mathematical Relations

Comparison of Alternative Forms

The Fourier integral identity may be written in the form

$$f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \operatorname{cas} \omega t, \qquad (1)$$

$$\psi(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \operatorname{cas} \omega t, \qquad (2)$$

where

$$\operatorname{cas} x = \cos x + \sin x,$$

is an abbreviation for cosine and sine. This is to be compared, from the standpoint of symmetry, with the more usual forms,

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty} d\alpha\, f(\alpha) \cos \omega(t - \alpha), \qquad (3)$$

or its equivalent,

$$f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega [A(\omega) \cos \omega t + B(\omega) \sin \omega t], \quad (4)$$

$$A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \cos \omega t, \quad (5)$$

$$B(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \sin \omega t, \quad (6)$$

and

$$f(t) = \frac{\ }{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, C(\omega) \exp (i\omega t), \quad (7)$$

$$C(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \exp (- i\omega t).$$

To derive (1) and (2), we write

$$\psi(\omega) = A(\omega) + B(\omega).$$

Then (2) follows from (5) and (6). Since $A(\omega)$ is an even function of ω and $B(\omega)$, an odd,

$$0 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega [A(\omega) \sin \omega t + B(\omega) \cos \omega t].$$

If we add this to the right member of (4) it reduces to (1).

Equations (3) to (6) are similar to (1) and (2) in that, when $f(t)$ is real, all the other quantities are also real. They differ in that the variables t and ω enter the equations symmetrically in the latter and not in the former. Equations (7) and (8) resemble (1) and (2) more closely in form. They differ in that the symmetry of (7) and (8) is marred by the difference in sign of the two exponents. Also when $f(t)$ is real, $C(\omega)$ is complex, and vice versa.

We may then set up the following expressions for the even and odd components of $f(t)$ and $\psi(\omega)$:

$$\begin{aligned} f_e(t) &= \tfrac{1}{2}[f(t) + f(-t)], \quad (t > 0), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi_e(\omega) \cos \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \cos \omega t, \end{aligned} \quad (9)$$

$$\begin{aligned} f_0(t) &= \tfrac{1}{2}[f(t) - f(-t)], \quad (t > 0), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi_0(\omega) \sin \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \sin \omega t, \end{aligned} \quad (10)$$

$$\begin{aligned} \psi_e(\omega) &= \tfrac{1}{2}[\psi(\omega) + \psi(-\omega)], \quad (\omega > 0), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f_e(t) \cos \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \cos \omega t, \end{aligned} \quad (11)$$

$$\begin{aligned} \psi_0(\omega) &= \tfrac{1}{2}[\psi(\omega) - \psi(-\omega)], \quad (\omega > 0), \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f_0(t) \sin \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \sin \omega t. \end{aligned} \quad (12)$$

Equations (3) to (6) differ from (1) and (2) also with respect to negative values of ω. Since the first integrand in (3) is an even function of ω, the component of $f(t)$ corresponding to integration over negative values of ω is identical with that over positive. If then we regard (3) as an analysis of $f(t)$ into sinusoidal components, we may say that one half of the value of the function is represented by components for which ω is positive and one half by those for which it is negative. In (1) however we note that

$$\begin{aligned} \operatorname{cas} (-\omega t) &= \sqrt{2} \cos \left(-\omega t - \frac{\pi}{4}\right), \\ &= \sqrt{2} \cos \left(\omega t + \frac{\pi}{4}\right), \end{aligned} \quad (13)$$

and

$$\operatorname{cas} (\omega t) = \sqrt{2} \sin \left(\omega t + \frac{\pi}{4}\right).$$

We may, therefore, say that a pair of equal positive and negative values of ω in (1) correspond to a pair of components which vary as the sine and cosine of the same angle. Thus (5) and (6) represent a resolution into sine and cosine components each of which is further resolved into components corresponding to ω and $-\omega$, whereas in (1) these two resolutions are accomplished together.

This difference gives rise to a corresponding one in the functions of ω by which a given function of t may be represented. Equation (4) suggests that use is made of two functions, $A(\omega)$ and $B(\omega)$, each defined for both positive and negative values of ω. However, in view of their evenness and oddness, they are completely determined by their values over either range alone. In (1), on the other hand, we have a single function $\psi(\omega)$, the value of which for $-\omega$ is independent of that for ω; and so it must be defined over the entire range of ω.

Analogous Functions of Time and Frequency

The symmetry of (1) and (2) makes possible some analogies between functions of t and ω. The discussion of these may be simplified, without loss of generality, if we identify t with time and ω with angular frequency. It will be further simplified if we replace ω by 2π times the cyclic frequency ν, writing (1) and (2) as

$$f(t) = \int_{-\infty}^{\infty} d\nu\, \Phi(\nu) \operatorname{cas} 2\pi\nu t, \quad (14)$$

$$\Phi(\nu) = \int_{-\infty}^{\infty} dt\, f(t) \operatorname{cas} 2\pi\nu t, \quad (15)$$

where

$$\Phi(\nu) = \sqrt{2\pi}\, \psi(2\pi\nu) = \sqrt{2\pi}\, \psi(\omega).$$

We have interpreted equations such as (1) and (4) as representing a resolution of $f(t)$ into sinusoidal components. We may also interpret (2), (5), and (6) as representing the resolution of their respective functions of frequency into components which vary sinusoidally with frequency. For example in (5) (as modified), the component corresponding to a particular instant t_1 has the form $dt\, f(t_1) \cos 2\pi t_1 \nu$, as shown in Fig. 1. This value lens properties which may not have been noted previously. They make possible a quick and comprehensive comparison of the characteristics of different lenses or of lenses of the same type with different dimensions. Such a comparison is shown in Fig. 7 which shows the effect of changing the ratio of aperture diameter to aperture spacing in an aperture lens. In this figure, object distance and image distance are measured from the first aperture, A is the aperture diameter, and D is the axial distance between apertures.

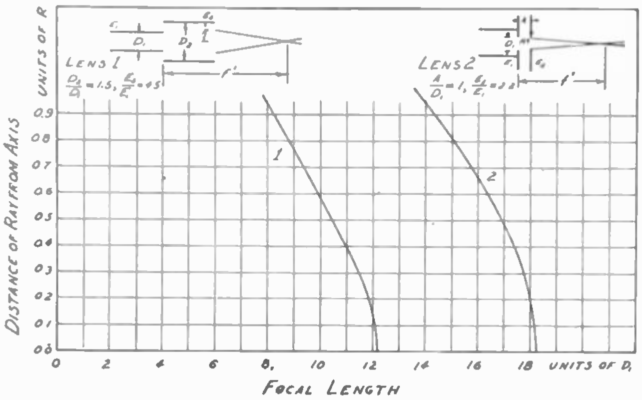

Fig. 8—Spherical aberration of lenses: Variation of focal distance with aperture.

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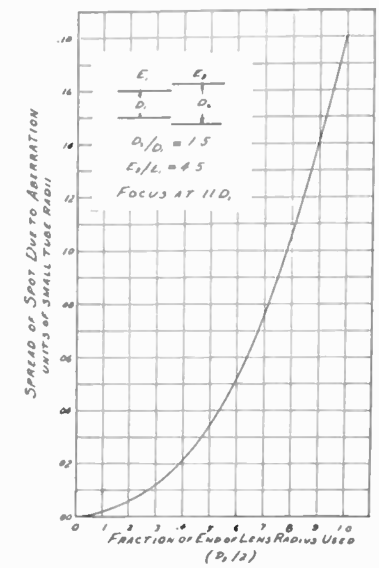

Fig. 9—Aberration curve: Variation of minimum spot size with aperture.

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A More Symmetrical Fourier Analysis Applied to Transmission Problems*

R. V. L. HARTLEY†, FELLOW, I.R.E.

Summary—The Fourier identity is here expressed in a more symmetrical form which leads to certain analogies between the function of the original variable and its transform. Also it permits a function of time, for example, to be analyzed into two independent sets of sinusoidal components, one of which is represented in terms of positive frequencies, and the other of negative. The steady-state treatment of transmission problems in terms of this analysis is similar to the familiar ones and may be carried out either in terms of real quantities or of complex exponentials. In the transient treatment, use is made of the analogies referred to above, and their relation to the method of "paired echoes" is discussed. A restatement is made of the condition which is known to be necessary in order that a given steady-state characteristic may represent a passive or stable active system (actual or ideal). A particular necessary condition is deduced from this as an illustration.

A NEW formulation of the Fourier integral identity is derived and compared with the familiar ones and its properties are discussed. The application of the resulting analysis to transmission problems, steady-state and transient, follows.

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Mathematical Relations

Comparison of Alternative Forms

The Fourier integral identity may be written in the form

$$f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \operatorname{cas} \omega t, \tag{1}$$

$$\psi(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \operatorname{cas} \omega t, \tag{2}$$

where

$$\operatorname{cas} x = \cos x + \sin x,$$

is an abbreviation for cosine and sine. This is to be compared, from the standpoint of symmetry, with the more usual forms,

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty} d\alpha\, f(\alpha) \cos \omega(t - \alpha), \tag{3}$$

or its equivalent,

$$f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega [A(\omega) \cos \omega t + B(\omega) \sin \omega t], \quad (4)$$

$$A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \cos \omega t, \quad (5)$$

$$B(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \sin \omega t, \quad (6)$$

and

$$f(t) = \frac{}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, C(\omega) \exp (i\omega t), \quad (7)$$

$$C(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \exp (- i\omega t).$$

To derive (1) and (2), we write

$$\psi(\omega) = A(\omega) + B(\omega).$$

Then (2) follows from (5) and (6). Since $A(\omega)$ is an even function of ω and $B(\omega)$, an odd,

$$0 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega [A(\omega) \sin \omega t + B(\omega) \cos \omega t].$$

If we add this to the right member of (4) it reduces to (1).

Equations (3) to (6) are similar to (1) and (2) in that, when $f(t)$ is real, all the other quantities are also real. They differ in that the variables t and ω enter the equations symmetrically in the latter and not in the former. Equations (7) and (8) resemble (1) and (2) more closely in form. They differ in that the symmetry of (7) and (8) is marred by the difference in sign of the two exponents. Also when $f(t)$ is real, $C(\omega)$ is complex, and vice versa.

We may then set up the following expressions for the even and odd components of $f(t)$ and $\psi(\omega)$:

$$f_e(t) = \tfrac{1}{2}[f(t) + f(-t)], \quad (t > 0),$$
$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi_e(\omega) \cos \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \cos \omega t, \quad (9)$$

$$f_0(t) = \tfrac{1}{2}[f(t) - f(-t)], \quad (t > 0),$$
$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi_0(\omega) \sin \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \sin \omega t, \quad (10)$$

$$\psi_e(\omega) = \tfrac{1}{2}[\psi(\omega) + \psi(-\omega)], \quad (\omega > 0),$$
$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f_e(t) \cos \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \cos \omega t, \quad (11)$$

$$\psi_0(\omega) = \tfrac{1}{2}[\psi(\omega) - \psi(-\omega)], \quad (\omega > 0),$$
$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f_0(t) \sin \omega t = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(t) \sin \omega t. \quad (12)$$

Equations (3) to (6) differ from (1) and (2) also with respect to negative values of ω. Since the first integrand in (3) is an even function of ω, the component of $f(t)$ corresponding to integration over negative values of ω is identical with that over positive. If then we regard (3) as an analysis of $f(t)$ into sinusoidal components, we may say that one half of the value of the function is represented by components for which ω is positive and one half by those for which it is negative. In (1) however we note that

$$\begin{aligned} \text{cas}(-\omega t) &= \sqrt{2} \cos \left(-\omega t - \frac{\pi}{4} \right), \\ &= \sqrt{2} \cos \left(\omega t + \frac{\pi}{4} \right), \end{aligned} \quad (13)$$

and

$$\text{cas}(\omega t) = \sqrt{2} \sin \left(\omega t + \frac{\pi}{4} \right).$$

We may, therefore, say that a pair of equal positive and negative values of ω in (1) correspond to a pair of components which vary as the sine and cosine of the same angle. Thus (5) and (6) represent a resolution into sine and cosine components each of which is further resolved into components corresponding to ω and $-\omega$, whereas in (1) these two resolutions are accomplished together.

This difference gives rise to a corresponding one in the functions of ω by which a given function of t may be represented. Equation (4) suggests that use is made of two functions, $A(\omega)$ and $B(\omega)$, each defined for both positive and negative values of ω. However, in view of their evenness and oddness, they are completely determined by their values over either range alone. In (1), on the other hand, we have a single function $\psi(\omega)$, the value of which for $-\omega$ is independent of that for ω; and so it must be defined over the entire range of ω.

