VOLUME 25, JULY, 1937 NUMBER 7

PROCEEDINGS
of
The Institute of Radio Engineers

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Institute of Radio Engineers
Forthcoming Meetings

PACIFIC COAST MEETING
Spokane, Washington
September 1 and 2, 1937

WASHINGTON SECTION
September 13, 1937

TOTH

PROCEEDINGS OF

The Institute of Radio Engineers

VOLUME 25 | July, 1937 | NUMBER 7

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The Institute of Radio Engineers

GENERAL INFORMATION

INSTITUTE. The Institute of Radio Engineers was formed in 1912 through the amalgamation of the Society of Wireless Telegraph Engineers and the Wireless Institute. Its headquarters were established in New York City and the membership has grown from less than fifty members at the start to several thousand.

AIMS AND OBJECTS. The Institute functions solely to advance the theory and practice of radio and allied branches of engineering and of the related arts and sciences, their application to human needs, and the maintenance of a high professional standing among its members. Among the methods of accomplishing this is the publication of papers, discussions, and communications of interest to the membership.

PROCEEDINGS. The PROCEEDINGS is the official publication of the Institute and in it are published all of the papers, discussions, and communications received from the membership which are accepted for publication by the Board of Editors. Copies are sent without additional charge to all members of the Institute. The subscription price to nonmembers is $10.00 per year, with an additional charge for postage where such is necessary.

RESPONSIBILITY. It is understood that the statements and opinions given in the PROCEEDINGS are views of the individual members to whom they are credited, and are not binding on the membership of the Institute as a whole. Papers submitted to the Institute for publication shall be regarded as no longer confidential.

MANUSCRIPTS. All manuscripts should be addressed to the Institute of Radio Engineers, 330 West 42nd Street, New York City. They will be examined by the Papers Committee and the Board of Editors to determine their suitability for publication in the PROCEEDINGS. Authors are advised as promptly as possible of the action taken, usually within two or three months. Manuscripts and illustrations will be destroyed immediately after publication of the paper unless the author requests their return. Information on the mechanical form in which manuscripts should be prepared may be obtained by addressing the secretary.

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	West Lafayette, 23 Waldron St.	Jensen, R. M.
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Proceedings of the Institute of Radio Engineers
Volume 25, Number 7 *July, 1937*

APPLICATIONS FOR MEMBERSHIP

Applications for transfer or election to the various grades of membership have been received from the persons listed below and have been approved by the Admissions Committee. Members objecting to transfer or election of any of these applicants should communicate with the Secretary on or before July 31, 1937. Final action will be taken on these applications on August 4, 1937.

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	Los Angeles, 240 W. Santa Barbara Ave.	Ziegler, W.
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	Grosse Ile, U. S. Naval Aviation Base	Rickards, H. B.
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	New York, 891 Southern Blvd.	Mond, L. I.
	New York, 765 E. 175th St.	Russ, B. H.
	Rochester, 37 Mildorf St.	Town, G. R.
	Scotia, 714 Riverside Ave.	Johnson, M. R.
North Carolina	Charlotte, c/o Radio Station WBT	Minor, M. J.
Ohio	Cincinnati, 1708 Howland Pl.	Huntington, C.
	Cincinnati, 4240 Verne Ave.	Jordan, D. M.
	Cincinnati, 330 Straight St.	McDowell, R. B.
	Cincinnati, 339 Ludlow Ave.	Schwesinger, W. L.
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	Cranford, Middlesex, 7 Firs Dr.	Fleming-Williams, B.
	Hampstead, N. W., 15 Wendover Ct.	Heyne, W. O.
France	Paris (XVe), Ministere de l'Air	Abeles, L.
Hungary	Budapest, Legrady Karoly-utca 24	Szilasi, A.
Latvia	Riga, c/o VEF Brivibas gatve Nr. 19	Vasilevskis, H.

For Election to the Junior Grade

Minnesota	Duluth, Safety Projector Company, 310 W. 2nd St.	Sarazen, E. P.
Virginia	McLean, "Salona"	Smoot, W. S., III.

For Election to the Student Grade

New Jersey	Rahway, R.D. 1, Box 167	Turnbull, H. A. Jr.
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INSTITUTE NEWS AND RADIO NOTES

Standard Frequency and Other Services Broadcast by the National Bureau of Standards

On June 1, 1937, the National Bureau of Standards made some changes and extensions in the services broadcast by its radio station WWV, at Beltsville, Md., near Washington, D.C. The services include (1) standard radio frequencies, (2) standard audio frequency, (3) standard time intervals in the form of pulses accurately spaced one second apart, (4) the standard of musical pitch, 440 cycles per second, and (5) bulletins of information on the ionosphere and radio transmission conditions.

1. Standard Radio Frequencies

This service makes generally available the national standard of frequency, which is of value in scientific or other measurements requiring an accurate frequency, and is useful to radio transmitting stations for adjusting their transmitters to exact frequency, and to the public generally for calibrating frequency standards. This service is given every Tuesday and Friday, (except nationally legal holidays), as heretofore, but the times, character, and frequencies of the emissions are somewhat changed. The emissions each Tuesday and Friday are continuous unmodulated, unkeyed waves (CW) except for a short pulse each second as described under 3 below.

The service is given successively on three radio carrier frequencies, as follows:

10:00 to 11:30 A.M., E.S.T., 5,000 killocycles
Noon to 1:30 P.M., E.S.T., 10,000 kilocycles
2:00 to 3:30 P.M., E.S.T., 20,000 kilocycles.

The power of the transmitter used is approximately twenty kilowatts. The emissions on 5000 kilocycles are particularly useful at distances within a few hundred miles from Washington, those on 10,000 kilocycles are useful for most of the rest of the United States, and those on 20,000 kilocycles are useful in the western part of the United States and in other parts of the world.

From any single frequency, using harmonic methods, any frequency may be checked.

During the first four and the last four minutes of the ninety-minute emission on each carrier frequency, announcements are given; they are made by telegraphic keying and by voice, and include the station call letters (WWV) and a statement of the frequency and the accuracy. The accuracy of the frequencies is at all times better than a part in five million.

2. Standard Audio Frequency

On each Wednesday (except nationally legal holidays), a frequency of 1000 cycles is transmitted as a modulation on the same radio carrier frequencies and at the same times of day as listed above. The radiated power will be approximately twenty kilowatts, with thirty per cent modulation.

Except during announcements, the emissions consist of the uninterrupted 1000-cycle frequency superposed on the carrier frequency. During the first four and the last four minutes of the ninety-minute emission on each carrier frequency, announcements are given; they are made by telegraphic keying and by voice, and include the station call letters (WWV) and a statement of the radio carrier frequency and the audio modulation frequency and the accuracy.

The accuracy of the frequencies (both carrier and modulation) as sent out from the transmitting station is at all times better than a part in five million. Transmission effects in the medium (Doppler effect, etc.) may result in slight fluctuations in the frequency as received at a particular place. As far as the carrier radio frequencies are concerned, such fluctuations practically never exceed a part in five million; furthermore, the presence of the audio modulation frequency does not reduce the accuracy of the carrier radio frequency. Under occasional extreme conditions, momentary fluctuations as great as one cycle may occur in the audio modulation frequency as received. It is generally possible, however, to use the audio frequency with an accuracy better than a part in a million by employing that one of the three carrier frequencies which has the least fading. It is helpful to use automatic volume control and audio-frequency filters to reduce the effects of fluctuations in amplitude or phase of the received audio frequency.

Any desired frequency may be measured in terms of any one of the standard frequencies, either audio or radio. This may be done by the aid of harmonics and beats, or, in the case of the 1000-cycle standard, also by the operation of a simple motor generator.

The standard 1000 cycles is especially useful in the accurate measurement of audio frequencies and time intervals, calibration of tuning forks, etc.

3. Standard Time Intervals

The CW standard frequency emissions each Tuesday and Friday, described under 1 above, will be modulated (30%) by a short pulse once each second (except during announcements). The pulse lasts about 0.005 second and consists of a 1000-cycle modulation on the carrier frequency; this type of pulse was chosen to facilitate its reception by ordinary radio receivers. The length of the intervals thus marked between each second and the next is accurate within 0.00001 second, as sent out from the transmitter. Measurements to this accuracy have not been made of these signals as received, but measurements made at one receiving location showed no error within the limits of precision of the measurement, which was about 0.00003 second. Vagaries occurring in the transmission medium may cause fluctuations materially greater than this at particular places or times where there is excessive fading.

These standard seconds signals constitute a standard frequency of one cycle per second, and are derived from the Bureau's primary standard of frequency which is in turn based upon the standard time service maintained by the U. S. Naval Observatory. They are of special value in physical measurements, in geodetic, seismological, and similar work, in rapid checking of pendulums and chronometer rates, and wherever short time intervals of great accuracy are needed. They are not capable of giving absolute time, as needed in navigation, for example, for which astronomical observations or the Navy's time signals are required.

4. Standard of Musical Pitch

The American standard of musical pitch, 440 cycles per second for A above middle C, is broadcast as a modulation frequency every night except Saturday and Sunday (and except nationally legal holidays). It is a 440-cycle modulation on a radio carrier frequency of 5000 kilocycles. The service is given daily from 4:00 P. M., to 2:00 A.M., E.S.T. The station call letters (WWV) are given every ten minutes on the even ten minutes by telegraphic keying, so that musicians using the service may be sure they are listening to the right station. The letters WWV are dots and dashes, as follows: · — — · — — · · · — The radiated power is one kilowatt, with 100 per cent modulation. The accuracy of the 440-cycle standard pitch is approximately the same as that of the 1000-cycle tone as described under 2 above; i.e., far beyond any musical requirements.

5. Ionosphere Bulletins

Data on the ionosphere and a summary of high-frequency radio transmission conditions are broadcast each Wednesday afternoon, the same day on which the 1000-cycle modulated emissions are given. The bulletin is given by voice on each of three radio carrier frequencies, as follows:

1:30 to 1:33 P.M., E.S.T., 10,000 kilocycles
1:40 to 1:43 P.M., E.S.T., 5,000 kilocycles
1:50 to 1:53 P.M., E.S.T., 20,000 kilocycles.

The broadcast includes statements of the normal incidence critical frequencies and virtual heights of the ionosphere layers, and estimated skip distances for a number of frequencies, all based on observations at Washington the day of the broadcast. Both day and night values are given. The information is an aid in choosing optimum frequencies for long-distance communication.

Further information is given in the Bureau's Letter Circular, "The Weekly Radio Broadcasts of the National Bureau of Standards on the Ionosphere and Radio Transmission Conditions."

General

Information on how to receive and utilize these various services is given in pamphlets obtainable on request addressed to the National Bureau of Standards, Washington, D.C.

The Bureau welcomes reports of use and comments upon the services. It is desired that users report to the Bureau their experience in using them, including description of method of use; statement of relative fading, intensity, interference, etc., on the three carrier frequencies; and suggestions for improvement of any details. Correspondence should be addressed to the National Bureau of Standards, Washington, D.C.

Institute Meetings

Boston Section

A meeting of the Boston Section was held on January 22 at Harvard University with E. L. Bowles, chairman, presiding. The attendance was seventy-five.

A paper on "The Frequency Stability of 100-Megacycle Oscillators" was presented by Arnold Peterson, research assistant in the department of electrical engineering of Massachusetts Institute of Technology. The subject was introduced with a discussion of vacuum tubes and tank circuits for use at ultra-high frequencies and the result of an experimental investigation of such oscillators was presented. The effect of changes in electrode voltages on the frequency of oscillation was first considered. High-Q circuits showed greater ability for stabilization than the more usual types of tank circuits. The observed relative ineffectiveness of parallel wire transmission lines for frequency stabilization was attributed to the radiation from the line. Measurements on an oscillator using a lumped concentric element tank circuit were used as a basis for a discussion of drift in frequency and the effect of loading. The paper was discussed by Messrs. Bowles, Hunt, Lamson, and Mimno.