Analogous Functions of Time and Frequency

The symmetry of (1) and (2) makes possible some analogies between functions of t and ω. The discussion of these may be simplified, without loss of generality, if we identify t with time and ω with angular frequency. It will be further simplified if we replace ω by 2π times the cyclic frequency ν, writing (1) and (2) as

$$f(t) = \int_{-\infty}^{\infty} d\nu\, \Phi(\nu) \,\text{cas}\, 2\pi\nu t, \quad (14)$$

$$\Phi(\nu) = \int_{-\infty}^{\infty} dt\, f(t) \,\text{cas}\, 2\pi\nu t, \quad (15)$$

where

$$\Phi(\nu) = \sqrt{2\pi}\, \psi(2\pi\nu) = \sqrt{2\pi}\, \psi(\omega).$$

We have interpreted equations such as (1) and (4) as representing a resolution of $f(t)$ into sinusoidal components. We may also interpret (2), (5), and (6) as representing the resolution of their respective functions of frequency into components which vary sinusoidally with frequency. For example in (5) (as modified), the component corresponding to a particular instant t_1 has the form $dt\, f(t_1) \cos 2\pi t_1 \nu$, as shown in Fig. 1. This value of t determines the amplitude, $dt\ f(t_1)$, and is itself equal to the number of cycles per unit frequency range. Its reciprocal $1/t_1$ is the frequency range occupied by one cycle of the sinusoid. This role of t_1 is the analog of that of the frequency ν_1 of a single frequency component of $f(t)$ as given by (4). It seems logical

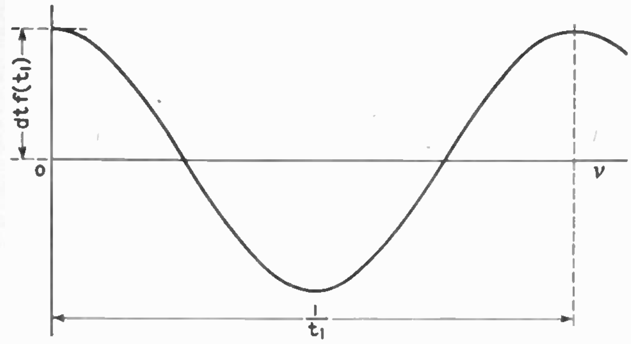

Fig. 1

therefore to refer to one of these sinusoids on the frequency scale as a single instant component of $\phi(\nu)$ and to the corresponding instant as the instant of the component.

The resolution of $\phi(\nu)$ may follow either the familiar method, as in the foregoing example, or the alternative one described above. It would seem that our intuitions would be best satisfied by that resolution in which the values of $f(t_1)$ and $f(-t_1)$ best maintain their separate identities in the components of $\phi(\nu)$. From this standpoint the newer analysis is preferable. In (2) the components corresponding to instants t_1 and $-t_1$ constitute a pair of sine and cosine components as in Fig. 2. The corresponding pair in (5) and (6) are found by compounding the components of instants t_1 and $-t_1$ for the sine and cosine separately. The amplitudes of the resultants are proportional to $f(t_1)-f(-t_1)$ and $f(t_1)+f(-t_1)$, respectively. Here the identities of the positive and negative instants are pretty well lost.

If we apply the Fourier analysis to a function of time of the form

$$f_1(t) = A \text{ cas } 2\pi\nu_1 t,$$

the resulting function $\Phi_1(\nu)$ is zero except at ν_1 where it has an infinite value such that

$$\Phi_1(\nu_1)d\nu = A.$$

Thus the transform of a cas function of time of finite amplitude is a finite pulse of infinite height and infinitesimal length. When the function $f(t)$ comprises an infinitude of cas components, as indicated in (14), the amplitude of each component is infinitesimally small. For example, the component of frequency ν_1, say, has an amplitude of $\Phi(\nu_1)d\nu$. The transform of this component then is an infinitesimal pulse of finite height $\Phi(\nu_1)$, and length $d\nu$ located at ν_1. Suppose that we transform in the same way all of the other cas components of $f(t)$. The result is a succession of pulses spaced at intervals of $d\nu$, each of a height equal to the corresponding value of $\Phi(\nu)$. The same succession of pulses would result from the well-known resolution of $\Phi(\nu)$ into a succession of infinitesimal pulses of length $d\nu$, each of a finite height, given by the average value of $\Phi(\nu)$ over the particular interval $d\nu$. Also, from sym-

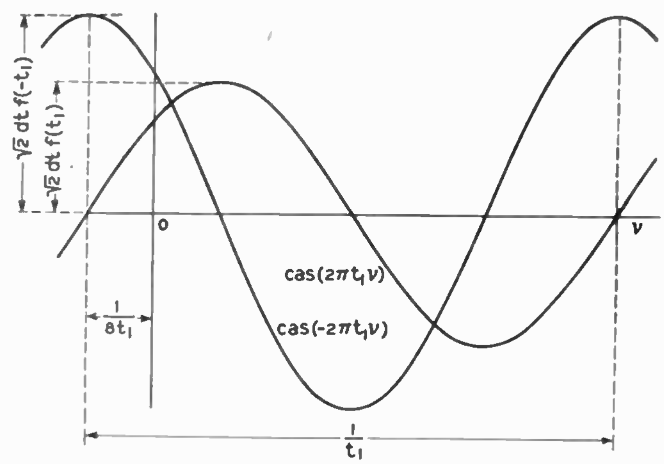

Fig. 2

metry, if we analyze $f(t)$ into pulses $f(t)dt$, and transform these individually we get the same sinusoidal components of $\Phi(\nu)$ that we do if we transform $f(t)$ into $\Phi(\nu)$ and analyze it into sinusoidal components. In general, the amplitude of a sinusoidal component of a function is equal to the magnitude of the corresponding pulse of its transform.

Close approximations to sinusoidal components of a time function are in common use. More rarely experimental use is made of an approximate pulse in the form of a current of finite duration, the magnitude of which is made to vary inversely as the duration as the latter is decreased. The transform of such a wave approximates to a sinusoidal Φ function of finite amplitude. If also the pulse is an even function of time and occurs at the instant zero, the corresponding Φ function approaches a uniform finite value for all frequencies.

By analogy with the Fourier series, it is obvious that $\Phi(\nu)$ can be represented over a limited frequency range, by an infinite series of finite, single-instant cas components which are finitely spaced. These correspond to a series of equally spaced finite pulses on the time scale, each of infinite height and infinitesimal duration. The finite time interval separating the pulses is the reciprocal of the range of frequency over which the function of frequency is to be represented. These pulses will be distributed over the entire time scale. If the Fourier integral analysis be applied to this sequence of pulses, the resulting function of frequency will repeat itself on the frequency scale, the interval of repetition being equal to that over which the original function was to be represented.

As an example of this relationship may be mentioned a property of telegraph signals derived by

Nyquist.[1] He assumed that in a synchronous telegraph system employing any number of elements, the duration of each signal pulse is made small compared with the signal interval. He then showed that the spectrum of the over-all disturbance repeats itself on the frequency scale, except for a factor dependent on the form of the pulse. Presumably if the duration of the pulse is sufficiently decreased, the effect of its form can be made negligible. With this assumption, the result becomes a special case of the analog of the Fourier series relation.

Application to Transmission Problems

In applying the foregoing to transmission problems it will be assumed that the systems under consideration are linear with constants which do not vary with time. They will be assumed to be either passive or stable active systems, except where unstable active systems are specifically mentioned.

Steady-State Transmission in Terms of ψ Components

By the steady-state characteristic of such a system we mean a description, in terms of functions of frequency, of how it transmits sinusoidal waves of various frequencies. This amounts to a statement, for each frequency, of the relation between some two waves associated with the system. If they are the current and voltage at the same point, the relation takes the form of an impedance, consisting of a resistance and a reactance. As the relation between any other pair of waves may be expressed in similar form, there will be no loss of generality if we carry on the discussion in terms of an impedance.

The resistance gives the ratio, to the amplitude of the current, of the amplitude of that component of the voltage which is in phase with the current. The reactance gives a similar ratio for the component in quadrature. When the familiar analysis is used, it is convenient in computing the impedance to choose the current as a sine wave of unit amplitude. The amplitudes of the computed sine and cosine components of the voltage then give the resistance and reactance.

If we wish to carry out the computation in terms of the new analysis, we again assume that the current is represented by one of the quadrature components, in this case that of positive frequency $\psi(\omega_1)$ cas $\omega_1 t$, $(\omega_1 > 0)$. If we analyze this into its sine and cosine components, compute the accompanying voltages in the familiar way, and resolve their resultant into cas components of positive and negative frequency, we get

$$\psi(\omega_1)[R(\omega_1) \operatorname{cas} \omega_1 t + X(\omega_1) \operatorname{cas}(-\omega_1 t)]. \tag{18}$$

Obviously, if we make $\psi(\omega_1)$ unity, the resistance is given by the magnitude of the voltage component of positive frequency and the reactance by that of negative frequency.

[1] H. Nyquist, "Certain topics in telegraph transmission theory," *Trans. A.I.E.E.* (*Elec. Eng.*, April, 1928), vol. 47, pp. 617–644; 1928.

More often perhaps, we know the impedance and wish to compute the voltage which accompanies a given current. If the current is sinusoidal we resolve it into cas components of positive and negative frequency. The voltage accompanying the component of frequency ω_1 is given by (18). That accompanying the component of frequency $-\omega_1$ is obtained by reversing the sign of ω_1 in (18). It is

$$\psi(-\omega_1)[R(-\omega_1) \operatorname{cas}(-\omega_1 t) + X(-\omega_1) \operatorname{cas} \omega_1 t], \tag{18'}$$

where

$$R(-\omega_1) = R(\omega_1), \quad X(-\omega_1) = -X(\omega_1), \qquad (\omega_1 > 0).$$

From these results it follows that if the current is a transient which can be represented by

$$I = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \operatorname{cas} \omega t, \tag{19}$$

the voltage is

$$E = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega)[R(\omega) \operatorname{cas} \omega t + X(\omega) \operatorname{cas}(-\omega t)], \tag{20}$$

provided $R(\omega)$ and $X(\omega)$ satisfy certain well-known conditions.

The new analysis lends itself to the use of complex algebra in a manner exactly analogous to that of the familiar analysis. In the familiar case we carry out the operations in terms of exp $(i\omega t)$, the real part of which is cos ωt. When this is multiplied by the impedance $R(\omega) + iX(\omega)$, the real part of the product gives the voltage. In the new analysis, we recognize that the sum of the real and imaginary parts of exp $(i\omega t)$ is cas ωt. Hence if we multiply exp $(i\omega t)$ by the complex impedance as before, the sum of the real and imaginary parts of the product gives the voltage. We may then write (19) and (20) in the form

$$I = \text{real} + \text{imaginary part of } \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, \psi(\omega) \exp(i\omega t),$$

$$E = \text{real} + \text{imaginary part of } \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} d\omega\, Z(\omega)\psi(\omega) \exp(i\omega t),$$

where $\psi(\omega)$ is real and $Z(\omega)$ is the complex impedance. An alternative method is based on the relation

$$(1 + i) \exp(i\omega t) = \operatorname{cas}(-\omega t) + i \operatorname{cas}(\omega t).$$

If the real part of this represents the current, then

$$\text{real part of } (1 + i) Z \exp(i\omega t) = R \operatorname{cas}(-\omega t) - X \operatorname{cas} \omega t,$$

which from (18′) is the voltage. Here the cas component of negative frequency has a role similar to that of the cosine component and that of positive frequency to that of the sine, which is consistent with (13). It is also consistent with the fact that it is the sine and the positive-frequency components of current which are accompanied by voltage components which are equal to the resistance and reactance, respectively. For the cosine and negative-frequency components the quadrature component of the voltage is equal to minus the reactance.

Systems Characteristics as Spectra of Transients

It is well known that under suitable conditions the functions of frequency which give the steady-state characteristic of a system are identical with those which describe the transient which accompanies excitation by an ideal pulse at time zero.[2] Such a transient may be analyzed into components of positive and negative frequency, the magnitudes of which are expressed in terms of the system characteristics. The resulting function of frequency bears a more symmetrical relation to the time function representing the transient than do the familiar frequency functions. This symmetry is found to be helpful in establishing relations between the steady-state and transient characteristics of a system.

Let us first review the well-known relation between the impedance and the transient voltage which accompanies a pulse of current at time zero. For this purpose, we may make use of some of the relations given above. We shall assume that the current approaches as closely as we wish to a finite pulse of infinite height and infinitesimal length as discussed above. The corresponding Φ function then approaches a constant finite value. This means that the single-frequency components of the current are all cosines of the same infinitesimal amplitude. The corresponding components of the voltage are each made up of a cosine component proportional to the resistance and a sine component proportional to minus the reactance at the particular frequency. Formally these are the same as the components of the spectrum of a function of time. Whether or not they represent the spectrum of the transient voltage, depends on whether the impedance function is such that the integration involved in their summation has meaning. This will be true only if the impedance approaches zero at infinite frequency at a sufficiently rapid rate. In what follows we shall consider only systems which satisfy this condition.

We wish now to represent the spectrum of the transient in terms of the new analysis. Since the amplitudes of the voltage waves are $R(\nu)$ and $-X(\nu)$, $(\nu>0)$, those of their components of frequencies ν and $-\nu$ will be each half those values, so

$$\Phi(\nu) = \tfrac{1}{2}[R(\nu) - X(\nu)],$$

$$\Phi(-\nu) = \tfrac{1}{2}[R(\nu) + X(\nu)],$$

$$= \tfrac{1}{2}[R(-\nu) - X(-\nu)].$$

Also

$$\Phi_e(\nu) = \tfrac{1}{2}R(\nu), \qquad (21)$$

$$\Phi_0(\nu) = -\tfrac{1}{2}X(\nu). \qquad (22)$$

The Φ function corresponding to the transient voltage is then given by one half of the resistance minus the reactance. The application of this relation will next be illustrated by some practical examples.