The February 26 meeting was held at Massachusetts Institute of Technology with Chairman Bowles presiding and fifty were in attendance. D. F. Foster of the RCA License Division Laboratory presented a paper on "Broadcast Receiver Design." It was pointed out that in the manufacture of a highly technical product such as a radio receiver, the engineer is generally responsible for the success or failure of the enterprise. He functions as liaison between sales and manufacturing. In designing receivers basic specifications are dictated by market considerations but the engineer makes sure that the merchandising re quirements are technically feasible and can be produced economically with available equipment. With basic requirements in mind, the design proceeds from the original conception through consideration of electrical and mechanical layout, costs, and specifications, to final field tests prior to manufacturing. The general problem was illustrated by an example of basic chassis design. Other designs were considered as additions to or subtractions from the basic designs to meet specific requirements as to performance and cost. Examples were given of design variations in power supply, output, automatic volume control, and amplifier systems. Special features to improve operation were described and included variable selectivity, tuning indicators, automatic frequency control, and volume expansion.

The March meeting of the section was held on the 29th at Harvard University with Chairman Bowles, presiding. There were fifty in attendance.

E. A. Leach, engineer in the radio transmitter engineering department of the General Electric Company presented a paper on "Radio Transmitter Design Problems." Mechanical considerations in the design of commercial radio transmitters for both fixed and mobile applications were discussed. Typical requirements were described and methods commonly used to meet these were outlined. Examples of transmitter construction included the use of various metallic and insulating materials best adapted for specific purposes. Design economies reached by employing proper materials and forms for each purpose were stressed as being one of the most important problems involved.

On April 13 the Boston Section met at Massachusetts Institute of Technology with the Boston Section of the American Institute of Electrical Engineers. The attendance was 250 and Professor Bowles presided.

"High-Frequency Broad-Band Wire Transmission" was the subject of a paper by H. A. Affel, toll transmission development director of the Bell Telephone Laboratories. It was pointed out that developments make possible the use of increasingly higher frequencies on all types of conductors in long-distance telephony which include open wire lines, cables, and coaxial lines. Carrier transmission permits an increased number of channels over a given set of conductors and in the case of the coaxial structure wide bands suitable for television purposes may be had. On long circuits, repeaters are required at short intervals and are sometimes only ten miles apart. A description was given of developmental work in designing high-frequency amplifiers and automatic regulating equipment to compensate for the effects on the line of temperature and weather variations. This new broad-band technique has been made possible by such developments as negative feedback amplifiers, crystal filters, copper-oxide modulators, and other devices. A twelve-channel carrier system for open wire lines and another for existing cables, and an experimental million cycle 240-channel coaxial system were described.

Cincinnati Section

There were fifty-five present at the meeting and dinner of the Cincinnati Section held on May 25 at the Maketewah Country Club. G. F. Platts, chairman, presided.

A paper on "Obtaining High Fidelity Transmission with a 500-Kilowatt Transmitter" was the subject of a paper by R. J. Rockwell, technical supervisor of WLW, WSAI, and W8XAL. He presented first a brief history of the present WLW transmitter. At the time the 500-kilowatt transmitter was started, high fidelity programs and receivers seemed far in the future as viewed by the different companies participating in its design. The maximum allowable distortion was therefore set at ten per cent. With the advent of better receivers, this limit was intolerable and it has been possible to reduce the maximum distortion in the transmission to less than one tenth of its former value. Because of the power involved, each step in the process of reducing distortion required careful attention and progress has been necessarily slow. The paper was discussed by Messrs. Kilgour, Nyman, Wells and others.

A second paper on "Application of Stabilized Feedback to a 350-kilowatt Modulator" was presented by G. F. Leydorf, transmitter engineer at WLW, WSAI, and W8XAL. He presented first the fundamentals of stabilized feedback and pointed out how its application to a 350-kilowatt modulator differed from the problem of dealing with low power amplifiers. It was shown that 300,000 volts at six amperes peak must be available. Therefore it became necessary to add three stages of amplification ahead of the existing five-stage modulator. With feedback a lattice network was installed to prevent oscillation in the modulator at eighteen cycles. The paper was discussed by Messrs. Hultberg, Kilgour, Kolo, Wells and others. In addition to these papers, five reels of home motion pictures, which were descriptive of a recent tour of continental Europe made by Mr. Jaeckel were shown by him.

Connecticut Valley Section

The Connecticut Valley Section met on April 22 in the auditorium of the Hartford Electric Light Company. F. H. Scheer, chairman, presided and there were forty present.

"Ceramics and Iron-Dust Cores" was the subject of a paper by H. L. Crowley, President of the Henry L. Crowley Company. In introducing his paper, he pointed out that from ancient times ceramics have been made from natural clays, the plasticity of which permitted easy forming before hardening by baking. Natural clays place definite limitations on the electrical and mechanical characteristics of the finished ceramic. This has resulted in a new technique in the manufacture of ceramics which permits production of almost any desired characteristic. Use is made of the diagonal law which refers to a line from the upper left to the lower right corner of the periodic table of chemical elements designating a group of elements the oxides of which are excellent insulators. The ores of these elements are reduced to finely divided and refined powders which may be mixed in desired proportions and after various processes "squirted" by high pressure through dies giving the desired form. The ceramic form is fired in an oven the temperature of which is raised rapidly to within one hundred degrees of the desired value and thereafter carefully controlled. Cooling is important for mechanical characteristics. A ceramic binder, magnesium silicate, is used in the manufacture of iron-dust cores to separate and insulate the iron particles. Losses in the cores were then treated and the use of alloyed materials rather than special heat treatments was covered.

Detroit Section

Members of the Engineering Society of Detroit were invited to the May 21 meeting of the Detroit Section held at the Hotel Statler. There were 350 present and R. L. Davis, chairman, presided.

"The Stroboscope and Sound Level Meter" was the subject of a paper by H. H. Scott of the General Radio Company. He described first the principle of the stroboscope and two types were demonstrated. The Edgerton stroboscope gives a light intensity sufficient to illuminate several square feet of surface. The flashes of light are accurately timed and last about one one hundred thousandth of a second. This equipment was demonstrated. A small stroboscope was calibrated to give the frequency of light flashes which permits the speed of moving equipment to be computed. The speaker then described a high speed camera which operates in conjunction with the stroboscope. The object to be photographed is illuminated by the stroboscope and one hundred feet of film may be exposed each second. Pictures of good definition have been obtained at speeds of six thousand per second. A portable noise level measuring set was also described and demonstrated.

Montreal Section

On April 14 the Montreal Section met in the Engineering Institute Building with A. M. Patience, chairman, presiding. There were sixty in attendance.

A paper on "Current Developments in Radio Tubes in the United States" was presented by R. M. Wise, chief engineer of the Hygrade Sylvania Corporation. He discussed the new higher tensile strength filaments for battery operated tubes, higher sensitivity battery pentodes such as the 1G5G, beam power tubes, and converters. Graphical illustrations were shown of the effect on plate current, mutual conductance, and amplification factor of varying the distances between grids and changes in the grid wire sizes. In conclusion, he pointed out the desirability of greater co-operation between set manufacturers and tube manufacturers in order not to increase the already large number of tube types on the market. The paper was discussed by Messrs. Farley, Fisher, Hackbusch, Moore, Oxley, Parker, Patience, and Vennes.

The May 26 meeting of the Montreal Section also was held in the Engineering Institute Building and presided over by Chairman Patience. There were forty present.

A. B. Oxley, quality control engineer of the RCA Victor Company, Limited, presented a paper on "Vibrational Analysis of Radio Tubes." It dealt with the new method of analyzing tube structures by mechanical modulation of various elements and the interpretation of results on a cathode-ray oscillograph registering synchronous plate current variations. The exact measurement of microphonic susceptibility at critical frequencies was demonstrated and a method of classification provided together with a way of attacking the problem looking toward the elimination of these troubles. The usefulness of the method was demonstrated for both tube design and production test purposes. Fundamental equations of natural resonance and common modes of complex mechanical shapes were reviewed together with short cuts in diagnosis. The detection of loose welds, faulty suspension and improper clearance in standard tubes was demonstrated and the relation of quantitative mechanical tests to electrical tests in production examined. The paper was discussed by a number of those present.

Philadelphia Section

On May 8, Irving Wolff, chairman, presided over a meeting of the Philadelphia Section which was held in the Engineers Club and attended by 200. As this was the annual meeting, the election of officers took place and resulted in the naming of A. F. Murray of the Philco Radio and Television Company as chairman; H. J. Schrader of the RCA Manufacturing Company, vice chairman; and R. L. Snyder was re-elected secretary-treasurer.

The first of two papers was by E. D. Blodgett of the RCA Manufacturing Company and entitled "Features and Theory of Operation of an Aircraft Radio Compass, the Functions of Its Controls and Its Optional Characteristics." It covered a comparatively inexpensive aircraft compass designed for the use of itinerant or private fliers. It uses the combination of a loop and the ship's open antenna and functions over three separate bands of frequencies; which are 200–410, 550–1500, and 2200–6700 kilocycles designated as X, A, and B bands. It may be operated as a radio compass on the X and A bands and employs for this purpose both the loop and open antennas. In some sets the loop can be rotated but generally it is fixed in a plane perpendicular to the direction of flight to permit its use in keeping a ship on the radio beam. A compass indicator which is a direct-current microammeter with a center zero scale indicates the "on-course" position or angular deviation of the loop from a straight line to the station. When the ship is pointing directly toward or away from the station, the indicator reads zero. If the plane is turned left from the course, the indicator needle also points left providing the plane is flying toward the station. It was pointed out that with a ninety-eight-cycle oscillator used as a keying system the radio impulses received from the open and loop antennas can by phase shifting be made to indicate when the ship is on or off course. The loop antenna signals work through two tubes arranged in a push-pull system with their plates in parallel so as to give a polarizing effect by which loop signal impulses can be added to or subtracted from the signals received over the open antenna depending upon the direction of the ship's flight. The paper was discussed by Messrs. Murray, West, and others.

A paper on "The Fading Characteristics of the Top-Loaded WCAU Antenna" was presented by G. H. Brown of the RCA Manufacturing Company and J. G. Leitch of WCAU. This paper appeared in the May, 1937, issue of the PROCEEDINGS.

Rochester Section

The Rochester Section met at the University of Rochester on March 11. L. A. DuBridge, chairman, presided and there were 208 in attendance.

"Adventures in Electricity" was the subject of a paper by Phillips Thomas, research engineer, Westinghouse Electric and Manufacturing Company. It was primarily a demonstration of the applications of electricity and covered such devices as the electrostatic air filter, transmission line vibration, new magnetic alloys, stroboscope, sensitive relays including the infrared phototube application for burglar alarm systems and various pieces of equipment utilizing electronic amplifiers and apparatus requiring a knowledge of radio fundamentals.

More recent research work by Dr. Thomas has been in the development of electronic and light-sensitive devices. Many of these were demonstrated.

On April 1, a meeting of the section was held at the Sagamore Hotel with Mr. Branson, director of research of the General Railway Signal Company presiding. There were seventy-five present.

Vladimir Karapetoff, professor of electrical engineering at Cornell University preceded his paper with a fifteen-minute piano recital broadcast from WHAM. His paper was on the "Propagation of Electromagnetic Waves Along Parallel Conductors." The treatment was made of traveling waves on transmission lines which were caused by the release due to a lightning stroke of the previously bound charges on the conductor. The meaning of the "surge impedance" of the line and the effect on the reflected surge of the impedance at the termination of the line were discussed. An analogy was presented between electrical waves traveling along a conductor and waves along a hydraulic canal. He also discussed the application of diagrams devised by him for facilitating calculations of the effect of such terminal impedance.

San Francisco Section

Two meetings of the San Francisco Section were held during April. The first on the 14th was in the Down Town Association meeting rooms and presided over by Noel Eldred, vice chairman. There were thirty present.

W. W. Hansen, professor of physics at Stanford University led the discussion on the paper of which he was coauthor with J. G. Beckerly concerning "New Methods of Calculating Radiation Resistance With or Without Ground" which appeared in the December, 1936, issue of the PROCEEDINGS.

Robert Buss, a student at Stanford University had charge of the discussion of the paper on "Feed-Back Amplifier Design" by F. E. Terman which was published in the January issue of *Electronics*.

The second meeting was on the 29th and was held in the Pacific Telephone and Telegraph auditorium. There were thirty present and V. C. Freiermuth, chairman, presided. This meeting was devoted to the presentation of two papers by students. The first by E. B. Patterson of the University of California was on "An Investigation of Long-Line Frequency Control for Ultra-High-Frequency Transmitters." It was pointed out that contrary to experience below thirty megacycles, the radiation resistance of the control line is not negligible in its effect on the Q of a circuit. It was found to be several times as large as other losses. This accounted for the discrepancy in Q noted in the operation of an oscillator at two hundred megacycles. Frequency stability at that frequency indicated a Q of approximately a thousand instead of several times that value as would be indicated by an exclusion of radiation effects.

The second paper on "Application of the Autosynchronizer Oscillator to Frequency Demodulation" was by J. R. Woodyard of Stanford University. It appeared in the May, 1937, issue of the PROCEEDINGS.

The choice of the judges was the paper by Mr. Patterson who will receive the annual student paper prize given by the section. The award is the entrance fee and a year's dues as an Associate member of the Institute.

SEATTLE SECTION

On May 28 the Seattle Section met at KVI, Point Heyer, Vashon Island. There were forty-eight present and J. W. Wallace, chairman, presided.

"New Radio Developments of Bell Telephone Laboratories" was presented by F. H. McIntosh of the Graybar Electric Company who was recently associated with Bell Telephone Laboratories. He described briefly principal improvements made in radio transmitters since 1920. The contributions toward better performance obtained by broad bias modulation, concentric transmission lines, Doherty amplifier and the Black stabilized feed-back amplifier were mentioned. The paper was closed with a discussion of the need for producing higher field strengths to obtain further improvement and reliability in transmission. The paper was discussed by Messrs. Taylor and Wallace.

J. W. Wallace, chief engineer for the Puget Sound Broadcasting Company presented a paper on "KVI Radio Station." In it he described the new five-kilowatt Western Electric transmitter, the 444-foot self-supporting radiator, coaxial transmission line, and other features of the station. An inspection of the station followed the meeting.

Toronto Section

The following four meetings of the Toronto Section were held at the University of Toronto. The meeting on March 8 was attended by sixty-three and B. deF. Bayly, chairman, presided.

A paper on "Application of Negative Regeneration in Amplifiers" was presented by C. B. Fisher, radio engineer of the Northern Electric Company, Limited. He outlined the early work of the few investigators of the problem and discussed nomenclature. He suggested the use of the term "revertion" to describe what is otherwise known as "negative regeneration." Present uses of revertion includes special line amplifier circuits, program and some telephone circuits, speech amplifiers and broadcast transmitters, and some radio receivers. Although amplifier gain is reduced by revertion substantial improvements in stability result. This is particularly valuable in a line amplifier which must operate under conditions of varying plate and filament voltage. The stability and widened frequency response is highly desirable. It was shown that stable characteristics over a broad range of audio frequencies were possible even when working into a load of such variable impedance as is offered by a dynamic loud-speaker. An additional valuable characteristic of these amplifiers is the tendency to cancel out such spurious electrical disturbances as hum, tube noise, and harmonics generated in the amplifiers.

The meeting on April 12 which was attended by sixty-five was in charge of Chairman Bayly. It was devoted to a paper on "Vibrational Tube Analysis" by A. B. Oxley of the RCA Victor Company, Limited. A description of this paper is given in the report on the May meeting of the Montreal Section.

R. H. Klingelhoeffer, vice chairman, presided at the April 26 meeting which was attended by 157.

A paper on "Television Principles" was presented by R. B. Dome, development engineer of the General Electric Company at Bridgeport. No attempt was made to present the early history of television and the speaker devoted his time to the presentation of modern systems. Various methods of scanning were described such as the flying spot, film pickup, neon tube, and Kerr cell. The limitations of these methods have been overcome by using electronic means employing cathode-ray tube methods. It was pointed out that cathode-ray picture reproducing tubes require sensitive coatings which must not be phosphorescent and screens as fast as a tenth of a microsecond for good reproduction. The use of lenses and reflectors for obtaining larger pictures was described. It was pointed out that large cathode-ray tubes were too difficult to construct, have a tendency to collapse, and require high polarizing voltages.

Scanning devices supply very low output which must be amplified in order to control the transmitter. Frequencies between sixty cycles and 2.5 megacycles must be handled which requires careful design of all equipment to reduce distortion. It is necessary to transmit a timing pulse to synchronize the operation of the receiver with the transmitter scanning device. A discussion was then given of coaxial cables and their use in coupling to the transmitting antenna. Antenna design was also covered with special attention to the wide frequency band which must be radiated.

On May 10 the annual meeting of the section was held with Chairman Bayly presiding. There were fifty-one present.

"Radio Broadcast Transmission Problems in Canada" was the subject of a paper by K. A. MacKinnon, chief development and research engineer of the Canadian Broadcasting Corporation. The speaker restricted his discussion to transmission problems as viewed from the transmitting antenna. He discussed methods of measuring field intensity and methods of plotting it. In many instances the antenna system may be modified to provide greater effectiveness at a cost much less than that of increasing transmission power. Polar graphs of various types of antennas were presented and their characteristics outline. The effects of the ground and sky waves were discussed. The effective ground conductivity was considered and a geological map of Canada was shown on which were indicated those areas of good and poor conductivity. The paper was concluded with a report of recent information on the proposed international radio conferences and the matters with which they will deal. Although transmitter power and frequency assignments might best be handled by international agreement, the competition between various countries for the available allocations makes it a difficult problem. It was proposed that a joint engineering and standards committee be established at the conference to settle any differences by actual measurements of the conditions on which they are based. There exists today a lack of agreement in standards to bring about engineering answers to these questions.

In the election of officers, R. H. Klingelhoeffer of the International Resistance Company was named chairman; W. H. Kohl of Rogers Radio Tubes Limited was elected vice chairman; C. G. Irwin of Philco Products, Limited, recording secretary; and N. Potter of the Canadian National Carbon Company, secretary-treasurer.

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TECHNICAL PAPERS

SOME FUNDAMENTAL EXPERIMENTS WITH WAVE GUIDES*

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Summary—*This paper describes in considerable detail the early apparatus and methods used to verify some of the fundamental properties of wave guides. Cylinders of water about ten inches in diameter and four feet long were used as the experimental guides. At one end of these guides were launched waves having frequencies of roughly 150 megacycles. The lengths of the standing waves so produced gave the velocity of propagation. Other experiments utilizing a probe made up of short pickup wires attached to a crystal detector and meter enabled the configuration of the lines of force in the wave front to be determined. This was done for each of four types of waves. For certain types the properties had already been predicted mathematically. For others the properties were determined experimentally in advance of analysis. In both cases analysis and experiment proved to be in good agreement.*

PREVIOUS papers† have set forth the mathematical theory and a few of the experimental results concerning the transmission of electromagnetic waves through hollow metal tubes, through pipes filled with insulation, and also through cylinders of dielectric material. The purpose of this paper is to describe in considerable detail the methods by which the verifying experiments were made and to add data which it was not feasible to present previously. The methods described are believed to be of interest not only for the way in which they are able to verify the theory but also because they seem to be pointing toward a new technique of electrical measurements.

The previous papers have described four of the many forms of waves that may be propagated through guides. These waves may be distinguished by such propagating characteristics as velocity and characteristic impedance and also by the various configurations of the lines of force which go to make up their wave fronts. Also there is a critical or limiting frequency below which power is not transmitted. For convenience of reference certain of the standard configurations have been reproduced as Fig. 1 below for the particular case of a hollow metal pipe of circular cross section. These four configurations have been designated rather arbitrarily as E_0, E_1, H_0, and H_1 waves, re-

* Decimal classification: R110. Original manuscript received by the Institute, March 9, 1937. Several illustrations in this paper are published through the courtesy of the Engineering Institute of Canada and appear in its *Engineering Journal*, vol. 20, pp. 186–190; April, (1937).

† See references (6) and (7) of Bibliography.

spectively. Somewhat similar waves are also possible in wires of dielectric material where no metal shield is present but in that case the lines of force which are shown above as terminating on the conducting boundary extend into the surrounding space and close as loops.

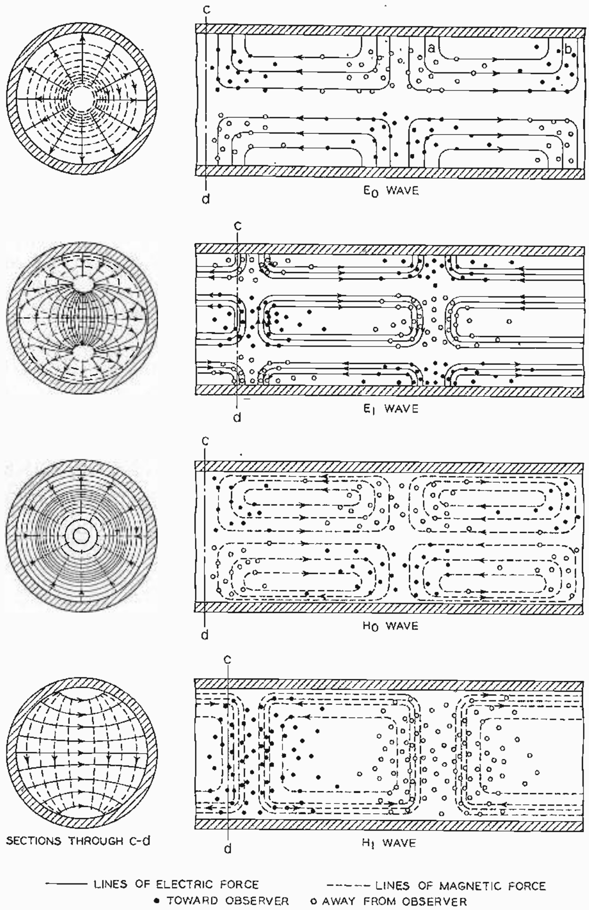

Fig. 1—Approximate configuration of lines of electric and magnetic force in a typical wave guide. Small solid circles represent lines of force directed toward the observer. Propagation is assumed to be directed to the right and away from the observer.

Obvious questions that might be asked at this time are: (1) Do the nice geometrical configurations shown in Fig. 1 actually exist in practice? (2) How are these waves launched and received? (3) How can their velocities be measured? The following paragraphs are directed at these answers.

Experimental Verification

The verification of the above-mentioned properties of waves and their guides has involved two rather different ranges of frequencies. In the earlier work which is the particular object of this paper, frequencies between 100 and 400 megacycles were used. In this case the waves were propagated through cylinders of water which served as the experimental guides. More recently it has been feasible to use air-core guides. However, this has called for much higher frequencies.

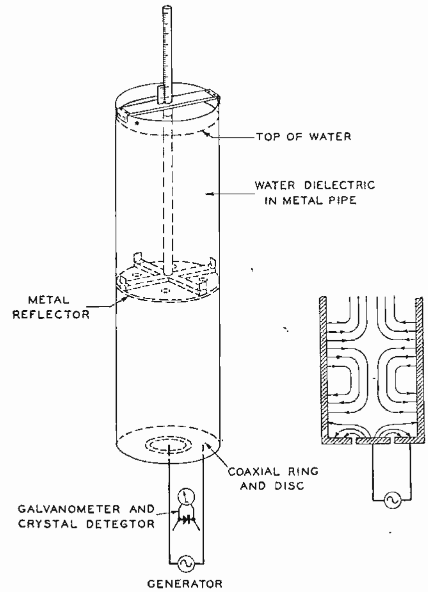

Fig. 2—Schematic of apparatus used to test theory of propagation through wave guides.

The latter are of the order of 1000 megacycles ($\lambda = 30$ centimeters) and 4000 megacycles ($\lambda = 7.5$ centimeters). The results obtained by the two methods are, however, very similar so that the more recent work can be said to be largely confirmatory.

Apparatus

The apparatus used in this preliminary study is shown in very simple schematic form in Fig. 2 and in greater detail in Fig. 3. As already explained the dielectric guide under observation consisted of a cylinder of water about four feet long. In the course of the experiments four such columns were used. Two were enclosed in copper tubes ten inches and six inches in diameter, respectively, and two were within bakelite tubes of these same diameters. The bakelite was considered sufficiently thin and its dielectric constant so low compared with water that the whole could be regarded as a cylinder of water only.