Echoes as Single-Instant Components

To arrive at a more concrete picture of a single pulse, at a time other than zero, as corresponding to a sinusoidal function of frequency, let us consider what happens when a finite pulse of current of the kind just discussed is sent into a distortionless line at time zero by a generator of infinite internal impedance. First suppose the line to be of infinite length, or terminated in its own impedance, so that there is no reflected wave. The voltage across the input is also a pulse, the spectrum of which is made up of cosine components of uniform amplitude. This is consistent with the impedance of the line being a uniform resistance. Suppose now that the distant end be opened. The initial voltage pulse will then be followed by an echo, delayed by a period t_1 equal to twice the transmission time of the line. Owing to the infinite generator impedance no current will accompany this pulse and it will be reflected as from an open circuit. Let us assume that the line attenuation is great enough that subsequent echoes are negligible. The first echo then constitutes a finite voltage pulse at time t_1. The Φ function corresponding to it will be a finite sinusoid, for which the number of cycles per unit frequency range is given by t_1. This may be added to the uniform value of $\Phi(\nu)$ representing the initial pulse. Since the attenuation is assumed large, the sinusoidal part will appear as a ripple on the larger uniform value. When this resultant Φ function is resolved into its even and odd components, we have the functions which represent the resistance and minus the reactance of the open-circuited line. These will each have a sinusoidal component, the phases of the two being in quadrature. This picture of the line impedance will be recognized as that in common use for locating points of reflection by means of the sinusoidal variations in impedance.

Suppose now that we greatly reduce the attenuation. The initial pulse will then be followed by a long series of equally spaced pulses of gradually diminishing magnitude. Together they constitute the analog of a Fourier series, with t_1 as a fundamental. Each pulse will contribute to $\Phi(\nu)$ a sinusoidal component for which the number of cycles per unit frequency range is nt_1 and the wavelength on the frequency scale is $1/nt_1$. These combine to form a Φ function which has a sharp peak at the fundamental resonant frequency $1/t_1$ of the line. Also this Φ function repeats itself on the frequency scale in successive intervals of $1/t_1$ thus providing peaks corresponding to resonance at the harmonic frequencies. This point of view resembles very closely that used by Mason[3] in treating the steady-state properties of circuits in terms of multiple echoes.

[2] R. V. L. Hartley, "The transmission of information," *Bell Sys. Tech. Jour.*, vol. 7, pp. 535–563; July, 1928.

[3] W. P. Mason, "A new method for obtaining transient solutions of electrical networks." *Bell Sys. Tech. Jour.*, vol. 8; pp. 109–134; January, 1929.

Distortion in Terms of Paired Echoes

The correspondence between echoes and sinusoidal variations in impedance was carried further by MacColl[4] in a study of phase distortion. He noted that in certain circuits the departure of the phase characteristic from linearity was approximately sinusoidal. He therefore assumed small sinusoidal variations in the magnitude and phase of the transfer admittance and showed that the resulting transient distortion of the current could be represented by reduced replicas of the applied signal displaced in both directions along the time axis. More recently Wheeler[5] and Strecker[6] have represented the distortion of a television signal in terms of two groups of similar "paired echoes." In one group each pair corresponds to a sinusoidal component of the attenuation-frequency function of the system and in the other to a component of the phase-frequency function. The relations underlying this correspondence are approximate and the method is applicable only when the distortion is relatively small. Burrows[7] has suggested a method of successive approximations based on MacColl's results, which increases the accuracy and evaluates the residual error. He points out that in the amplitude case, the relations become exact if the amplitude itself is used, rather than its logarithm, the transmission loss, as used by Wheeler. Still more recently Strecker[8] has pointed out what is obvious from the present point of view, that the method of paired echoes may be made to give exact results for all values of distortion, if logarithmic relations are avoided and the system is described in terms of its transfer impedance, or admittance. As an alternative we may represent the system by its Φ function, and analyze this into its components of negative and positive instants, in accordance with (1). The amplitudes of these give directly the magnitudes of the resultant echoes which precede and follow the signal by particular intervals.

Another example of the representation of pulses on the time scale by sinusoids on the frequency scale will be found in Kallmann's[9] treatment of "transversal filters." By adjusting the amplitudes and signs of components corresponding to pulses having different arrival times, he constructs a function of frequency to fit the desired filter characteristic.

[4] L. A. McColl, "The distortion of signals by linear systems having amplitude and phase characteristics of a certain type," unpublished memoranda, December, 1931.

[5] Harold A. Wheeler, "The interpretation of amplitude and phase distortion in terms of paired echoes," PROC. I.R.E., vol. 27, pp. 359–384; June, 1939.

[6] F. Strecker, "Über den Einflus kleiner Phasenverzerrungen auf die Übertragung von Fernsehsignalen," *Elec. Nach. Tech.*, vol. 17, pp. 51–56; March, 1940.

[7] Charles R. Burrows and C. W. Carnahan, Discussion on Wheeler paper, footnote 5, PROC. I.R.E., vol. 27, pp. 384–386; June, 1939.

[8] F. Stecker, "Beeinflussung der Kurvenfarm von Vorgängen durch Dämpfungs- und Phasenverzerrung," *Elec. Nach. Tech.*, vol. 17, pp. 93–107; May, 1940.

[9] Heinz E. Kallmann, "Transversal filters," PROC. I.R.E., vol. 28, pp. 302–310; July, 1940.

Representation of a Stable System by a Function of Positive Frequencies Only

The pairs of functions of frequency which represent the steady-state characteristics of linear systems have been the subject of much study. Many years ago, MacColl questioned the need of two independent functions, or components of a complex function. He was able to show, in particular, that the susceptance of a passive circuit can be computed from its conductance. Work along this line has continued, and Bode[10] has extended these relations to include amplitude and phase. As a result of these studies it has come to be recognized that the performance of a passive system or a stable active one should be adequately described by a single function of positive frequencies. If so there should be, and there is, something in the nature of such systems which makes it unnecessary to specify the Φ function for both negative and positive frequencies.

This something is the fact that when a pulse is applied to such a system, the transient response is confined to the period following the pulse. In an unstable system the existence of a finite "response" is not dependent on a corresponding finite applied "stimulus." We saw above that the frequency characteristic may usually be interpreted as the spectrum of the transient response to an exciting pulse at time zero. If we call this response $f(t)$, $t>0$, then $f(-t)$ is always zero. From (9) and (10), then

$$f_e(t) = f_0(t) = \tfrac{1}{2}f(t),$$

and so either $f_e(t)$ or $f_0(t)$ alone is sufficient to determine $f(t)$. From (9), $f_e(t)$ is determined by $\Phi_e(\nu)$. But $\Phi_e(\nu)$ is an even function and so is completely described by its values for positive frequencies. Similarly from (10), $\Phi_0(\nu)$ is also adequate, and so either component of the familiar spectrum contains all the essential information. In more familiar language, the transient response may be deduced from either the real or the imaginary component of the steady-state response.

Necessary Conditions for a Stable System

The above result suggests some alternative formulations for the conditions which must be met by a steady-state characteristic if it is to correspond to a physically possible passive system or stable active system. When a pulse is applied to such a system at time zero, the transient $f(t)$ is zero for $t<0$. The amplitude of a single-instant component of the system characteristic, $\Phi(\nu)$, is $f(t)dt$. The condition, therefore, is that the amplitudes of all such components which correspond to negative values of t shall be zero. Also, it follows from (13), that if $\Phi(\nu)$ be analyzed into sine components of variable amplitude and phase, in accordance with the familiar Fourier analysis, the condition requires that the phases of all the components be

[10] H. W. Bode, "Relations between attenuation and phase in feedback amplifier design," *Bell Sys. Tech. Jour.*, vol. 19, pp. 421–454; July, 1940.

$\pi/4$. Again, since the even and odd functions of time cancel for all negative instants they must be equal for all positive instants. Hence from (9), (10), (21), and (22), it must be true that

$$\int_{-\infty}^{\infty} d\omega \tfrac{1}{2} R(\omega) \cos \omega t_1 = \int_{-\infty}^{\infty} - d\omega \tfrac{1}{2} X(\omega) \sin \omega t$$

or

$$\int_{0}^{\infty} d\omega\, R(\omega) \cos \omega t = - \int_{0}^{\infty} d\omega\, X(\omega) \sin \omega t \qquad (23)$$

for all positive values of t, if the characteristic is to be realizable. This relation is given by Guillemin.[11]

This criterion permits certain conclusions to be drawn regarding the paired echoes discussed by Wheeler and Strecker. In most transmission systems the reproduced signal is delayed by an interval t_1 to be determined by the slope of the linear component of the phase shift. Relative to this displaced zero of time the criterion says that all single-instant components of $\Phi(\nu)$ corresponding to instants before $-t_1$ must be zero. In order then for an assumed pair of variations in amplitude and phase to be realizable, it is necessary that, if the variation of one quantity corresponds to pre-echoes before $-t_1$, that of the other must correspond to equal echoes of opposite sign over this part of the time scale.

A Particular Necessary Condition

While the satisfaction of (23) for all positive values of t constitutes a necessary condition, its application to a particular case involves considerable labor. It is possible, by considering particular values of t, to deduce necessary conditions which are less general. As an example of this let us derive a relation which Bode[12] has established for the resistance of a circuit across the terminals of which there is a shunt capacitance C. The relation is

$$\int_{0}^{\infty} R(\omega)\, d\omega = \frac{\pi}{2C}\,.$$

We assume a pulse of current of infinitesimal duration to be sent into the circuit at time zero. The accompanying charge first accumulates in the shunt condenser and then proceeds to flow into the rest of the circuit. We select an instant t_1 so close to zero that the part of the charge which has left the condenser is negligible. The voltage at that instant is independent of the rest of the circuit and is determined solely by the condenser. So far as this instant is concerned, then, we may neglect the rest of the circuit. This is the equivalent of Bode's choice of a frequency so high that the impedance is equal to the capacitive reactance of the condenser. We then say that the voltage is to be zero at $-t_1$ and so (23) holds for that instant. By making t_1 small enough, $\cos t_1\omega$ may be made substantially equal to unity for any value of ω. If we substitute $-1/\omega C$ for $X(\omega)$, we have

$$\int_{0}^{\infty} R(\omega)\, d\omega = \int_{0}^{\infty} \frac{\sin t_1\omega}{C\omega}\, d\omega,$$

$$= \frac{1}{C}\int_{0}^{\infty} \frac{\sin t_1\omega}{t_1\omega}\, d(t_1\omega) = \frac{\pi}{2C}\,.$$

A word of caution should perhaps be inserted regarding the application of this relation to physical circuits. The arrangement assumed neglects the inductance of the leads which must become appreciable as we approach infinite frequency. Once it does, the condenser is no longer shunted directly across the terminals. If this inductance is L, it can be shown by assuming the application of an impulsive voltage, that the conductance $G(\omega)$ is limited by the relation

$$\int_{0}^{\infty} G(\omega)\, d\omega = \frac{\pi}{2L},$$

instead of being infinite for all frequencies as was assumed. It is evident from this that if the impedance of an ideally lumped artificial line, having series L and shunt C, is measured at mid-shunt, the integral of its resistance is limited, while at mid-series, that of its conductance is limited. However if we make it approach a uniform line by reducing L and C, both of these limits approach infinity as they must if both R and G are to become constant for all frequencies.

Note added in proof: Since the above was written, a paper[13] has appeared in which Wheeler, in a treatment of unsymmetrical sidebands in terms of a zero-frequency carrier, makes use of functions of frequency which are defined independently for positive and negative frequencies, and of the resolution of these into even and odd components. The analysis, however, follows (7) and (8) above, and the object is not, as here, the development of a more symmetrical form of the Fourier identity.

[11] E. A. Guillemin, "Communication Networks," vol. 2, John Wiley and Sons, New York, N. Y., 1935, p. 503.
[12] H. W. Bode, United States Patent No. 2,242,878, 1941.

[13] H. A. Wheeler, "The solution of unsymmetrical-sideband problems with the aid of the zero-frequency carrier," Proc. I.R.E., vol. 29, pp. 446–458; August, 1941.

Supplement to "A Stabilized Frequency-Modulation System"*

ROGER J. PIERACCI

The analysis for the distortion-correction system was carried out on the basis of a single-tone modulating frequency. However, the system is operative for multitone operation or when a complex speech or music wave is applied to the audio terminals of the modulators. Referring to the circuit diagram of Fig. 6, the distortion-corrector tubes V_7 and V_8 generate the function $K_1+K_2 \cos 2pt$ in which K_1 is a direct-current component and $K_2 \cos 2pt$ an approximate expression for the modulation of the direct-current component. The limitation for proper operation is that K_1 must always be larger than K_2. When this limitation is applied, the output of V_8 consists of a direct-current component and a superimposed audio-frequency component. As such the system can not strictly be called an audio-frequency doubler. If the direct-current component were removed by the insertion of an audio transformer, the system would function as an audio-frequency doubler only when a single frequency is applied. It is not possible to multiply or divide a complex band of frequencies. It is the presence of the direct-current component which permits the circuit as shown to function properly when a complex wave is applied. Consider the application of a square wave to the modulator. The output of the rectifier V_7 would be a constant direct voltage. When applied to V_8 it would reduce the carrier amplitude during modulation. This would give a wider phaseshift angle for the same sideband amplitude and in no way distort the square wave. If K_2 were adjusted to such a value that the carrier were reduced to zero, the phase-shift angle would then be shifted through plus or minus ninety degrees during the modulation cycle. The output would obviously be a square wave. However, if a transformer were inserted at the output of V_8, the direct-current component would be removed and the tubes V_7 and V_8 would have no effect whatever on the operation of the circuit.

* Proc. I.R.E., vol. 30, pp. 76–80; February, 1942.

Institute News and Radio Notes

Board of Directors

A meeting of the Board of Directors was held on February 4 and was attended by A. F. Van Dyck, president; Austin Bailey, A. B. Chamberlain, I. S. Coggeshall, H. T. Friis, Alfred N. Goldsmith, editor; J. K. Johnson, F. B. Llewellyn, B. J. Thompson, H. M. Turner, H. A. Wheeler, and H. P. Westman, secretary.