Waves generated by the source (1) (Fig. 3) were set up in the water column (2) through the intermediary of tuned parallel wires

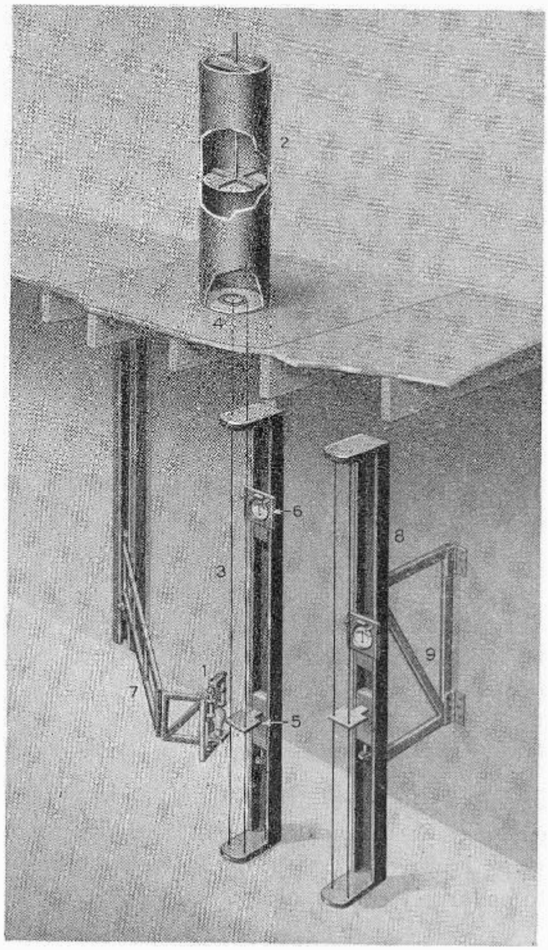

Fig. 3—Arrangement of oscillator, Lecher wires, and water column used in testing the theory of waves in dielectric guides.

(3) to which the water column was only loosely coupled. The kind and the degree of coupling could be varied through the use of different arrangements at the base of the column. These were sometimes referred to as "pads." In some cases this coupling was analogous to a mutual capacitance and in others it might be regarded as conductive or

inductive. The shape of the conductors on the pad determined the type of wave produced. When the E_0 type of wave was desired the pad took the form of metal disk surrounded by a metal ring. The two Lecher wires were then connected to the center and outside rings of the pad, respectively. If other types were wanted pads were used made up of other electrode arrangements as illustrated in Fig. 4 below.

The essential components of the assembled apparatus are shown in detail in Fig. 3. A shielded platform about six feet square separated in a general way the water column from the rest of the apparatus. The removable pads which afforded the coupling made close contact with the shield, thereby minimizing the wave power that might reach the dielectric from spurious sources. This isolation was acceptable but by no means perfect as the whole room was sometimes found to contain standing waves.

The parallel wires were capable of adjustment for length by means of a 4-$\times$4-inch brass bridge (5) which was movable along the wooden supporting frame. A permanently mounted scale enabled the position of the bridge to be read. A 0- to 200-microampere meter (6), to which was attached a sensitive crystal detector, was loosely coupled to the parallel wire system. This showed conditions of resonance in the parallel wires. This parallel wire system proved to be a moderately accurate wavemeter but it was not relied upon for this purpose. Its main function was that of impressing on the end of the dielectric guide waves of a definite configuration. This was considered to be more feasible than to couple the oscillator direct to the column.

The source (1) was mounted on the end of a wooden arm (7) hinged at two points. This permitted a wide range of couplings to the parallel wires. In some instances the separation was but a few inches but in other cases it was two or more feet. This arm was also capable of vertical displacement in order to meet the wide range of conditions due to wave length changes. The power leads to the oscillator were cabled and laced to the arm. There was little trouble from standing waves on these leads.

An independent wavemeter system (8) also made up of parallel wires was arranged vertically on a second hinged arm (9). This would be brought in from the right when it was desired to measure wave length. In this case the wires were much larger and the mechanical arrangement was such that more accurate bridge settings could be made than for the case of the parallel wires described above. This arrangement permitted measurements when the oscillator was under normal load. Its sensitivity was such that it led to no appreciable reaction on the source.

Standing waves were detected in the water column by three rather different methods. Substantially the same results were obtained by all. In one case the parallel wire system was adjusted for resonance, as shown by the meter (6), with no water in the column. Water was then admitted slowly through a hole in the bottom of the column. As the level of the water rose the deflection of the meter varied periodically through rather wide limits, indicating points of resonance in the column with a corresponding absorption of power from the parallel wire system. When the coupling between the column and the parallel wire circuit could be made small, the reaction between the two was also small except at points close to where absorption took place. This

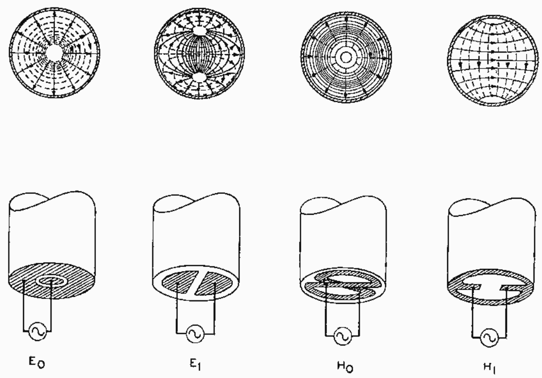

Fig. 4—Conductor arrangements used in launching various forms of guided waves.

method is very similar, of course, to the scheme that was at one time generally used in radio measurements where resonance in a secondary circuit was indicated by absorption in a primary. In this experiment the distance between successive absorption points was taken as one half of the wave length as measured in the medium.

In another method of detecting standing waves, the column was nearly filled with water and the parallel wires again adjusted for resonance. A circular disk of sheet copper which contacted the sides of the column was lowered into the water. This showed the same reactionary effects on the primary circuit as that of the changing water level. In the third method which was used in connection with E_0 waves, the copper reflector was divided into three coaxial rings between which "waterproofed" crystal detectors were connected. This is shown in Fig. 5(b) below. Connecting wires from the detectors were brought out to an external microammeter which indicated maximum conditions. The second of these three methods was most generally used.

Fig. 4 shows various coupling pads that were used. Each of the four pads was designed respectively for one of the types of waves shown in Fig. 1.

Fig. 5 shows some of the reflectors. That shown in (a) was most generally used. It would of course reflect any of the principal types

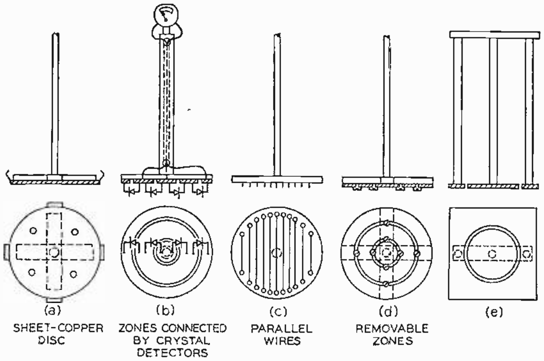

Fig. 5—Various arrangements used to reflect guided waves.

of waves. That shown in (c) was used to investigate the state of polarization in H_1 waves. That shown in (d) had removable sections and indicated what zones of the cross section of the guide contained the greatest E_0 wave power. That shown in (e) was used to determine the magnitude of fields outside of the guide itself. Two other reflectors not shown made up respectively of radial wires and wires arranged as coaxial circles were used in investigating the orientations in E_0 and H_0 waves.

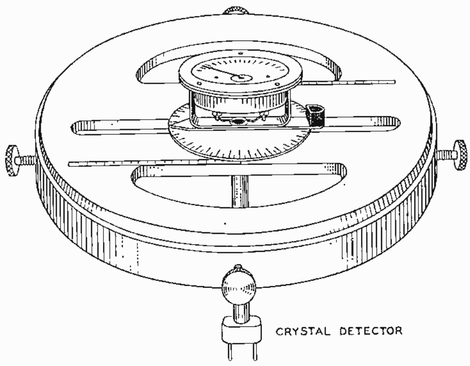

Fig. 6—Crystal detector and meter used as a probe in verifying the arrangement of the lines of electric force in a wave guide.

A meter and detector combination similar in principle to that used on the wavemeter served as a probe in determining the direction and intensity of the field in and about the dielectric wire. Fig. 6 shows the details of both the probe and its bakelite mounting. The latter was clamped to the top of the water column and adjusted so that the probe wires just reached the water. The probe could rotate about its axis as well as be moved laterally along the slot shown. The part in which the slot is located was also free to rotate with respect to the column so that the probe could be carried over the entire surface of the water. The two rotating parts were laid off in degrees and the slot carried a centimeter scale. Typical data obtained by this method are shown in Figs. 11, 12, and 13 below.

Experimental Results

The primary purpose of these experiments was to establish the existence of guided electric waves, particularly for the case of a guide surrounded by a conductor. This simple objective was readily accomplished as standing waves of a kind were produced with little or no difficulty. However, the waves first found turned out to be rather complicated usually indicating a mixture of two or more types each traveling with different velocities. It then became necessary to disentangle the component parts.

It is not feasible to discuss here all of the difficulties that were encountered except to say that, unless certain precautions are used in the design of the launching mechanism, many spurious waves may be set up in a guide. In most cases, however, these spurious waves may now be identified as a mixture of two or more of the standard types. The various coupling pads shown in Fig. 4 were evolved from some of these early experiments with a view to a fairly pure wave of the desired kind. It was in connection with this problem that the simple probe meter shown as Fig. 6 was first used. This disentangling process led to forms of waves not at first appreciated. However, mathematical analysis was soon able to account for these and other waves as well.

The method for determining velocity of propagation using the principle of standing waves was not essentially different than that commonly involved for the velocity of sound waves in air columns or for electric waves on Lecher wires or in free space. It is based on the simple fact that two oppositely directed waves of the same length and approximately the same amplitude give rise to a series of successive maxima and minima that appear to be at rest. Measurements of the distances between alternate maxima (or minima) give wave length λ_g as observed in the guide. This together with a knowledge of the frequency f permits velocity in the guide to be calculated by the simple relation $V_g = f\lambda_g$.

After methods had been found for producing a relatively pure wave, the measurements of the lengths of standing waves in the guide were generally consistent. Such measurements were subsequently made under a large range of conditions for each of the four water columns described above and for each of the types of waves under study. Typical amongst the results is the curve for the E_0 wave shown as Fig. 7. This was plotted from corresponding readings of the reflector levels as measured above the bottom of the column and deflections of the indicating meter coupled to the parallel wires. In order to show how these effects vary with frequency, several of these curves are shown in Fig. 8 for the case of a ten-inch diameter copper column.

In general, two limitations were encountered in this work. At the shorter wave lengths the minima were so close together that only the

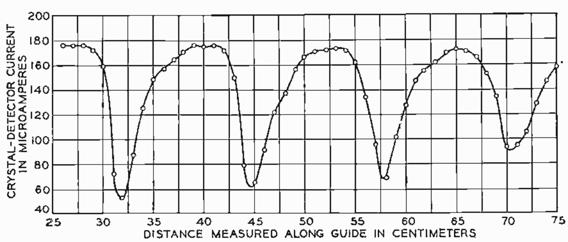

Fig. 7—Typical standing waves in a dielectric guide.

extremes could be located definitely. At the longer waves insufficient minima were included in the relative short columns at hand to measure wave length. This latter limitation, unfortunately, prevented observations near the critical or cutoff wave length. This difficulty was partially overcome by a different type of observation which will be described later. The close coupling which was necessary to give a readable deflection at the shortest wave lengths indicated high attenuation and strongly suggested that the operating frequency was then near an absorption band for liquid water.

It will be noted that corresponding to each curve in Fig. 8, three values are recorded. The first is the wave length λ_a, measured in air. The second is λ_g, or the wave length measured in the guide, while the third is a ratio of these quantities and is designated as K. The latter may be regarded as the relative slowness at which waves travel in the medium as compared with free space and is a quantity susceptible to calculation from the theory of guided waves. The orderly manner by which the relative slowness approaches the value nine, which is the value assumed for the index of refraction of water, is made more evident by the upper curve of Fig. 9. The points are experimental. The curves result from a calculation of wave slowness.