The Secretary reported that acceptances had been received from the five Directors appointed to serve during 1942.

The American Standards Association is about to standardize on the use of E as a symbol for electric field intensity. In our existing standards we have used $\mathcal{E}$ for this quantity. A recommendation by the chairman of the Technical Committee on Symbols, concurred in by the committee and by the chairman of the Standards Committee that we adopt E, was approved. It was necessary to take this action as a special case in order that a report on radio wave propagation, which is now being, printed might be modified to use the newly adopted symbol.

Executive Committee

The Executive Committee met on February 3. Those present were A. F. Van Dyck, chairman; I. S. Coggeshall, Alfred N. Goldsmith, editor; R. A. Heising (guest), F. B. Llewellyn, B. J. Thompson, and H. P. Westman, secretary.

Approval was granted of 95 applications for Associate, 2 for Junior, 64 for Student, and 45 for transfer to Associate grade.

FORTHCOMING MEETINGS

Summer Convention
Cleveland, Ohio
June 29, 30, and July 1, 1942

Proceedings Questionnaire

During the summer, questionnaires were mailed to members of the Institute asking for opinions on a number of subjects. About 1600 of these questionnaires have been analyzed and the results are given in the accompanying table.

These data are being placed before all those concerned with the procurement of papers and the publication of the PROCEEDINGS as a guide in future activities.

INDICATED PREFERENCES BY SUBJECTS

Subject	*1st Choice* Per cent	*2nd Choice* Per cent	*3rd Choice* Per cent	*1, 2, and 3 Choice* Per cent
1. Theory, Circuit and General	42	12	9	62
2. Generating Apparatus	3	7	6	16
3. Receiving Apparatus	6	9	9	25
4. Transmission through Space	3	6	4	13
5. Measurements and Standards	6	12	10	29
6. Vacuum Tubes, Receiving	3	6	6	15
7. Vacuum Tubes, Transmitting	2	3	4	9
8. Antennas	4	9	9	22
9. Acoustics and Audio-Frequency Systems	3	6	7	16
10. Aircraft Radio	4	3	4	10
11. Stations and Operating, Broadcasting	6	3	3	12
12. Television	4	3	4	11
13. Facsimile	1	1	1	2
14. Piezoelectricity	1	1	2	3
15. Radio Communication Systems	4	6	6	15
16. Ultra-High-Frequency and Microwaves	6	9	10	25
17. Phonographic Recording and Reproduction	1	3	6	10
18. Others	1	1	0	2
	100	100	100	

INDICATED PREFERENCES BY TYPES OF PAPERS

Type	*1st Choice* Per cent	*2nd Choice* Per cent	*1st and 2nd Choice* Per cent
1. Research and Development	71	13	82
2. Design, Production, and Shipping	8	28	36
3. Operations Engineering	9	13	21
4. Testing and Installation	3	13	16
5. Maintenance and Servicing	3	6	10
6. Historical	0	2	2
7. Summaries of Developments in Broad Fields	4	22	26
8. Patent Practice and Patent Abstracts	1	2	3
9. Economic and Social Aspects of Engineering	1	1	1
	100	100	

Ursigrams Discontinued

As a result of wartime conditions, the Navy transmissions of ursigrams have been suspended. Similar action has been taken in regard to the distribution of cosmic data by means of the weekly Science Service Research Aide Announcement.

Those who have a legitimate need for these data should address Dr. J. A. Fleming, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington, D. C.

Section Meetings

BOSTON

"Radio Manufacturing Industry," by H. B. Richmond, General Radio Company, December 19.

BUENOS AIRES

"Fourth Discussion on Propagation," November 6.

CHICAGO

"Engineering Radio Receivers," by K. W. Jarvis, Consulting Engineer, January 16.

"Automatic Radio Relay Systems Above 500 megacycles," by J. Ernest Smith, R.C.A. Communications, Inc., January 16.

CLEVELAND

"Developments in Insulation for Radio Stations," by A. O. Austin, Insulator Consultant, January 29.

DETROIT

"Recent Developments in Electronic Control Devices," by R. A. Powers, Electronic Control Corporation, January 16.

"The Effect of Static Electricity on Auto Radios," by N. E. Handel, United States Rubber Company, January 16.

EMPORIUM

"Tube Noise Phenomena," by W. L. Krahl, Hygrade Sylvania Corporation, January 22.

INDIANAPOLIS

"Simplified Band-Spread Circuit for Multiband Receivers," by Sarkes Tarzian, RCA Manufacturing Company, Inc., January 16.

"Oscillator-Coil Design for Permeability Tuners," by Robert Trachtenberg, RCA Manufacturing Company, Inc., January 16.

"Kinescope Contrast Range Improvements, by Circuit Means," by G. C. Sziklai, RCA Manufacturing Company, Inc., January 16.

LOS ANGELES

"Generation of Ultra-High Frequencies," by John Lentz, California Institute of Technology, January 20.
"Wave Guides," by William Pickering, California Institute of Technology, January 20.

PHILADELPHIA

"The Technical Aspects of Television Program Production," by R. E. Shelby and F. A. Wankel, National Broadcasting Company, February 4.

PITTSBURGH

"Behind the Scenes of Broadcasting," by J. B. Rock and D. A. Myer, Radio Station KDKA, January 12.

SAN FRANCISCO

"Radio-Frequency Bridge Measurements up to 60 Megacycles, Laboratory Session with Operating Equipment," by Frederick Ireland, General Radio Company, January 21.

TORONTO

"Problems Encountered in Erecting Canada's First Directive Broadcast Station," by E. Swan, Radio Station CKCL, January 26.
"The Minshall Electro-Organ," by Bert Minshall, Minshall Electro-Organ Company, February 9.

WASHINGTON

"Reference Recording," by S. A. Sollie, Memovox, Inc., February 9.

W. C. WHITE

Underwood and Underwood

C. B. JOLLIFFE

White Named Director of New Laboratory

William C. White (A'15-M'25-F'42) was recently appointed director of the newly established electronics laboratory of the General Electric Company. In this laboratory will be centralized all of the development activities in the field of electronics.

Mr. White was born in Brooklyn, New York, on March 24, 1890. He received the Electrical Engineering degree from Columbia University in 1912 and immediately entered the employ of the General Electric Company.

Mr. White has been identified with much pioneering work in the development of vacuum tubes. His activites through the years in the research laboratory resulted in his being placed in charge of the vacuum-tube section of that laboratory in 1927. Two years later he was put in charge of the vacuum-tube engineering department.

Mr. White has served the Institute as a member of various committees and as a contributor to the PROCEEDINGS. The Fellow grade was awarded to him at the 1942 winter convention.

Charles B. Jolliffe Appointed Assistant to the President of R.C.A.

Dr. Charles B. Jolliffe (M'25-F'30) was recently named assistant to the president of the Radio Corporation of America. He will continue as chief engineer of the RCA Laboratories.

He was born in Mannington, West Virginia, on November 13, 1894. He received the B.S. degree in 1915 and the M.S. degree in 1920 from West Virginia University. Cornell conferred on him the Ph.D. degree in 1922.

From 1922 to 1930, Dr. Jolliffe was a physicist and assistant chief of the radio section of the National Bureau of Standards.

He served as chief engineer of the Federal Radio Commission and the Federal Communications Commission from 1930 to 1935. He was then appointed engineer in charge of the R.C.A. frequency bureau. He was named chief engineer of the RCA Laboratories in 1941.

Dr. Jolliffe has contributed to the PROCEEDINGS and has also served on a number of Institute committees.

Membership

The following admissions or transfers (where indicated as such) to Associate grade were approved by the Board of Directors on February 4, 1942.

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Altman, D., 2215 Newkirk Ave., Brooklyn, N. Y.
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Batt, F. E., c/o Central Technical Library, The Consolidated Mining and Smelting Company of Canada, Ltd., Trail, B. C., Canada
Beckman, C., 14 Seymour St., Montclair, N. J.
Beggs, G. E., Jr., 4901 Stenton Ave., Philadelphia, Pa.
Benham, E. E., Jr., KMYC, Marysville, Calif.
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Bergerson, W., 97 Sterling, Buffalo, N. Y.
Berman, M., 1002 E. 17 St., Brooklyn, N. Y. (Transfer)
Boghosian, E., 6218 Catherine St., Philadelphia, Pa. (Transfer)
Bollinger, W. P., 109 Chestnut, Audubon, N. J. (Transfer)
Boss, B. B., 145 E. 45 St., New York, N. Y. (Transfer)
Bulger, R. J., 290 Overdale St., Winnipeg, Manit., Canada
Cataldo, A. R., 36 Oxford Park, Revere, Mass.
Chezik, T. W., 1720 Wilmington Ave., Richmond, Va.
Coleman, L. E., 115 Alder St., Bluefield, W. Va.
Coolidge, A. W., Jr., 210 Summer Ave., Reading, Mass. (Transfer)
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Contributors

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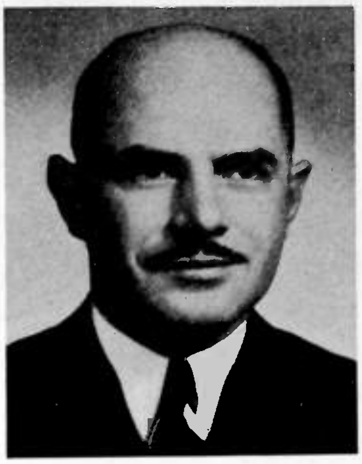

A. B. Chamberlain

Lester M. Field

Horace Atwood, Jr., (S'40-A'41) was born on April 22, 1918, at Morgantown, West Virginia. He received the B.A. degree from West Virginia University in 1939 and was a research assistant in physics there until 1941 when he was employed as a research physicist at the Allen B. Dumont Laboratories. He is a member of the American Physical Society.

❖

John E. Bailey (S'40) was born at Wheeling, West Virginia, on November 6, 1917. He received the B.S.E.E. degree from West Virginia University in 1940 and was a graduate assistant there until 1941. Since 1941 Mr. Bailey has been a second lieutenant in the 63rd Signal Battalion.

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A. B. Chamberlain (A'27-M'30-F'42) was born on February 3, 1901, at Franklin, Massachusetts. He was a naval radio operator from 1919 to 1923; broadcast engineer with WGY in 1923; chief broadcast engineer of WHAM in 1927; general manager of WHAM in 1928; and vice-president and technical director of the Buffalo Broadcasting Corporation in 1929. Since 1931 Mr. Chamberlain has been chief engineer of the Columbia Broadcasting System.

❖

Robert C. Colwell (A'21, M'29) was born at Fredericton, N. B., Canada, on October 14, 1884. He received the A.B. degree from Harvard University, the M.A. degree from the University of New Brunswick, and the Ph.D. degree from Princeton University. From 1913 to 1923 Dr. Colwell was professor of physics at Geneva College; since 1924 he has been assistant director of the Radio Laboratory at West Virginia University. He is a member of the American Physical Society, the Franklin Institute, and the American Mathematical Society.

❖

Lester M. Field (S'39) was born on February 9, 1918 at Chicago, Illinois. He received the B.S. degree in electrical engineering from Purdue University in 1939, and since that time has been a teaching and research assistant in the graduate school of electrical engineering at Stanford University. Mr. Field is a member of Tau Beta Pi, Eta Kappa Nu, and an associate member of Sigma Xi.

❖

Ralph V. L. Hartley (M'19, F'28 was) graduated from the University of Utah in 1909. He studied at Oxford for three years as a Rhodes Scholar, receiving the B.A. degree in 1912 and the B.Sc. degree in 1913. On his return, he entered the research laboratory of the Western Electric Company and had charge of the early development of radio receivers for the Bell System's transatlantic radiotelephone tests of 1915. The Hartley oscillating circuit was invented during that work. During the First World War he engaged in binaural sound-locator development and also set up the first demonstration of an inverted-band privacy system. At the end of the war he took charge of a group working on carrier telephony. By the addition of other groups, he eventually had charge of all wire transmission research.

In 1929 due to a prolonged illness, Mr. Hartley gave up the direction of his group, Since then, as improving health permitted, he has engaged in theoretical studies of which the present paper is typical.

❖

John E. Bailey

Robert C. Colwell

Kai den-Keystone

R. V. L. Hartley

F. B. Jewett

Willmar K. Roberts

S. P. Sashoff

Frank Baldwin Jewett (F'20) has for many years been intimately associated with the research and development activities of the Bell System. He entered upon his telephone career at a time when a transcontinental circuit was but a remote vision. He played an important part in adapting the vacuum tube to the requirements of long-distance telephony, both by wire and by radio. For sixteen years he served as President of the Bell Telephone Laboratories and is now Chairman of its Board. Since 1925 he has also been Vice President of the American Telephone and Telegraph Company.

Dr. Jewett is a member of the National Defense Research Committee and currently president of the National Academy of Sciences.

❖

Clee O. Marsh, Jr., (S'39-A'41) was born on April 4, 1918, at Clarksburg, West Virginia. He received the B.S.E.E. degree from West Virginia University in 1939 and was a graduate assistant there in physics until 1941 when he joined the National Bureau of Standards.

❖

Willmar K. Roberts (S'39) was born on August 26, 1918, at Jacksonville, Florida. He received the Bachelor of Electrical Engineering degree from the University of Florida in 1941. From 1938 to 1941 he was associated with the electrical engineering department of the University as research assistant in the communications laboratory. Since July, 1941, he has been a radio inspector in the Baltimore office of the Federal Communications Commission.