Similar but less extensive measurements of λ_g and K for E_0 waves

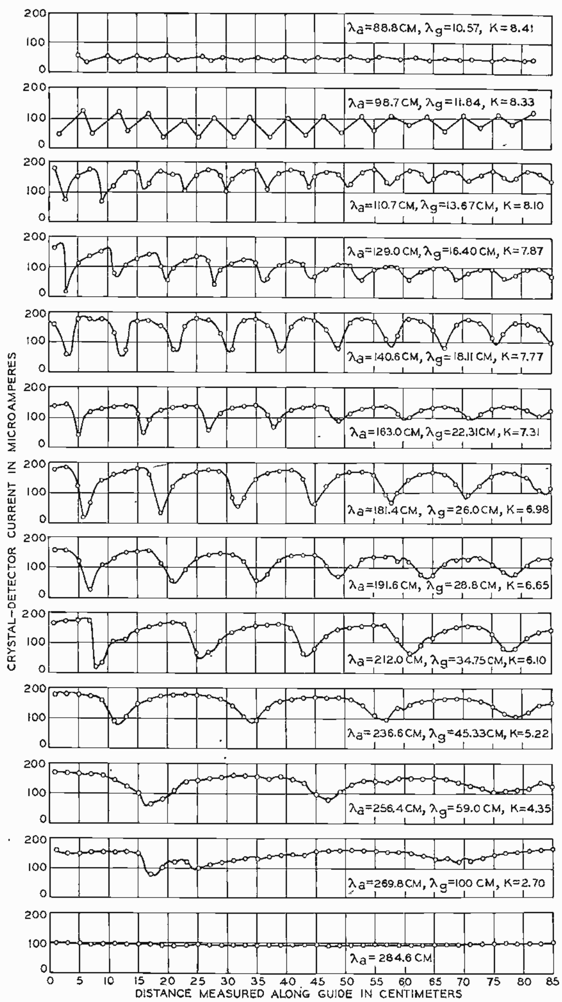

Fig. 8—Experimentally determined standing waves in a ten-inch diameter column of water surrounded by a copper sheath.

were made for other columns both with and without metal shields with results somewhat similar to those shown in Fig. 8. These latter curves are not regarded as being of sufficient general interest to be reproduced here. The resulting values of K are, however, plotted in

Fig. 9. It will be noted that the experimental data agree rather closely with those calculated. A comparison of the two curves corresponding respectively to a dielectric guide with and without a sheath indicates

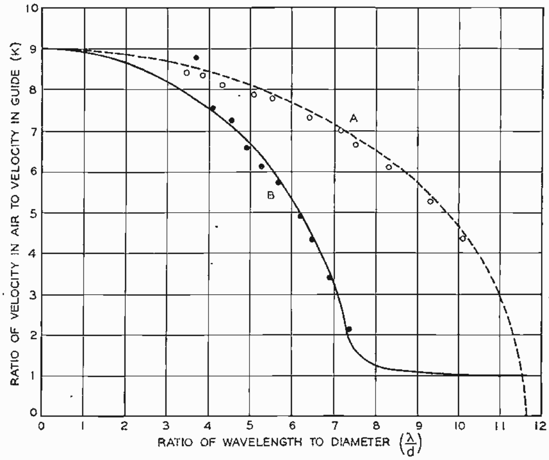

Fig. 9—Relative wave slowness in water columns. (A) water enclosed in a copper cylinder. (B) water enclosed in a bakelite cylinder.

that in general the velocity of propagation is greater without the sheath than with the sheath. This may be interpreted to mean that when there is no sheath the lines of electric force extend into the sur-

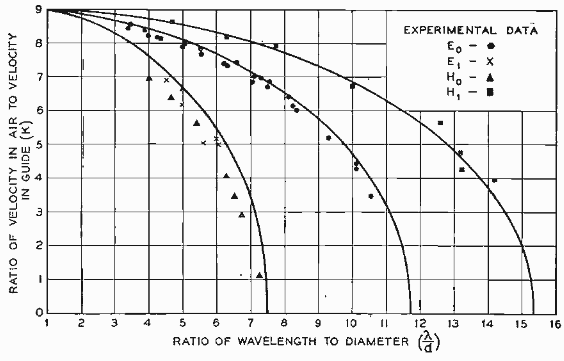

Fig. 10—Relative wave slowness in a copper sheathed water column for each of four principal types of waves.

rounding medium which in this case is air so that the resulting velocity is dictated not only by the dielectric constant and the dimensions of the guide but also by the properties of the external medium as well. The underlying theory also points to this view; Fig. 10 is a composite assemblage of the available data relative to a shielded guide using water as the dielectric material. It needs no further comment.

Limiting Cases

The data shown in Fig. 8 together with the values of K plotted in Fig. 9 indicate quite clearly that two limiting cases are being approached. The first is for $K=9$ where the wave length in air is relatively short and the second is for $K=0$, where this wave length approaches a critical value determined by the diameter of the guide. This corresponds of course to the critical frequency below which no substantial amount of wave power may theoretically be transmitted through a dielectric guide. Also it is at this frequency that the velocity of propagation approaches infinity. Under these circumstances the wave length becomes somewhat greater than the length of the test columns at hand. It was this limitation that made the method described above inadequate to determine the characteristics near the critical wave length.

Another approach to the behavior of guides near cutoff was made by a somewhat different method. To this end the coupling between the oscillator and the Lecher wires was kept constant. The electromotive intensity impressed on the guide therefore remained roughly constant. The probing meter described above was next arranged to give a convenient deflection. A reading of this meter was taken for each of several exciting frequencies as cutoff was approached. This was regarded as a rough measure of the amplitude of the received wave. It was, of course, necessary to adjust the parallel wires to resonance each time after the frequency had been changed.

These experiments showed that the cutoff property may be readily demonstrated in a qualitative way. When the core of the guide is air the cutoff frequency is very sharp and is close to that calculated. However when the core is water the cutoff frequency is as might be expected somewhat less well defined.

Experiments Confirming the Field Distribution

As already mentioned, a probe consisting of a crystal detector and microammeter such as shown in Fig. 6, may be used to determine the direction of the lines of electric force in the wave front. This proved to be very useful not only in verifying the standard forms of waves but also in studying the nature of complex or spurious waves. Typical results are shown in Figs. 11, 12, and 13 below. In these diagrams AOB and COD refer to two mutually perpendicular diameters of the guide along which the probe is carried. The diameter AOB is that along which the electromotive intensity is applied.

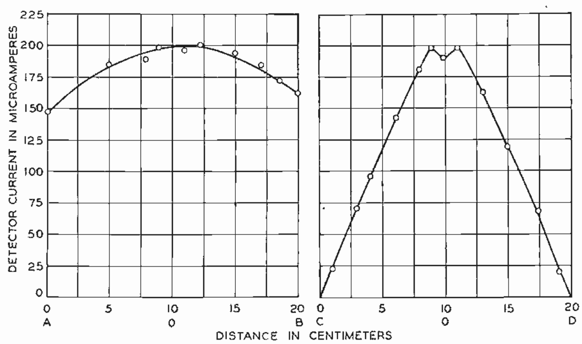

Fig. 11—Measured electric field intensity in the wave front of the H_1 wave. In all cases the probe wires were in the direction of greatest meter deflection.

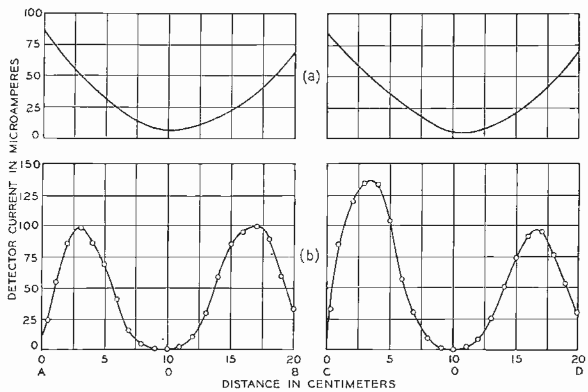

Fig. 12—Measured electric field intensity in the front of the E_0 wave. (a) Water column surrounded by copper sheath. (b) Bakelite sheathed column of water.

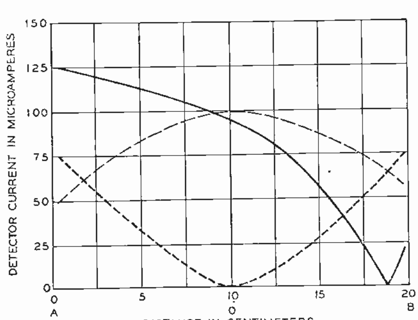

Fig. 13—Typical field distribution when spurious waves are present. Curve (3) represents distribution observed. Curves (1) and (2) represent components going to make up the distribution observed.

In exploring the field of a pure H_1 wave it was readily verified that the lines of force were chords generally parallel to the plane along which the electromotive intensity was applied. When the probe was carried across the diameter AOB the deflection was optimum only when the line connecting the probe wires was kept parallel to this plane and was zero or very small when oriented at right angles thereto. When the probe was carried along COD again the deflection was optimum when parallel with this plane. Fig. 11 indicates roughly the magnitudes of the deflection as the probe was carried along these two diameters. At points near the wall there was a definite tendency for the optimum position to be radial. This is of course in keeping with the idea that small areas of conductors may be regarded as equipotentials and that lines of electric force approach such conductors perpendicularly.

For the E_0 type of wave the probemeter reads a maximum when the line connecting the two probe wires is radial. A typical variation in meter reading as one carries the probe along two diameters of a shielded guide is shown by Fig. 12(a). Fig. 12(b) shows similar data for an unshielded dielectric cylinder.

Similar measurements on the H_0 type of wave in a sheathed guide gave results roughly the same as for E_0 waves in an unsheathed guide except that the line of the probe wires was kept in a tangential direction for maximum deflection. In practice it is not always possible to obtain an altogether symmetrical pattern in either of the E_0 and H_0 experiments. This is evidenced by Fig. 12.

No great effort was made to verify the shape of the E_1 wave. However, it was not difficult to establish the two null points that are evident from the configuration shown in Fig. 1.

Fig. 13 shows a typical distribution of field as found in a wave front where there is a mixture of E_0 and H_1 waves. In an early search for the E_0 wave a mixture of this kind persisted for some time. The results are now easily accounted for by combining say Fig. 11 with Fig. 12(a). Certain other spurious distributions were occasionally found in these experiments which might be ascribed to particular conditions of the setup or even to the presence of the observer himself. The latter was particularly true in cases where no metallic sheath surrounded the column.

Other Experiments Confirming the Field Distribution

A second method throwing some light on the field distribution in E_0 waves consisted of a measurement of the amplitudes of standing waves as reflection took place from different zones of the dissectible disk shown as Fig. 5(d) above. The results of one such test made near the lowest critical frequency are shown in Fig. 14. It will be noted that curve (a) produced by a solid reflector has well defined minima as has also curve (b) which was produced by all zones of the dissectible reflector combined. It appears from (c) that little loss is entailed by removing the central zone. This is substantiated by curve (d) which shows that the central zone alone produces little reflection. Curve (e) indicates that the outside zone plays a very important role in intercepting wave power but it is considerably less important than the

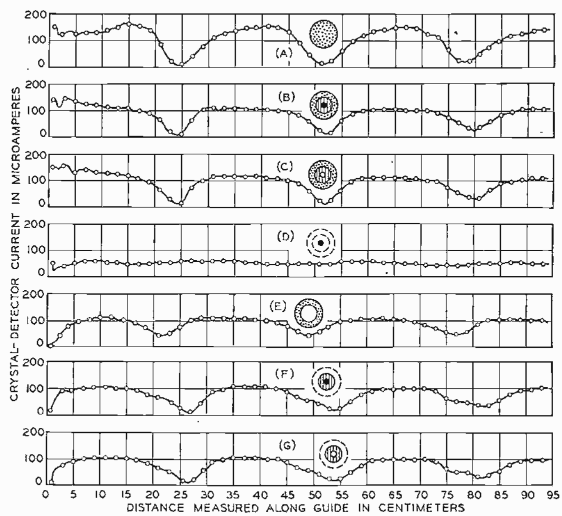

Fig. 14—Relative amplitudes reflected from various zones of a demountable disk.

intermediate zone as will be seen from curves (f) and (g) This method of studying the field distribution provided a very interesting check on the probe tests but it is perhaps too cumbersome for general use.