❖

Bernard Salzberg (J'25-A'30-M'38) was born on July 22, 1907. He received the E.E. degree in 1929, the M.E.E. degree in 1933, and the D.E.E. degree in 1941, all from the Polytechnic Institute of Brooklyn. Dr. Salzberg was with the Brooklyn Edison Company from 1923 to 1925 and during the summers of 1926 and 1927; with the Fada Radio Company during the summer of 1928; and with R.C.A. Communications from 1929 to 1931. From 1931 to 1941 he was in the Radiotron Division of the research and engineering department of RCA Manufacturing Company. Since the spring of 1941 he has been consulting engineer at the Naval Research Laboratory.

❖

Stephan P. Sashoff (M'41) was born on September 22, 1901, at Drenovo, Bulgaria. He received the B.S. degree in electrical engineering from Purdue University in 1925, and the M.S. degree in electrical engineering from the University of Pittsburgh in 1929. Mr. Sashoff joined the Westinghouse Electric and Manufacturing Company in 1925 and attended its engineering and design schools; he was a relay engineer for Westinghouse from 1929 to 1928; with the Westinghouse Research Laboratories from 1928 to 1932; and with the R.C.A. Television Research Laboratory in 1932. In the Fall of 1932 he became a member of the faculty of the College of Engineering, University of Florida, where at present he is an associate professor of electrical engineering and director of the electronics and communications laboratory.

❖

Karl Spangenberg (A'34) was born at Cleveland; Ohio, on April 9, 1910. He received the B.S. degree in electrical engineering in 1932 and the M.S. degree in 1933 from the Case School of Applied Science, and the Ph.D. degree in 1937 from Ohio State University. In 1934 he was a radio engineer at WHK, and during 1935 and 1936 he was an instructor in electrical engineering at Rose Polytechnic Institute. From 1937 to 1940, Dr. Spangenberg was an instructor in electrical engineering at Stanford University and since 1940 he has been an assistant professor. He is a member of Sigma Xi and the American Institute of Electrical Engineers.

❖

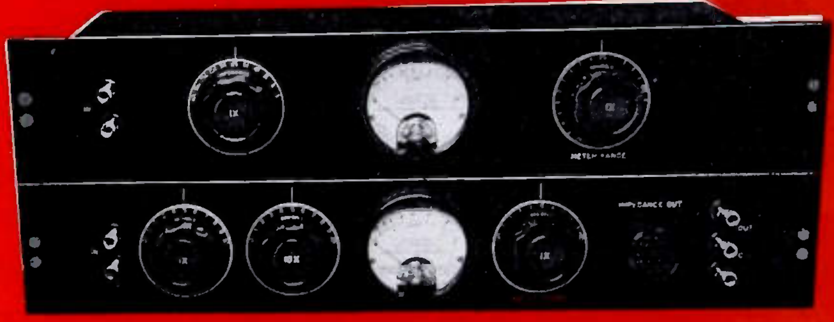
Clee O. Marsh, Jr.

Bernard Salzberg

Karl Spangenberg

TYPE 6-C

TRANSMISSION MEASURING SETS

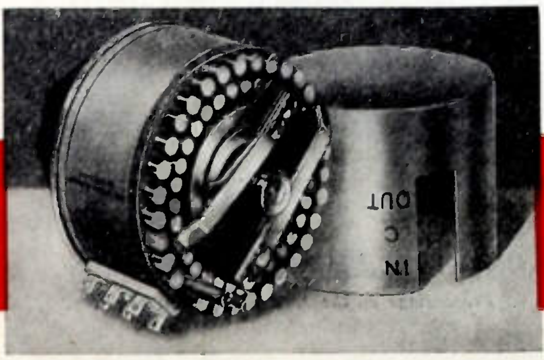


TYPE 685

TYPE 6-C Designed in co-ordination with the General Engineering Department of the Columbia Broadcasting System, the 6-C Transmission Measuring Set consists of complete transmission and load units assembled on a single rack type panel. With a frequency range from 30 to 17,000 cycles, this set provides an accurate and rapid method for measuring the transmission characteristics of networks at audio frequencies.

The reference level is the new standard of 1 mw. across 600 ohms. New Weston Type 30 meters are employed. The attenuation range is from Zero to 110 db. in steps of 1 db. Power range is calibrated from —16 to +45 db. Dial selection of useful network input and load impedances. No correction is required when changing impedances. Overall error is 2% **$325**

Many of your needs can be filled by standard DAVEN equipment. However, due to the specialized nature of high fidelity audio apparatus, a large number of requirements are encountered where existing units may not be suitable. If you have such a problem, write to our engineering department.



TYPE 685 An unusually flexible, universal gain measuring instrument for rapid and accurate measurement of overall gain, frequency response and power output of audio amplifiers, this assembly has a useful frequency range from 30 to 17,000 cycles.

It is direct reading in decibels and does not require correction factors or calibration charts. All networks meters and associated apparatus are shielded and carefully balanced, matched for uniform accuracy over this wide frequency range.

Attenuation range is +10 db. to —120 db. in steps of 1 db. Power measuring range is —20 db. to +36 db. Eleven load impedance values, ranging from 5 to 600 ohms are available. Output impedances may be changed from "balanced" to "unbalanced" and to any loss impedance by means of plug-in type matching networks. Overall error is 2% **$225**

THE DAVEN COMPANY

158 SUMMIT STREET NEWARK, NEW JERSEY

MOST COMPLETE LINE OF PRECISION ATTENUATORS IN THE WORLD

VETERANS of many outstanding achievements in radio, yet there's no such thing as an OLD tube type at Eimac. Past achievements paved the way for present leadership in the field. Leadership made possible by "heads-up" developments in tube construction and performance capabilities. The plates in Eimac tubes today are not the same, by a long way, as those originally used. And yet basically they are the same. Note the pictures above. See one of the early models and the improvement in the modern design which represents greater efficiency. By such constant improvement, Eimac tubes are kept "always NEW"...always a step ahead of the needs of the industry. Each tube has behind it the successful years of its predecessors...radical departure from conventional in tube design...ability to perform without strain where many others have failed.

Such is the Eimac 250T. Originally the Eimac 150T, it surprised the industry by performing so easily, the task of much larger tubes that, with slight modifications, its rated capabilities were boosted by more than 60%. The record today shows these comparatively small triodes being used in newer transmitters for jobs once thought impossible. Eimac tubes are like that, one and all. They are the only tubes on the market which carry unconditional guarantee against tube failures which result from gas released internally.

Follow the leaders to **Eimac TUBES**

Eitel-McCullough, Inc.
San Bruno, Calif.

EIMAC 250T

Plate Dissipation (normal)	*250 Watts*
Filament Voltage	*5 to 5.1 Volts*
Maximum Plate Voltage	*3000*
Power Output at 3000 volts on plate	*750 Watts*

EIMAC REPRESENTATIVES

California, Nevada
HERB BECKER, 1406 S. Grand Ave., Los Angeles, Calif.

Texas, La., Okla., Ark.
J. EARL SMITH, 2821 Live Oak St., Dallas, Texas.

Wash., Ore., Idaho, Mont.
GENERAL SALES CO., Verner O. Jensen, 2605-07 Second Ave., Seattle, Wash.

Colo., Wyo., New Mexico, Arizona, Utah
RICHARD A. HYDE, 4253 Quitman St., Denver, Colo.

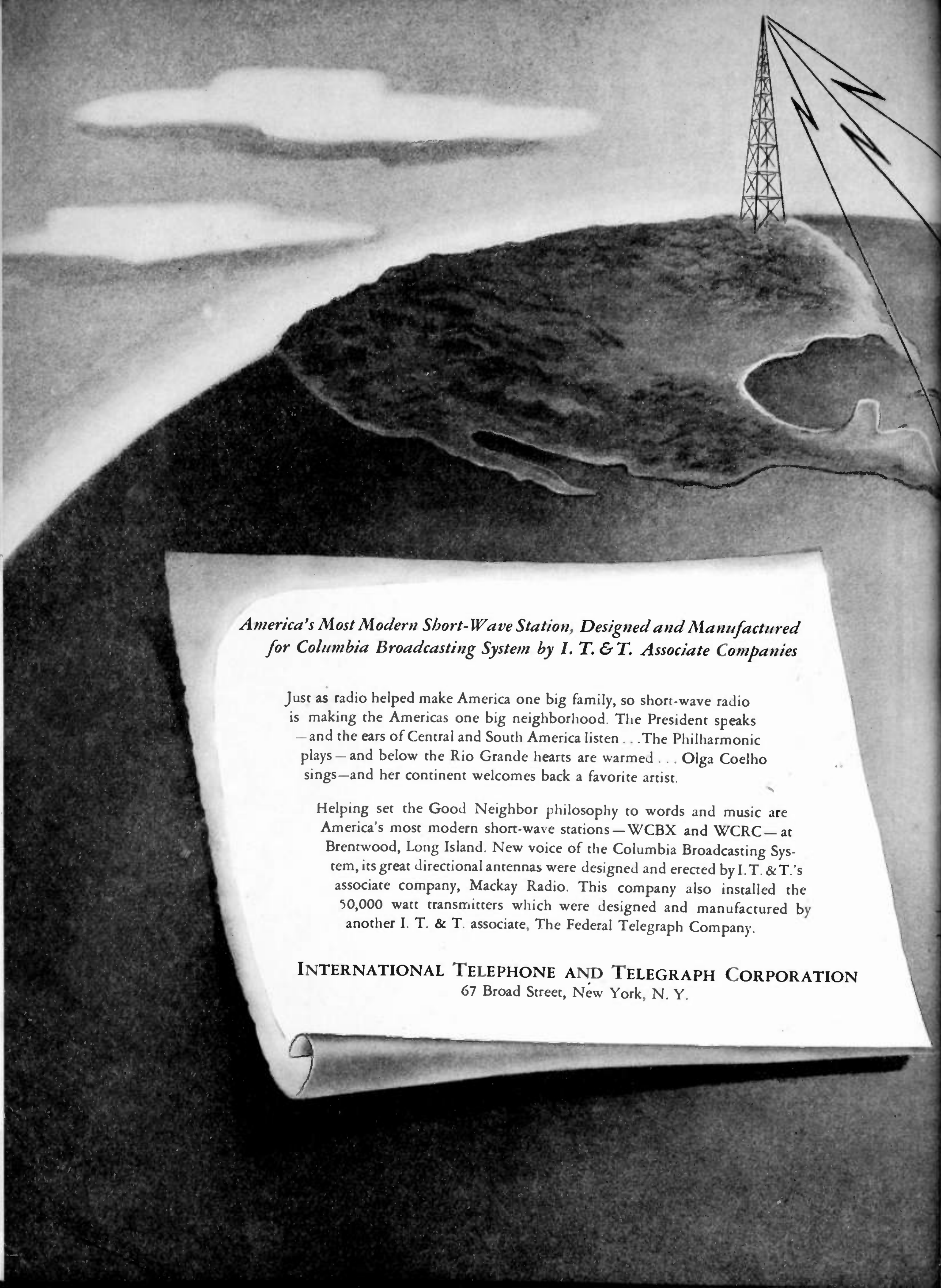
Chicago, Illinois, Wisconsin
G. G. RYAN, 549 W. Washington Blvd., Chicago, Ill.

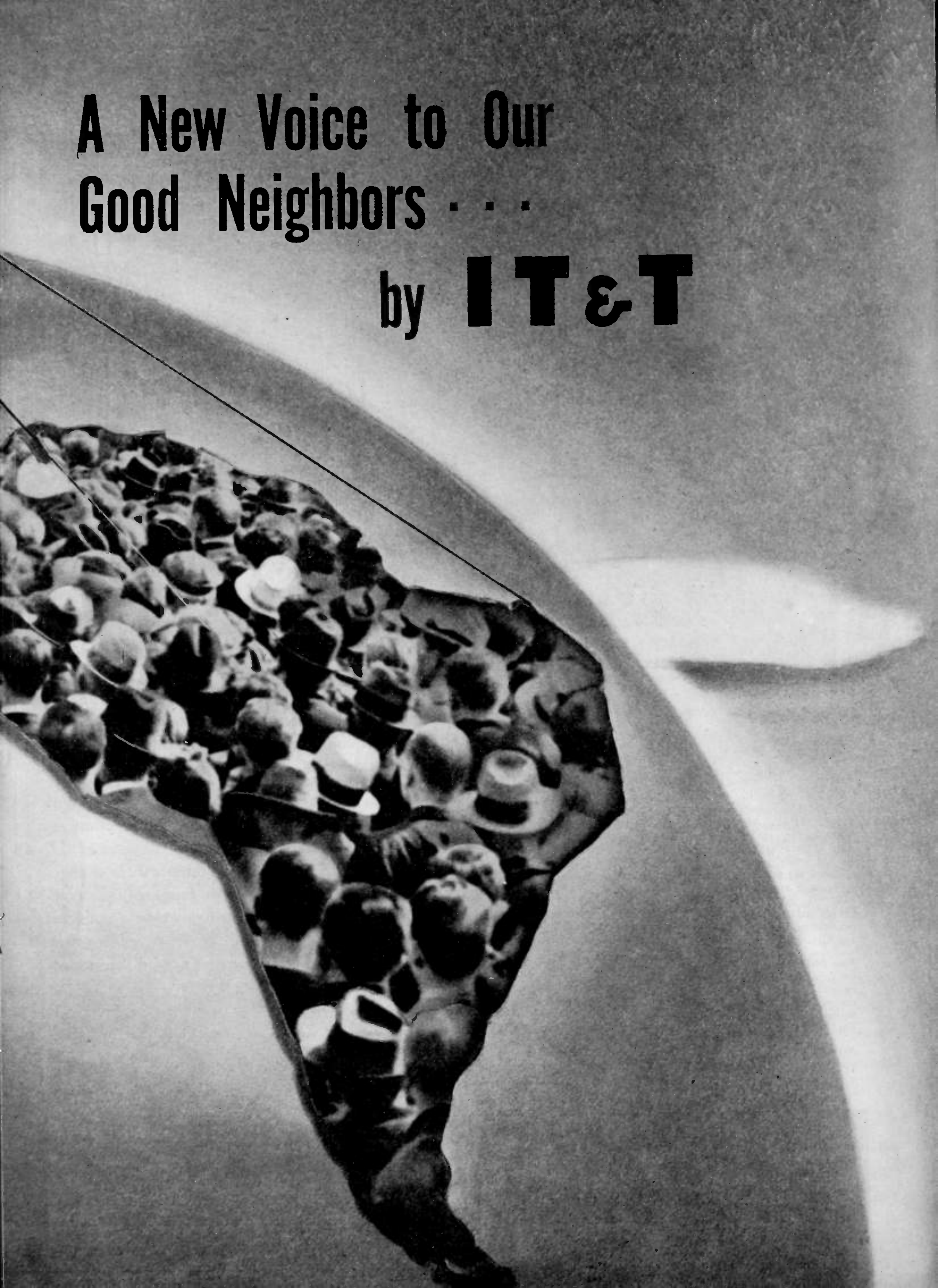
N. Caro., S. Caro., Georgia, Tenn., Flor., Ala., Miss.
JAMES MILLAR, 316 Ninth St. N.E., Atlanta, Georgia.

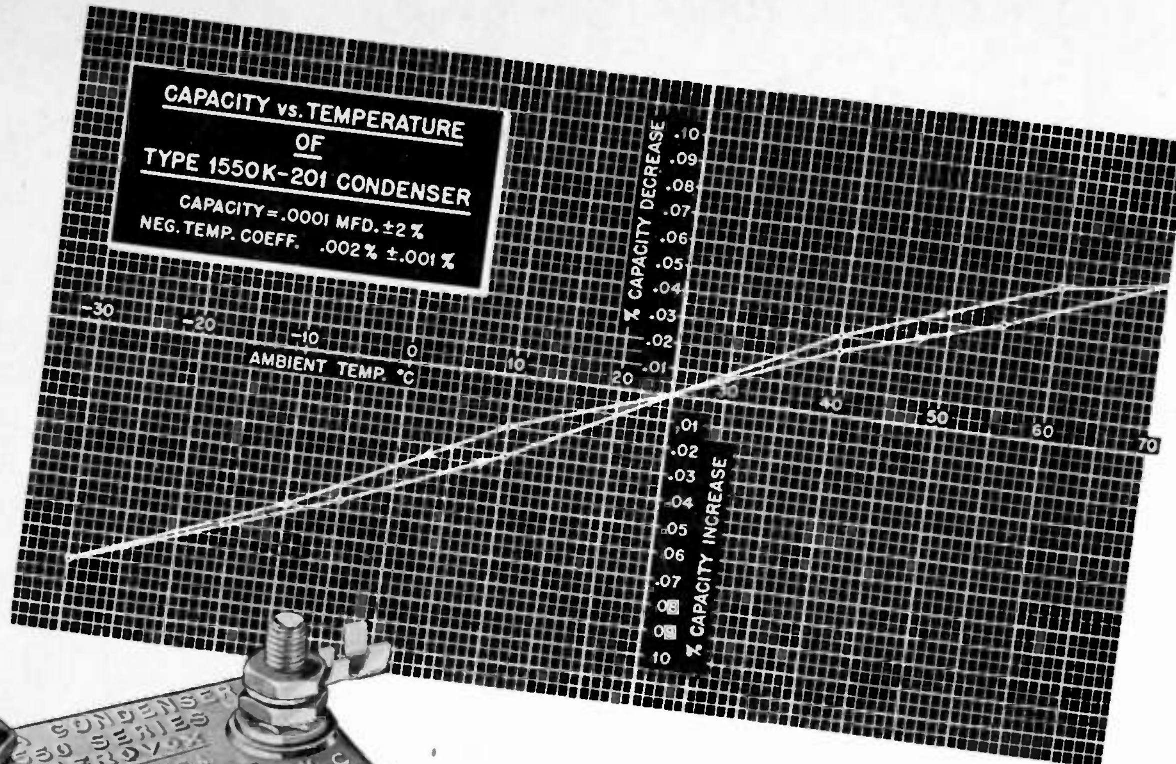
Ohio, Mich., Ky., Ind., Minn., Mo., Kan., Neb., Iowa
PEEL SALES ENGINEERING CO., E. R. Peel, 154 E. Erie St., Chicago, Ill.

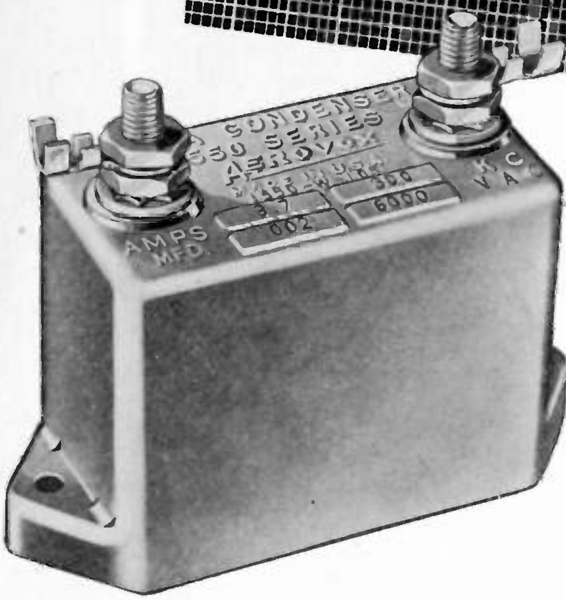
N.Y., N.J., Penn., Md., Del., Dist. of Col., Maine, N.H., R.I., Conn., Mass.
ADOLPH SCHWARTZ, 262 Grayson Place, Teaneck, New Jersey.

Export Agents: Frazar & Co., Ltd., 301 Clay Street, San Francisco


America's Most Modern Short-Wave Station, Designed and Manufactured for Columbia Broadcasting System by I. T. & T. Associate Companies
Just as radio helped make America one big family, so short-wave radio is making the Americas one big neighborhood. The President speaks —and the ears of Central and South America listen . . . The Philharmonic plays — and below the Rio Grande hearts are warmed . . . Olga Coelho sings—and her continent welcomes back a favorite artist.
Helping set the Good Neighbor philosophy to words and music are America's most modern short-wave stations — WCBX and WCRC — at Brentwood, Long Island. New voice of the Columbia Broadcasting System, its great directional antennas were designed and erected by I. T. & T.'s associate company, Mackay Radio. This company also installed the 50,000 watt transmitters which were designed and manufactured by another I. T. & T. associate, The Federal Telegraph Company.
INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION
67 Broad Street, New York, N. Y.


A New Voice to Our Good Neighbors . . .
by IT&T





COMPENSATING CAPACITORS . . .

● In order that the frequency of an oscillator or the constants of an amplifier circuit may remain constant with temperature change, it is necessary that either the inductance or the capacitance have temperature characteristics that compensate for any change in the characteristics of the other.

This is most readily accomplished by using an Aerovox Type K Compensating Capacitor, the temperature coefficient of which can be made so that the product of "L" and "C" will be independent of all temperature changes over normal operating temperature range. Such a combination used in an oscillator will provide a constant frequency source independent of any temperature variations in the units caused by current flow in the circuit.

● Type K capacitors (Types 1550K, 1560K, 1570K and 1580K) are available with negative zero or positive coefficient with —.005% to +.005% per degree C. over a temperature range of between —40° C. to +70° C. Extremely stable where L-C product must remain independent of temperature changes.

Furnished only in low-loss (yellow) bakelite. Sealed for immersion. Hot-tinned brass studs are standard. Special plating available on specifications, at extra cost.

Available in limited range of capacities and voltage ratings.

Inasmuch as capacity, voltage and temperature co-efficient are equally contributors to design and size of unit, specifications for individual requirements will be furnished on request.

Tolerances of plus or minus 5% is standard. Closer tolerances obtainable at extra cost. Maximum ambient temperature is 60° C.

When ordering compensated capacitors, specify temperature co-efficient required and furnish other essential information outlined in "Factors in the Application of Mica Capacitors," found in Aerovox Transmitting Capacitor Catalog.

Write for DATA . . .

● Engineering data on Type K compensating capacitors, sent on request, or refer to that section in the Transmitting Capacitor Catalog available to professional radio engineers.

AEROVOX CORPORATION

NEW BEDFORD, MASS., U. S. A.
Sales Offices in All Principal Cities

In Canada
AEROVOX CANADA LTD.
Hamilton, Ont.
EXPORT: 100 Varick St., N. Y.
Cable 'ARLAB'

THESE RESISTORS

DO THE JOBS THAT COULDN'T BE DONE

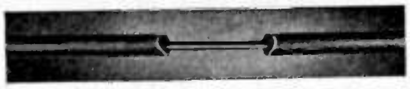
THE ONLY RESISTORS WOUND WITH CERAMIC INSULATED* WIRE!

*Flexible . . . Moisture-Proof . . . 1000° C. heat-proof . . . withstands high voltage

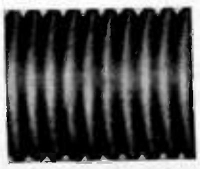
EACH TURN TOUCHES ANOTHER YET CANNOT SHORT

No "Swimming" of Turns

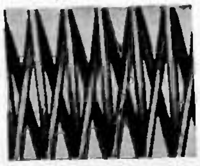
The exclusive Koolohm process of insulating the wire itself *before* it is wound, permits layer windings for higher resistance in less space; progressive windings for non-inductive resistors that are truly non-inductive even at 50 to 100 Mc.; larger wire sizes; faster heat dissipation; greater stability; extreme accuracy and greater humidity protection. No secondary insulations such as brittle cements or enamels are needed on the windings. For double protection, however, most Koolohm types are encased in a sturdy outer ceramic shell that will not peel or chip and which allows for quicker, easier mounting *directly* to metal parts.



Koolohm wire with section of ceramic insulation removed



Single layer winding



Progressive winding

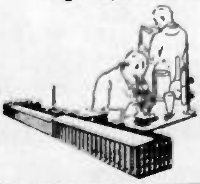
TOTALLY DIFFERENT—OUTSTANDINGLY SUPERIOR

Whereas other resistors are space-wound with bare wire, Sprague Koolohms are layer-wound with wire that is insulated before it is wound with a special ceramic material. This insulation is so flexible it can be wound on small forms without cracking. It is so moisture-proof it excels in any moisture test—so heat-proof that the insulation is actually applied to the wire at 1000° C.—and so good as an insulator that it has an insulation strength of 350 volts per mil. at 400° C. Small wonder then, that Koolohms outlast, outperform old style resistors where shorted windings cause trouble, where bare wires must be protected by outside coatings of brittle cements and enamels, and where heat and moisture represent problems that have been only partially solved. Koolohms are smaller, sturdier, better protected. They are more accurate—and they stay accurate because windings will not short.

UNEXCELLED FOR DEFENSE APPLICATIONS

Not only are Koolohm Resistors approved for much military and naval equipment but, in various instances, Koolohm insulated, layer-wound construction and resulting design features have enabled defense manufacturers to meet heretofore "impossible" specifications. Koolohms have set new standards of performance under adverse salt water immersion conditions. Complete Koolohm Catalog and samples on request.

SPRAGUE SPECIALTIES COMPANY, Resistor Division
NORTH ADAMS, MASS.

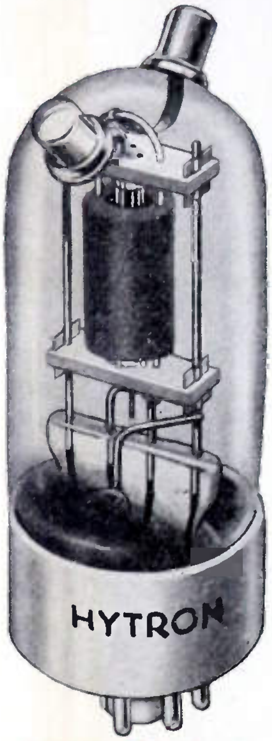


SPRAGUE KOOLOHMS

Greatest Improvement in Wire Wound Resistor Construction in 20 Years


1942
1952

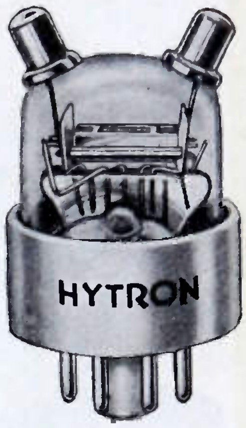
HYTRON GIVES YOU



HY75—$3.95 net

RECORD U-H-F PERFORMANCE

HY75—112 MC—335 miles*
HY615—224 MC—135 miles



HY615—$2.25 net
HY114B—$2.25 net

HY615 proved its record-making capabilities back in August, 1940, when used by W6IOJ and W6LFN to set a still-unbroken 224-MC record. HY615 tubes, used in simple transceivers, settled once and for all that efficiency, not size or price, is what counts in U-H-F tubes.

HY75, too, smashed to the front with a brand-new record. On August 21, 1941, at 8:38 p.m., just one year after the HY615 shattered all 224-MC records, W2MPY, working 112-MC portable on Mount Katahdin, Maine, raised W1JFF, at Newport, R.I.! This breath-taking, 335-mile QSO was made with an HY75.