In studying H_1 waves a reflector made up of parallel wires appeared fully as effective as a disk of solid metal so long as the wires were kept parallel to the lines of electric force. When they were rotated ninety degrees there was little or no reflection.

In another experiment a dipole having a length slightly less than the diameter of the water column was constructed by attaching wires to the two terminals of a flashlight bulb. This was mounted on the end of a wooden rod so it could be lowered into the water. At a point near the bottom of the column the lamp would light to full brilliancy so long as the dipole was in the direction of the lines of electric force. As the dipole was rotated still keeping it at this level the brilliance was reduced more or less as the cosine of the angle. Lifting the dipole up and down while oriented to the optimum angle showed the presence of nodes and loops of standing waves. The brilliance was progressively less at each successive loop indicating that the water gave rise to considerable attenuation.

The reflector made up of radial wires was very effective for E_0 waves but it had little or no effect on H_0 waves. In a similar way the reflector made up of circular wires mounted coaxially reflected the H_0 waves but it was indifferent to E_0 waves. This is of course what might be expected and is offered here only as a further confirmation of the predicted theory.

As might be expected, certain of these screen arrangements have proved to be useful devices in subsequent wave guide work. For instance, it sometimes happens that spurious components are present when the H_0 type of wave is generated. If such is the case we may interpose a screen made up of radial conductors and thereby discourage unwanted components. Similarly unwanted components may be filtered from E_0 waves by the use of strainers made up of coaxial metal circles.

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CHARACTERISTICS OF THE IONOSPHERE AND THEIR APPLICATION TO RADIO TRANSMISSION*

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Summary—*Results of ionosphere measurements near Washington, D.C., made at normal incidence over the period May, 1934, to December, 1936, inclusive, are presented in graphical form as monthly averages for each hour of the day. The general forms of the diurnal and seasonal variations of the critical frequencies and virtual heights have recurred from year to year. In addition to the seasonal variation there has been a continuous long-time increase of critical frequencies which is associated with the eleven-year sunspot cycle. Data are given only for those layers which are fairly regular in behavior—the normal* E, F, F_1, *and* F_2 *layers.*

The interpretation of properties of the ionosphere in terms of radio transmission over medium and long distances is discussed. The properties considered are absorption, virtual height, and critical frequency. It is pointed out that the long-time increase of critical frequencies indicates a corresponding rise in useful transmission frequencies. The paper also describes briefly two types of irregular disturbances of the ionosphere which affect radio transmission.

I. Introduction

A PROGRAM of measurement of critical frequencies and virtual heights of the ionosphere has been carried on at Washington, D.C., by the National Bureau of Standards since January, 1930. Results have been given from time to time in a number of published papers. One of these papers[1] gives systematic data on critical frequencies of the various regions of the ionosphere for the year May, 1933, to April, 1934, inclusive. These data were obtained with the multifrequency automatic recorder originated and developed[2] at the National Bureau of Standards in 1932. Experimental evidence of the beginning of a long-time increase of average critical frequencies was also given in that paper.

The use of the multifrequency automatic recorder has made it possible to secure hourly ionosphere records at the National Bureau of Standards since May, 1933. The recent adoption of the idea of

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[1] T. R. Gilliland, "Multifrequency ionosphere recording and its significance," *Nat. Bur. Stand. Jour. Res.*, vol. 14, p. 283; March, (1935); Proc. I.R.E., vol. 23, pp. 1076–1101; September, (1935).

[2] T. R. Gilliland, "Note on a multifrequency automatic recorder of ionosphere heights," *Nat. Bur. Stand. Jour. Res.*, vol. 11, p. 561; October, (1933); Proc. I.R.E., vol. 22, pp. 236–246; February, (1934).

multifrequency automatic recording and the principle of this recorder by the Carnegie Institution of Washington, British Radio Research Board, Australian Radio Research Board, and Harvard University will increase enormously the continuity and value of ionosphere data, which will in turn greatly increase our understanding of world-wide ionosphere and radio transmission conditions.

The graphs of the present paper present the results of observations continued since April, 1934, through December, 1936, and an extension of the F data to each hour of the day. The average, for each hour, of the critical frequencies and virtual heights of the three principal strata, the normal E, F_1, and F_2 regions, is given for each month. Curves are not plotted for the sporadic E, since its appearance was so erratic that average results would not be reasonably dependable, although it is known that sporadic E frequently determined the upper frequency limit of sky-wave transmission, especially during the summer. These graphs are intended to show the average diurnal variation of ionosphere characteristics for each month of the year, as well as long period changes. It is believed that the information will be useful in predicting propagation conditions.

Following the precedent established in earlier papers, the critical frequency for the ordinary ray is given for the F_1 layer while that for the extraordinary ray is given for the F_2 and F layers. In the case of the F_1 layer the ordinary ray is the more suitable for the purpose of averaging since it is much stronger and is therefore more frequently observed than the extraordinary ray. With regard to the F_2 and F layers the critical frequency for the extraordinary ray is, with the exception of irregular scattered reflection, the highest frequency returned at normal incidence. Its value gives a measure of the highest usable frequency for short-distance transmission. For long-distance transmission the extraordinary ray may however be expected to extend the usable frequency limit very little, if any, above that for the ordinary ray. If the critical frequency for either ray is known, that for the other may be determined by a simple calculation. At Washington the critical frequency for the extraordinary ray is roughly 800 kilocycles higher than that for the ordinary ray, for ordinary ray critical frequencies above 2500 kilocycles.

The graphs represent measurements obtained both with the multifrequency automatic recorder and by manual observations. The automatic recorder was arranged to cover the frequency band 2500 to 4400 kilocycles once each hour. The manual measurements were usually made during one day each week and principally at frequencies above 4400 kilocycles.

The results of the manual observations are averages for a 60-minute interval centered on the hour. The automatic records began on the hour and lasted $4\frac{3}{4}$ minutes. Although the upper limit of the automatic recorder was 4400 kilocycles, the critical frequency for the extraordinary ray could be determined to as high as 5200 kilocycles, by the 800-kilocycle separation relation mentioned above. Since December, 1935, the multifrequency records have been supplemented by measurements with a fixed-frequency recorder operating either on 7250 or 6200 kilocycles, giving a record of a few seconds duration every $4\frac{1}{2}$ minutes.

The symbols used are as follows:

h_E: E-region virtual height, (lowest measured height).
h_{F_1}: F_1-region virtual height, (lowest measured height).
h_{F_2}: F_2-region virtual height, (lowest measured height).
h_F: night F-region virtual height, (lowest measured height).
f_E: E-region critical frequency, in kilocycles , ordinary ray,
$f^0_{F_1}$: F_1-region critical frequency, in kilocycles, ordinary ray.
$f^x_{F_2}$: F_2-region critical frequency, in kilocycles, extraordinary ray.
f^x_F: night F-region critical frequency in kilocycles, extraordinary ray.
E.S.T.: Eastern Standard Time (=75 degrees West Meridian Time).

Figs. 1 to 15, inclusive, give the hourly averages of critical frequencies and minimum virtual heights for the E, F_1, and F_2 regions of the ionosphere for each month of the year from May, 1934, to December, 1936. For a given month the several years are plotted on the same figure through September, 1936. This arrangement makes it easy to see changes which have occurred from year to year. October to December, 1936, were plotted separately because the scale already in use was inadequate for the higher critical frequencies.

II. Virtual Heights

Referring to these figures, we shall consider first the virtual heights. In general, the maximum frequency of waves which may be returned from a region of given ionization density will be higher, the greater the angle of incidence. Since greater angles of incidence are obtained for transmission over a given distance, the lower the height of the reflecting layer, it follows that the virtual height of a layer is one of the important characteristics of the ionosphere in determining propagation conditions. It should be noted that on account of the curvature of the earth and the ionized regions, the angle of incidence at a layer must always be somewhat less than ninety degrees.

The virtual heights of the E and F_1 regions did not vary greatly

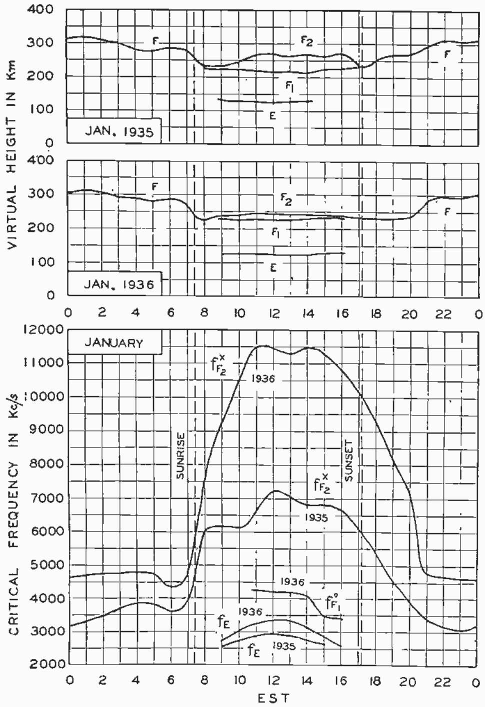

Fig. 1—Critical frequencies and virtual heights for January. Curves represent hourly averages.

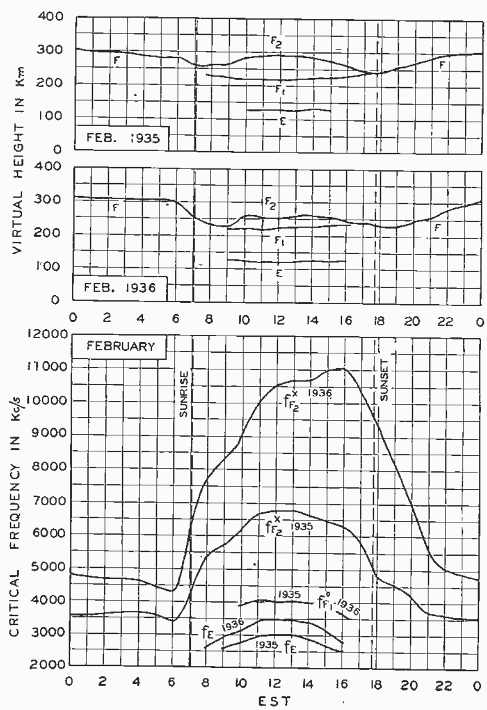

Fig. 2—Critical frequencies and virtual heights for February. Curves represent hourly averages.

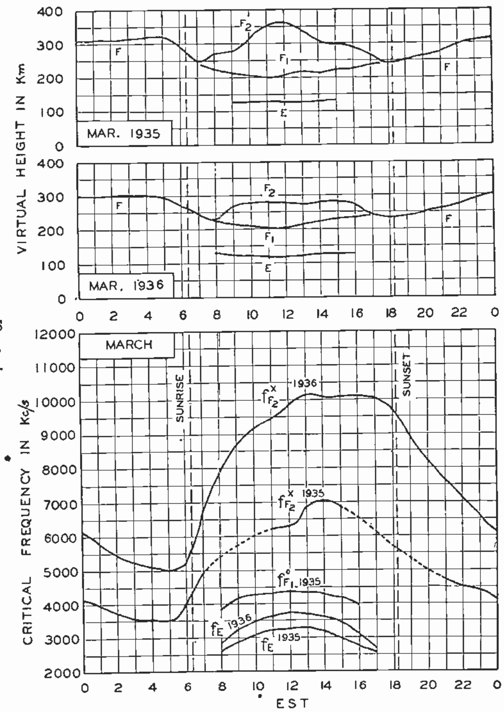

Fig. 3—Critical frequencies and virtual heights for March. Curves represent hourly averages.

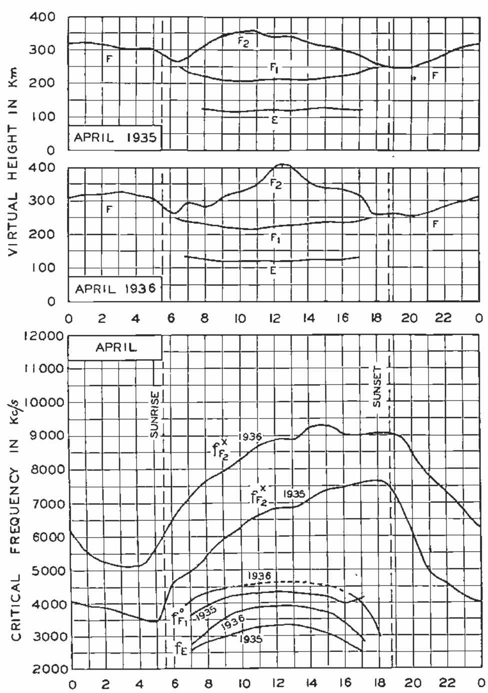

Fig. 4—Critical frequencies and virtual heights for April. Curves represent hourly averages.

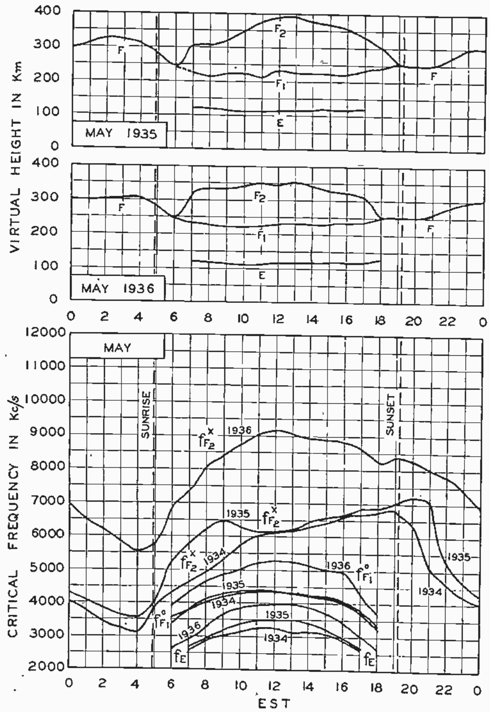

Fig. 5—Critical frequencies and virtual heights for May. Curves represent hourly averages.

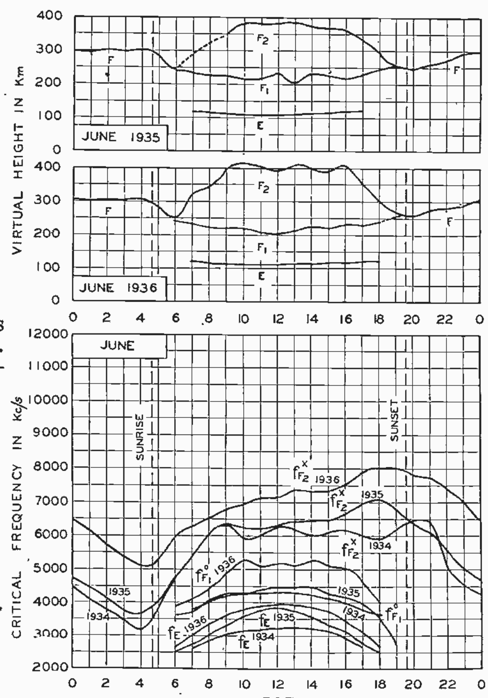

Fig. 6—Critical frequencies and virtual heights for June. Curves represent hourly averages.

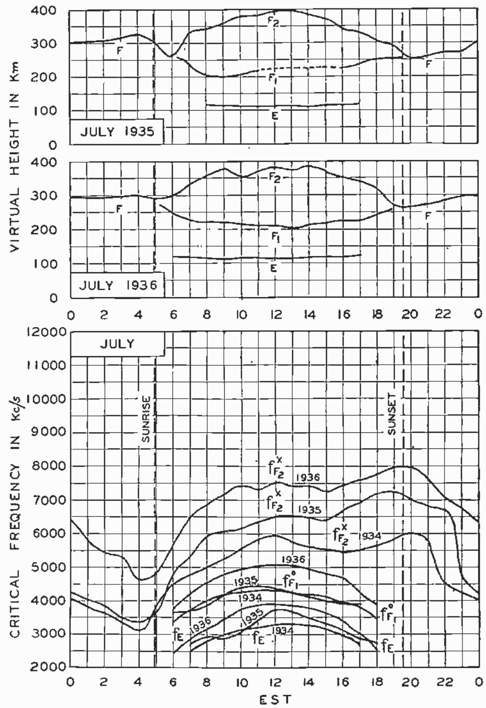

Fig. 7—Critical frequencies and virtual heights for July. Curves represent hourly averages.

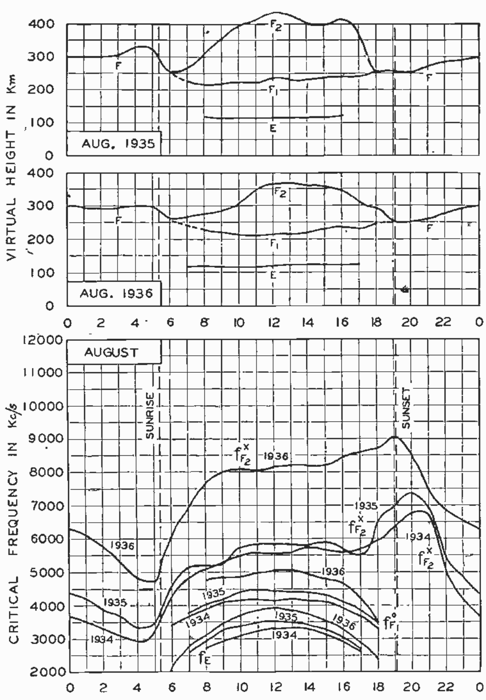

Fig. 8—Critical frequencies and virtual heights for August. Curves represent hourly averages.

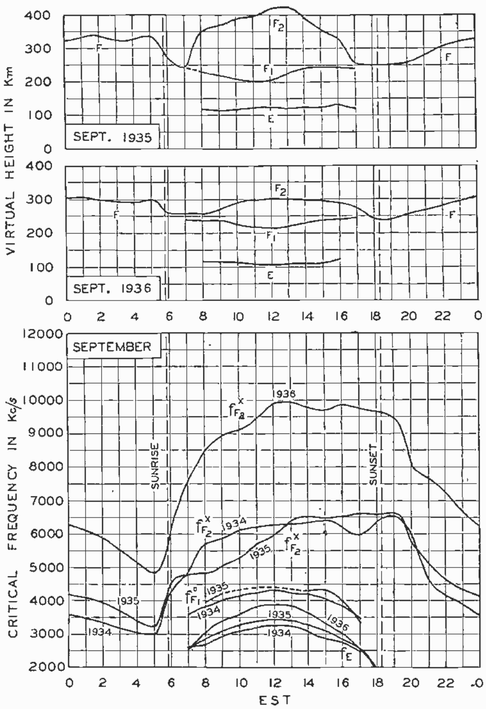

Fig. 9—Critical frequencies and virtual heights for September. Curves represent hourly averages.

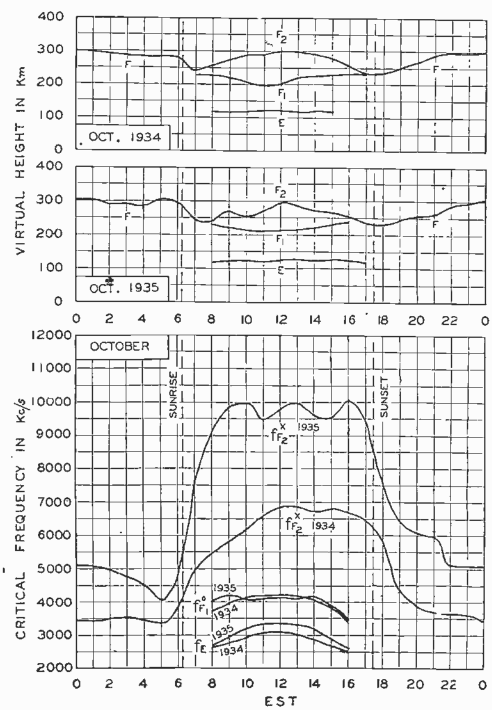

Fig. 10—Critical frequencies and virtual heights for October. Curves represent hourly averages.

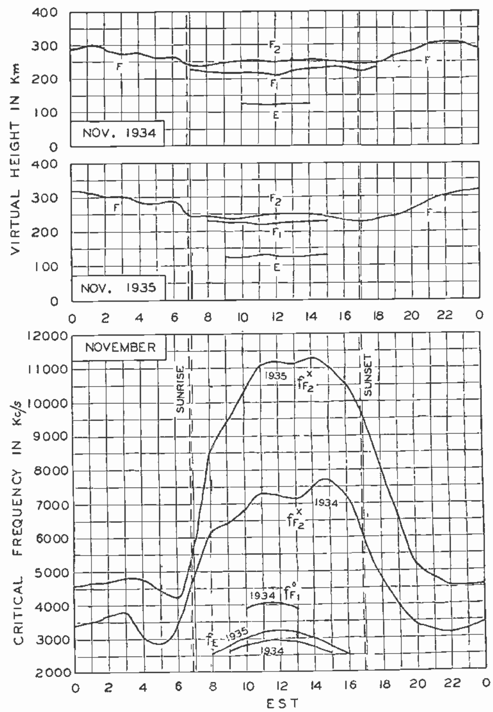

Fig. 11—Critical frequencies and virtual heights for November. Curves represent hourly averages.

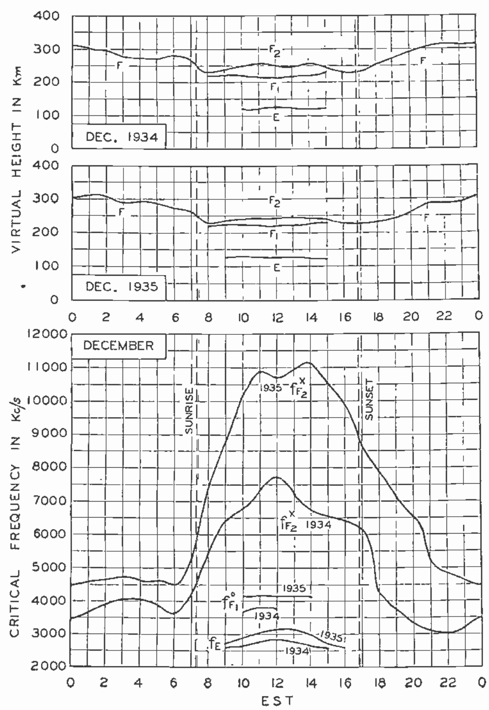

Fig. 12—Critical frequencies and virtual heights for December. Curves represent hourly averages.

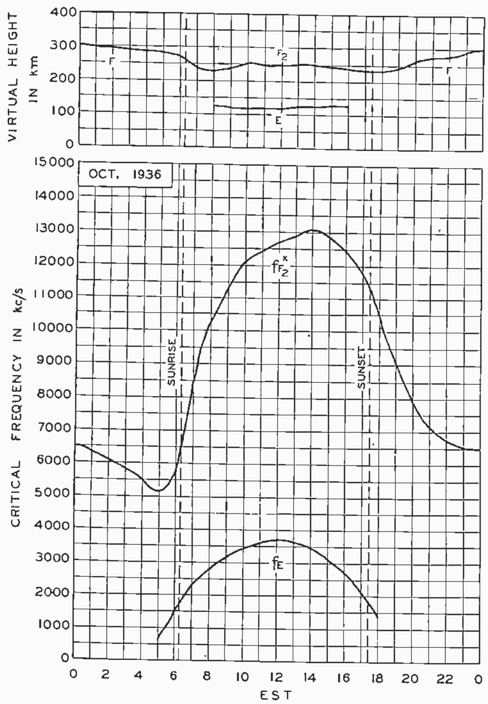

Fig. 13—Critical frequencies and virtual heights for October, 1936. Curves represent hourly averages.

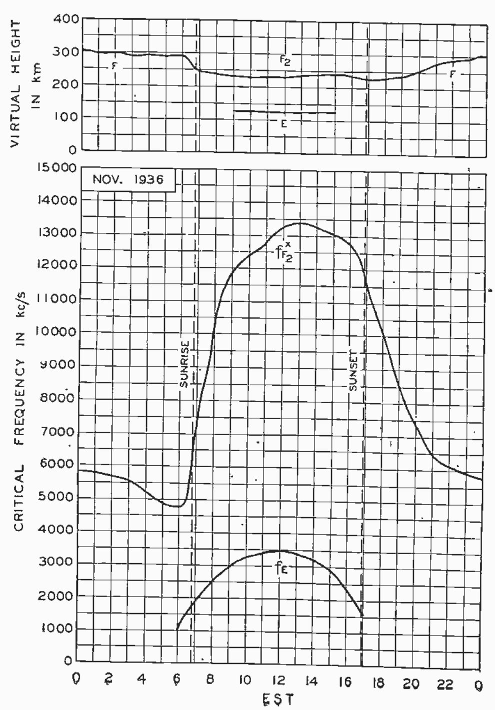

Fig. 14—Critical frequencies and virtual heights for November, 1936. Curves represent hourly averages.

either diurnally or seasonally; h_E varied from about 110 to 130 kilometers, while h_{F_1} varied from about 200 to 240 kilometers. The h_{F_2} and the night h_F varied through much wider limits than h_E or h_{F_1}. h_{F_2} varied from about 230 kilometers during a winter day to between 350 and 500 kilometers during a summer day. During both winter and summer the night h_F remained at about 300 kilometers. Around sunrise this height usually decreased to between 230 and 270 kilometers. An hour

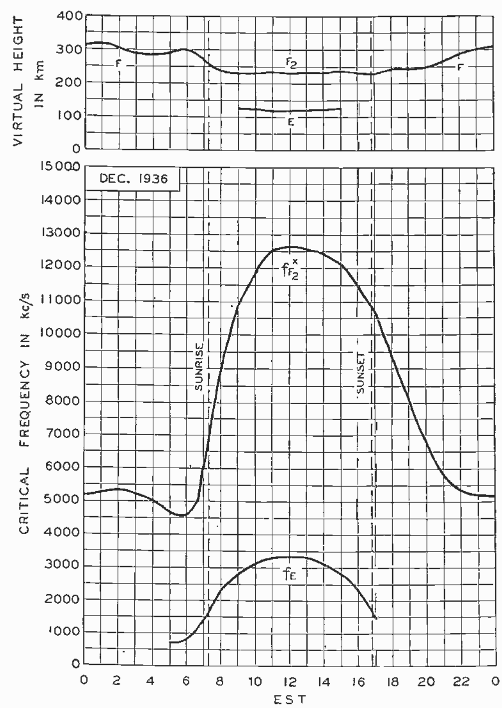

Fig. 15—Critical frequencies and virtual heights for December, 1936. Curves represent hourly averages.

or two after sunrise the F layer split into the F_1 and F_2 layers, h_{F_1} decreasing slightly and h_{F_2} increasing during the day. Shortly before sunset these two regions merged again into the night F layer, which rose again after sunset to the night level.

This separation was much more pronounced and clear-cut in the summer than in the winter, the daytime h_{F_2} in summer usually exceeding the night h_F. The amount and distinctness of the separation during the winter has progressively decreased over the period of these observations, and in October, 1936, completely disappeared, save on magnetically disturbed days.

The data given here on the h_{F_2} thus confirm and extend the results reported in previous papers.[3,4] Usually the virtual heights during a summer day are considerably greater than those during a winter day or a summer or winter night. If some allowance is made for the decrease of f^x_F at night it may be stated in a general may that h_{F_2} is great when $f^x_{F_2}$ is small, and vice versa. For example, h_{F_2} is greater and $f^x_{F_2}$ smaller during the summer day than during the winter day or summer evening. For the intermittent day-to-day variations h_{F_2} is greater for days of low $f^x_{F_2}$ than for days of high $f^x_{F_2}$.

III. Critical Frequencies

In addition to the virtual heights Figs. 1 to 13 show the diurnal and seasonal variations of critical frequencies.

The normal E critical frequencies varied fairly regularly both diurnally and seasonally. The f_E rose rapidly at sunrise out of the broadcast band and came to a broad maximum about noon both in summer and in winter. The summer values were greater than the winter values. The diurnal variation of f_E was symmetrical about noon. Neglecting the sporadic E the values at sunrise were about the same as those at sunset. Some observations made at night indicated that the f_E at that time was usually found between 600 and 1000 kilocycles. There was a long-time increase of f_E as well as of the other regions which will be discussed later.

The F_1 critical frequencies varied fairly regularly when they were observed; i.e., principally during the summer day. Both the ordinary and extraordinary F_1 rays were then normally found, the extraordinary ray being much weaker. F_1 critical frequencies never occurred at night since the F_1 layer lost its identity as a separate layer and merged with the F_2 layer shortly before sunset. They were also usually poorly defined or absent during the winter day. There was a long-time year-to-year increase of f_{F_1} similar to that for f_E. During the period of this increase the f_{F_1} became less and less well defined, especially during the winter, until, in October, 1936, it usually could not be found.

The diurnal variations of the $f^x_{F_2}$ may be classified into two general types: the winter type, centered in December, and the summer type, centered in June. In the winter type the $f^x_{F_2}$ began rising about one-half hour before sunrise and rose rapidly until two or three hours after sunrise, coming to a broad maximum centered about 1300 local time. It fell fairly rapidly from about two hours before until three hours

[3] E. O. Hulburt, "Theory of the ionosphere," *Terr. Mag.*, vol. 40, p. 193; June, (1935).

[4] E. B. Judson, "Comparison of data on the ionosphere, sunspots, and terrestrial magnetism," *Nat. Bur. Stand. Jour. Res.*, vol. 17, p. 323; September, (1936); Proc. I.R.E., vol. 25, p. 38–47; January, (1937).

after sunset and then more slowly during the night. The night decrease was not smooth but was broken up by plateaus and secondary maxima. The maximum at about 4 A.M., first observed in 1933 at the National Bureau of Standards,[5,1] has become progressively less and less marked in successive winters since the sunspot minimum in 1933. The minimum for the twenty-four hours usually occurred about an hour before sunrise. Except for rare occasions, on days of magnetic storms the day-to-day variations in the $f^x_{F_2}$ curves were small. Thus the behavior of the ionosphere was nearly always regular during the winter, and, indeed, could be predicted over short periods. This was especially true during the latter part of the period covered in this paper.

In the summer type the morning increase in $f^x_{F_2}$ began about sunrise. It occurred considerably later with respect to sunrise and was much slower than in the winter type. The $f^x_{F_2}$ continued to rise in this manner until about four hours after sunrise, after which it rose less rapidly during the remainder of the day.

The maximum occurred at about sunset, and was followed by a very slow and more regular decrease through the night, until the minimum was reached just before sunrise. The day-to-day variations in the $f^x_{F_2}$ were in general greater in summer than in the wintertime, and the behavior of the ionosphere could not be predicted as well, although the general shape of the diurnal curves was the same from day to day in the summer.

During the spring and fall the transition between winter and summer characteristics did not take place gradually, as would appear from the average curves, but the diurnal variation shifted erratically back and forth between the two types. In general, the whole day was of one type, although the value of $f^x_{F_2}$ differed widely on different days. The general shift in the average curves represents a relative predominance of winter or summer conditions during the month.

It may be seen from the graphs that the maximum $f^x_{F_2}$ for the year occurred during the winter day and a lesser maximum occurred near sunset in summer. Both maxima were fairly broad and indicated that a frequency near the maximum transmission frequency might be used for eight or nine hours during the day. This time centered at about 1300 local time during the winter and at about sunset during the summer.

IV. Long-Time Effects

Since the sunspot minimum in the winter of 1933–1934 the critical frequencies of the E, F_1, and F_2 regions have increased over a long

[5] T. R. Gilliland, "Ionospheric investigations," *Nature* (London), vol. 134, p. 379; September 8, (1934).

period which is associated with the eleven-year sunspot cycle. This long-time increase was superimposed on the seasonal variations and may be seen in the graphs of Figs. 1 to 15.

The largest and most striking long-time changes occurred in the $f^x_{F_2}$.

V. Interpretation and Applications

The three principal properties of the ionosphere affecting sky-wave transmission are absorption, virtual height, and critical frequency.

Absorption

The absorption of radio waves in the ionosphere determines the maximum distance and minimum frequency for practical high-frequency communication. The absorption varies in general with time of day, season, frequency, and length of path. Absorption seems to take place mainly in the lower ionosphere, that is, in the E layer or below. The absorption is greater during the summer day than during the winter day. It is greater for the lower high frequencies, that is, those frequencies which are close to or below the E critical frequency for a given distance. It is usually greater during the day than during the night, especially for these lower high frequencies. The evidence indicates that a higher frequency at large angles of incidence behaves, with respect to absorption, like a much lower frequency at small angles of incidence.

The effect of absorption at different frequencies is illustrated by field intensity measurements of two transmitting stations about 600 kilometers distant, one at 6060 kilocycles and the other at 9570 kilocycles. Measurements on the 6060-kilocycle transmission indicated day field intensities about two per cent of the night field intensities. For this distance this frequency was below the E critical frequency for several hours during the day. Similar measurements on the 9570-kilocycle station indicated day field intensities of approximately the same intensity as the night field intensities. For this distance this frequency was well above the E critical frequency at all hours of the day. These two examples illustrate the advantage of using a transmission frequency well above f_E if $f^x_{F_2}$ is high enough to reflect transmissions at such frequencies.

Virtual Height

The virtual height is an important characteristic of an ionized layer for determining the maximum frequency for which the waves will be reflected from the layer. For a given transmission distance the angle of incidence at a layer will be greater the lower the layer. On account of the curvature of both the earth and the ionized layers, the maximum possible angle of incidence is also greater the lower the layer. Since the critical frequency for a given ionization density varies approximately as the secant of the angle of incidence, it follows that for a given ionization density and distance a lower layer can reflect waves of a higher frequency. It is thus apparent that even though the E layer ionization density is lower than that of the F_2 layer, the former may frequently determine the maximum usable frequency. Because of the high f_F and low f_{F_2} during the summer day, this condition exists fairly regularly at that time. This condition also exists during days of severe magnetic disturbances when the $f^x_{F_2}$ is especially low and h_{F_2} is abnormally great in these latitudes. Sporadic E reflections frequently control long-distance transmissions both day and night. Good sporadic E reflections often provide intense signals at high frequencies and sometimes at ultra-high frequencies. These reflections are very common during the summer but occur at irregular intervals. The irregularities are both geographical and temporal.

For frequencies near the critical frequency the virtual heights increase rather rapidly and are considerably greater than the minimum values shown in the graphs, but undergo similar diurnal and seasonal variations. Since this is so the virtual height diminishes as the angle of incidence increases for a given frequency and the angles of incidence for several paths cannot be calculated from a single virtual height. Therefore a knowledge of the actual variation of the virtual height with frequency is necessary in order to calculate accurately the maximum usable frequency or the skip distance. In the interests of brevity the variations of virtual heights with frequency are not presented here but typical examples may be found in many of the papers on the ionosphere.

The following table gives a conservative estimate of the factors by which the normal incidence critical frequency may be multiplied to obtain approximately the maximum usable frequency over long distances, 2500 kilometers or more.

Normal E layer	$4\frac{1}{2}$
Sporadic E	5
F_2 layer (winter day and summer sunset)	$2\frac{1}{2}$
F_2 layer (summer day)	2
F layer (summer and winter night)	$2\frac{1}{4}$

Reception measurements indicate that these values may be modified by the slope of the land, near the transmitter or receiver, in the path of the wave. The reason for this is that the slope of the land affects the distribution of intensity of the energy transmitted or received in a given vertical plane, especially at low angles.

Critical Frequency

In contrast to the effect of absorption, the ionization density, measured by critical frequency, largely determines the minimum distance range and maximum frequency for practical high-frequency radio communication.

Because of the high $f^x_{F_2}$ and the low f_E during the winter day, the highest frequencies are transmitted by way of the F_2 layer at this time. During the summer day, however, $f^x_{F_2}$ is much lower and f_E is higher than in winter so that the band of frequencies which can penetrate the E layer and be returned by the F_2 layer is very small or nonexistent. This effect is