** Reception over 400 miles on 112 MC with an HY75 is reported on page 54 of QST for October 1941.*

IF YOU WANT a tube which will give powerful performance on the very high frequencies, the HY615 has been operated on frequencies above 400 MC.

IF YOU WANT a superbly efficient tube of small size, a tube which will give real output on the ultra-highs, the HY75 was made to order for you.

IF YOU WANT a battery-operated 1.4-volt tube for compact mobile operation, you will discover, as did QST (see "The Radio Amateur's Handbook" for 1942, pages 327 to 330) that the HY114B is what you have been seeking.

TUBES FOR VICTORY

PEACE-TIME operation on the ultra-highs has proved that Hytron offers you the best in efficiency, economy, and satisfaction for your U-H-F equipment. Now, for emergency communications, for radio locators, for a host of other uses, Hytron submits as part of its contribution to VICTORY, those electronic magicians of the ultra-highs, those national favorites, the HY75, HY114B, and HY615.

CHECK THESE CHARACTERISTICS
with
YOUR U-H-F REQUIREMENTS

CHARACTERISTIC	HY75	HY114B	HY615
Filament potential	6.3 v.	1¼-1.4 v.	6.3 v.
Filament current	2.5 a.	0.145 a.	0.17 a.
Plate potential (max.)	450 v.	180 v.	300 v.
Plate current (max.)	100 ma.	15 ma.	20 ma.
Plate dissipation (max.)	15 w.	2 w.	3.5 w.
Approx. Class C output at 112 MC	19 w.	2 w.	4.5 w.

HYTRON RADIO TUBES

HYTRONIC LABORATORIES
23 New Darby St., Salem, Mass.
MANUFACTURERS OF RADIO TUBES SINCE 1921

A DIVISION OF
HYTRON CORP.

POSITIONS OPEN

•

The following positions of interest to I.R.E. members have been reported as open on March 1. Make your application in writing and address to the company mentioned or to

Box No. ....

PROCEEDINGS of the I.R.E.
330 West 42nd Street, New York, N.Y.

I.R.E. ASSISTANT SECRETARY

The Institute has immediate need for the services of a man with some business experience and a good general knowledge of communications engineering for the position of Assistant Secretary. Duties include carrying on correspondence, assisting the Secretary in conducting the Institute's activities, acting as secretary to technical committees, etc. Writing ability and publication experience desirable. Apply in writing to the Secretary, Institute of Radio Engineers, 330 West 42nd Street, New York, N.Y.

MECHANICAL ENGINEER

We need a first-class mechanical engineer who is thoroughly familiar with the production problems involved in manufacturing high-grade variable air condensers. Radio-engineering experience desirable. Hammarlund Manufacturing Company, 424 West 33rd Street, New York, N.Y.

DESIGN ENGINEER

We have an opening for an engineer with experience in the design of frequency-modulated transmitters and receivers. It is desirable but not imperative that the applicant have some experience in the design of directional antenna equipment for standard broadcast stations. The firm is an established manufacturer of broadcast-station and sound equipment. Box 264.

LABORATORY ENGINEER

An eastern manufacturer of components has an opening in its laboratory for a young man with a college electrical-engineering background. Box 265.

VOCATIONAL TRAINING DIRECTOR

We have an opening for a vocational-training teacher who is capable of organizing and directing our in-plant training program. Trainees are supervisors and workmen engaged in soldering, inspection, calibration, etc. on variable air condensers. Hammarlund Manufacturing Company, 424 West 33rd Street, New York, N.Y.

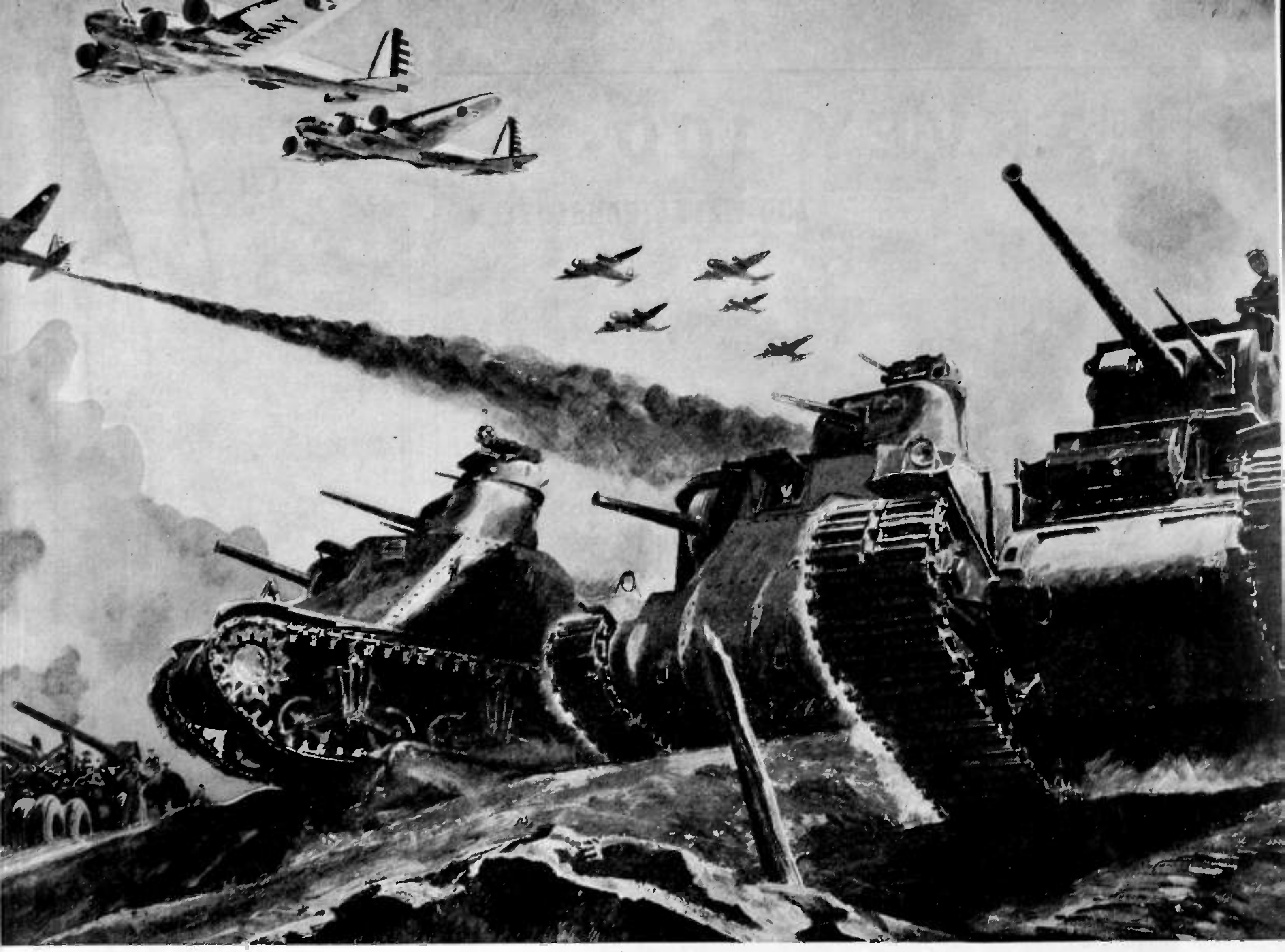
ELECTRONIC ENGINEER

There is an opening with a New York organization for an engineer experienced on communication circuits: auto telegraph, wire photo, or facsimile. He should be capable of directing layout for manufacturing. Box 266.

MICROPHONE MANUFACTURING

This firm wishes to employ an engineer experienced with the inspection and manufacture of carbon-button microphones. Duties include supervising the manufacture and inspection of microphones. Federal Manufacturing and Engineering Corporation, 211 Steuben Street, Brooklyn, N.Y.

(Continued on page xiv)



POSITIONS OPEN

(Continued from page xii)

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RADIO PHYSICIST

The United States Civil Service Commission has issued a call for physicists experienced in vacuum-tube circuits, short radio waves, and similar specialties at salaries ranging from $2,600 per year to $5,600 per year depending on the qualifications of the applicant. Additional information can be obtained by asking about examination No. 164 at the offices of the Commission in Washington or at any first- or second-class post office.

ENGINEERS FOR DEFENSE WORK

The Institute receives frequent calls from the government and private industry for engineers with experience in various specialized phases of radio engineering to engage in war work. If you are qualified and are not now in war work, you are invited to register with I.R.E. headquarters. A request will bring you 3 copies of a form on which you can summarize your experience. One copy is kept on file, the other two are available for circulation among interested employers. Box 260.

TRANSMITTING-TUBE ENGINEER

We have a permanent position with a real opportunity for a man with these qualifications: complete knowledge of all phases of advanced engineering—research, design, and methods—on all types of transmitting and electronic radio tubes. All correspondence will be treated confidentially. Taylor Tubes, Inc., 2341 Wabansia Avenue, Chicago, Ill.

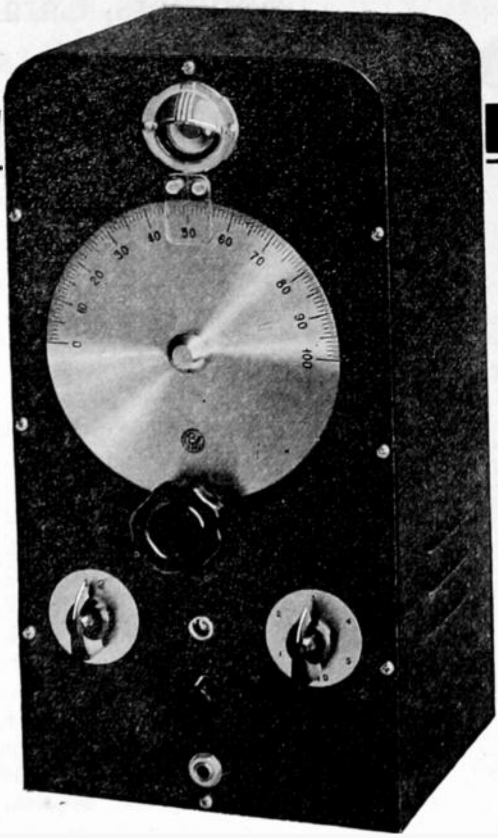
ENGINEERS AND PHYSICISTS

An activity of the United States Navy is in need of civil junior assistant and associate radio engineers, assistant and associate physicists and physicists for laboratory research and development work in conjunction with the national defense program. Salaries range from $2,600 to $3,800 per annum. For further information and application for employment form write the Director, U. S. Navy Radio and Sound Laboratory, San Diego, California.

Attention Employers . . .

Announcements for "Positions Open" are accepted without charge from employers offering salaried employment of engineering grade to I.R.E. members. Please supply complete information and indicate which details should be treated as confidential. Address: "POSITIONS OPEN," Institute of Radio Engineers, 330 West 42nd Street, New York, N.Y.

The Institute reserves the right to refuse any announcement without giving a reason for the refusal.



Booklets, Catalogs and Pamphlets

The following commercial literature has been received by the Institute.

TRANSFORMERS · · · *Acme Electric & Manufacturing Company, Cuba, New York.* "Specification Transformers for Radio, Television, and other Applications." *Illustrated Specification Sheets, 6 pages, 8½×11 inches.* Drawings with full dimensions and capacity ratings for 26 transformers offered by this company.

CAPACITORS · · · *Aerovox Corporation, New Bedford, Massachusetts. Transmitting Capacitor Catalog, 42 pages+cover, 8½×11 inches.* This Catalog contains not only a listing of such standard types as are deemed desirable for transmitting but also a compilation of essential technical data dealing with dimensions, terminals, mountings, electrical characteristics, and, in the case of the mica capacitors, radio-frequency current-carrying capacity, etc.

CAPACITORS · · · *Cornell-Dubilier Electric Corporation, Hamilton Boulevard, South Plainfield, New Jersey.* The Capacitor, *December, 1941, 16 pages, 5½×7½.* Describes an A-F Circuit Tester, and contains an article on Speedy Servicing.

INSULATION · · · *Corning Glass Works, Corning, New York.* "The Dielectric Strength of Glass—an Engineering Viewpoint." *Booklet, 8 pages 8½×11 inches.* Information regarding the dielectric break-down of glass, helpful in applying this insulation material more effectively for high dielectric strength.

IRON CORES · · · *Henry L. Crowley & Co., West Orange, New Jersey. Engineering Bulletin, 24 pages+cover, 8½×11 inches.* Presents data aimed at supplying the development engineer, confronted with the design of radio-frequency inductances, with suitable information in readily usable form so that it may be easily incorporated in coil design and used as the technical basis in selecting suitable core types particularly "Magicore" for specific applications.

CATHODE-RAY TUBE · · · *Allen B. Du Mont Laboratories, Inc., Passaic, New Jersey.* "Pioneering the Cathode-Ray and Television Arts." *Booklet, 6½×10 inches, 30 pages+cover.* A very complete history of ten years of research and progress in the development of cathode-ray tubes and the television arts together with the growth of the Du Mont organization. Interestingly illustrated.

POLICE RADIO · · · *General Electric Company, Schenectady, New York. Leaflet, 4 pages, 8×10½ inches.* Case histories on three 2-way police installations.

LINEAR VIBRATION MEASUREMENT · · · *General Radio Company, 30 State Street, Cambridge, Massachusetts.* "The General Radio Experimenter," *February, 1942, 8 pages, 6×9 inches.* A discussion of sound analyzing equipment, or electronic instruments for the measurement of linear and torsional vibrations. Also information and specifications for a 100-watt output power meter.

COMMUNICATIONS EQUIPMENT · · · *The Hallicrafters Company, 2611 Indiana Avenue, Chicago, Illinois. 1942 Catalog, 20 pages, 8½×11 inches.* Gives latest models of receiving, transmitting and radiophone equipment for commercial radio men, short-wave listeners, amateurs and boat owners.

TRANSFORMERS · · · *New York Transformer Company, 51 West 3rd Street, New York, New York. Leaflet, 4 pages, 8½×11 inches.* Describes and gives ratings for transformers, chokes and filters. Illustrated.

RADIO NOISE SUPPRESSORS · · · *Solar Manufacturing Corporation, Bayonne, New Jersey. Catalog 12—Section F, 4 pages, 8½×11 inches.* Describes and gives specifications for Solar "Elim-O-Stat" radio noise suppressors.

CAPACITOR ANALYZERS · · · *Solar Manufacturing Corporation, Bayonne, New Jersey. Catalog 12—Section G, 12 pages, 8½×11 inches.* Describes and illustrates with full specifications 6 Solar capacitors.

TRANSFORMER COMPONENTS · · · *United Transformer Company, 150 Varick Street, New York, New York. Bulletin No. PS-405, 32 pages+cover, 8½×11 inches.* This is an exceptionally complete catalog of transformers and components, well illustrated and with many helpful diagrams and tables. Tables on "Decibels vs. Voltage and Power" which are included should be useful to many radio engineers.

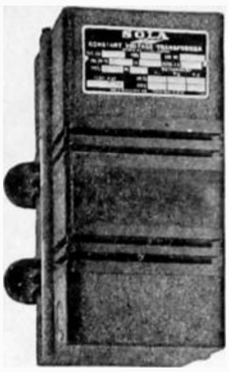
AIRCRAFT TRANSMITTERS AND RECEIVERS · · · *RCA Manufacturing Company, Inc., Camden, New Jersey. Data Sheets, 8 pages, 8½×11 inches.* Describes models AVR 100 and 101 receivers, and models AVT-110 and 111 transmitters.

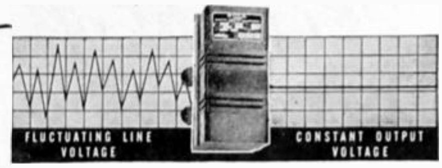
ANTENNA SYSTEM · · · *RCA Manufacturing Company, Camden, New Jersey. Data Sheets, 6 pages, 8½×11 inches.* Describes AVA-41A DeLuxe Antenna System, improved retractable type for aircraft.

CONSTANT VOLTAGE

is the answer to the precision demands of

SCIENCE and INDUSTRY for DEFENSE





Every COMMUNICATIONS system—every electrical INSTRUMENT employed in the production of materials of war needs CONSTANT VOLTAGE protection against line surges and fluctuating voltage levels caused by overloaded power lines. Sola CONSTANT VOLTAGE TRANSFORMERS will deliver a perfectly stabilized output voltage, even though line voltages vary as much as 30%. No moving parts. Instantaneous in action. Self-protecting against overload or short circuit.

Ask for Bulletin KCV-74

SOLA ELECTRIC COMPANY

SOLA ELECTRIC COMPANY

Constant Voltage **TRANSFORMERS**

2525 CLYBOURN AVE., CHICAGO, ILL.

A *New* AUTOMATIC FREQUENCY RESPONSE RECORDER

MANY NEW EXCLUSIVE FEATURES

A RECORD YOU CAN RELY ON

As its name implies, it will draw automatically and continually (on semi-log. paper, 4" wide) an accurate frequency characteristic of any audio transmission component or complete installation. Indispensable where rapid changes with respect to frequency occur and a continuous record is desirable. (Loud-speakers, microphones, etc.)

The frequency response is essentially flat from 40 to 40 KC; it responds to a .2 of a DB change of the input signal.

If the DB Potentiometer is replaced by a linear type potentiometer, the instrument will be a recording ampere meter or volt meter.

Completely AC operated — light weight (40 lbs.)—compact and portable.

The AUTOMATIC FREQUENCY RESPONSE RECORDER has many other new and exclusive features which are fully described in our Bulletin which we will send upon request.

• • • • •

SOUND APPARATUS COMPANY

150 West 46th St. **New York, N.Y.**

MEMBERSHIP EMBLEMS

The I.R.E. emblem is available to members in 3 useful forms: the lapel button, the pin, and the watch charm. Each is of 14-karat gold, enameled in color to designate the grade of membership.

Grade	Background Color
Fellow	Gold
Member	Blue
Associate	Maroon
Junior	White
Student	Green

●

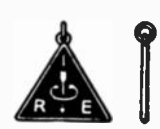
LAPEL BUTTON—$2.75

Supplied with a screw back having jaws which grip the cloth of the coat.

PIN—$3.00

Provided with a safety catch.

WATCH CHARM—$5.00



Enameled on *both* sides and equipped with a suspension ring for attaching to a watch charm or fob.

●

Prices on emblems are the same for all grades of membership and include postage and insurance or registered-mail fee.

Remittance should accompany your order

THE INSTITUTE OF RADIO ENGINEERS, INC.

330 West 42nd Street, New York, N.Y.

INDEX

DISPLAY ADVERTISERS

"TO PROVIDE FOR THE COMMON DEFENSE, TO PROMOTE THE GENERAL WELFARE"

Bad medicine for big bombers

ONE WAY to spoil a bomber's aim is to hang a curtain of steel over your ship and dare him to come down through it. To get that curtain of steel up there requires quick-firing, flexible guns.

To the plant of the Westinghouse Electric Elevator Company the Navy, a few months ago, brought its plans for such a gun. And to Westinghouse was given the important job of building the mounts that would control the aiming of these batteries of quick-firing guns.

And the Navy said, "Well done!"

Today, over the Westinghouse plant, there floats the Navy's "E" pennant—for excellence—eloquent testimony to the manner in which this Westinghouse plant performed the job. How was this plant able to get into growing production of these mounts so quickly? The answer lies in a Westinghouse characteristic called "know how"—the ability to get things done in the best possible way.

This Westinghouse "know how" makes itself felt wherever Westinghouse craftsmen build things. Whether for the common defense or the general welfare, this "know how" is doing a job. The same skill and ingenuity that made so many splendid things for peacetime living are now being applied to many important war weapons.

"Know how" will work for you again

We look forward to the day when we can give your home, your farm, or your factory the full benefit of Westinghouse "know how" again. To speed that day means just one thing to us: to produce, in ever increasing quantities, the tools with which to get the victory job done.

Westinghouse

For the Common Defense

Sterilamps
Bomb Fuses
Tank Equipment
Military Radio Equipment
Plastic Plane Parts
Seadrome Lighting Equipment
Navy Ship Turbines and Gears
Blackout Plant Lighting Equipment

For the General Welfare

Air Conditioning
Electric Refrigerators
Switchboards
Lamps
Steam Turbines
Elevators

These lists mention only some of the many thousands of Westinghouse products.

WESTINGHOUSE ELECTRIC & MANUFACTURING CO., PITTSBURGH, PENNSYLVANIA

INDUSTRY CAN COUNT ON MORE HOURS OF CAPACITOR USE PER DOLLAR

SOMEDAY, they'll ride serenely at anchor in our own ports in a world at peace — these mighty battleships of the United States Fleet. And when they come home, what stories their crews will tell — of the courage of American sailor-men, and the endurance of navy equipment.

Nowhere is dependability more vital than in the communications equipment of our Armed Forces, and in this Cornell-Dubilier plays an important part. C-D capacitors, long recognized for their *extra* dependability, today are setting new performance records in the service of Uncle Sam. From the experience of Cornell-Dubilier engineers, gained through more than thirty-two years of capacitor specialization, including all-out production during two world wars, American Industry stands to benefit — when peace comes — with more hours of capacitor use per dollar than ever before.

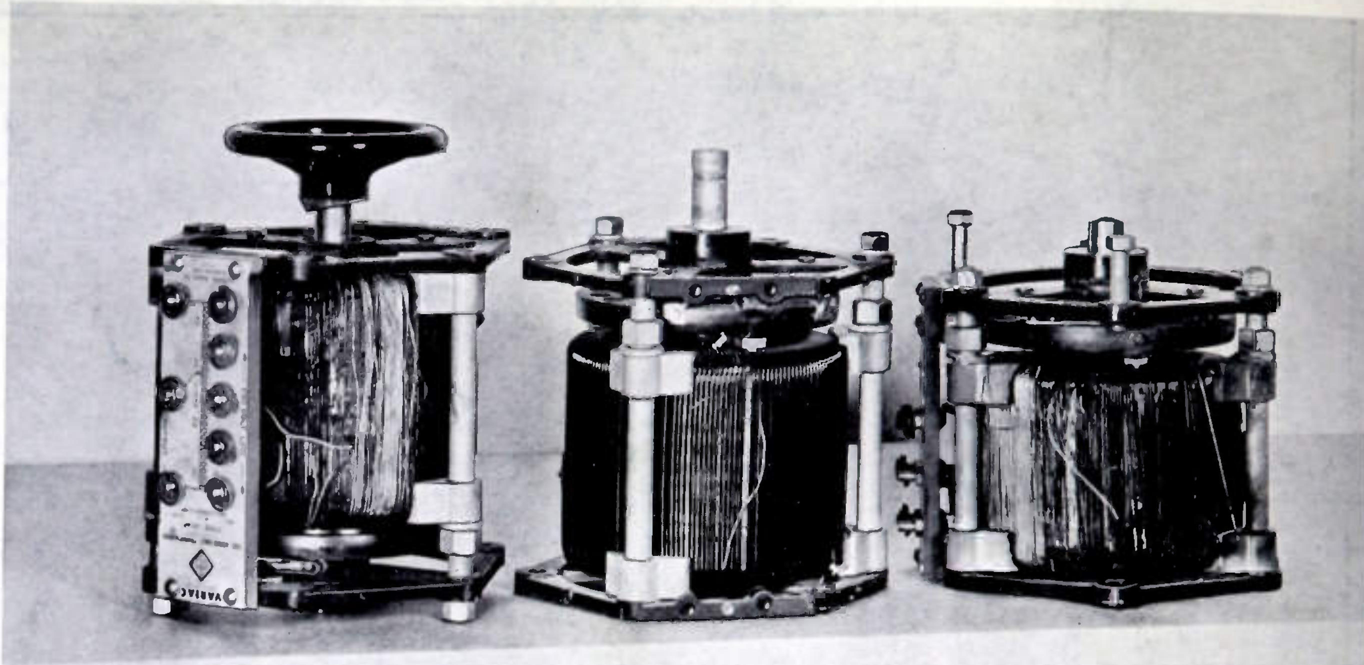
Cornell-Dubilier Electric Corporation, South Plainfield, New Jersey. New England Division; New Bedford, Mass.

DYKANOL TRANSMITTING CAPACITORS
Copied, imitated...but never duplicated.
Type TK Dykanol Capacitors are universally accepted as the finest quality capacitors ever offered in larger capacity and higher voltages for filter service. Hermetically sealed, these Dykanol capacitors are non-inflammable and non-explosive. Standard types available in capacities from .25 mfd. to 10 mfd. at voltages from 6,000 to 25,000 V.D.C. working.

Cornell Dubilier Capacitors

MICA • PAPER • DYKANOL • WET & DRY ELECTROLYTIC CAPACITORS

MORE IN USE TODAY THAN ANY OTHER MAKE



KEEPING THEM IN SERVICE

VERY FEW Variac auto-transformers give trouble even after years of fairly continuous use. Certain operating and maintenance precautions are necessary, however, to keep any Variac from passing out of the picture as did these in the illustration.

The five things to watch when using Variacs are:

- ***Worn Brushes***
- ***Dirt On Exposed Surface of Windings***
- ***Continual Overloads***
- ***Grounded Output Circuits***
- ***High-Voltage Surges***

The brushes should be inspected regularly and replaced before excessive wear causes the brass holder to come in contact with the winding. When this happens the holder short-circuits several turns: immediate fusing results and the Variac is ruined.

Variacs, when exposed to dirt, dust, grit and corrosive fumes, must be cleaned frequently to insure positive contact between the brush and the winding, and to prevent arcing.

When the windings become blackened or corroded they should be cleaned with crocus cloth or very fine sandpaper. All rough spots must be smoothed. Loose particles can be removed with a fine brush; the windings should then be cleaned with carbon tetrachloride or some similar cleaning fluid.

Overloading may cause excessive heating. While the winding may not be damaged if the load is removed quickly, the carbon brush may disintegrate. A new brush should be installed. Lengthy overloads may cause a turn or two of the winding to be displaced and raised from the core with danger of damage to the brush.

To keep surges from damaging the Variac when it is used in the primary circuit of a high-voltage transformer or other highly inductive load, it is necessary that either the voltage setting of the Variac be reduced to zero or the *output* circuit opened before the line circuit is broken.

Since the Variac is an auto-transformer, it should not be connected to a load circuit containing a ground, *unless* the same sides of the line and the load are grounded.

With these simple precautions, and an adequate supply of replacement brushes and line- and load-circuit fuses, the users of the Variac should expect many years of service from these transformers.

Write for a "Service Notes" order form to obtain a free copy of these "Service and Maintenance Notes" to help you secure greatest life and continued accuracy from G-R instruments.

GENERAL RADIO COMPANY
CAMBRIDGE, MASSACHUSETTS

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN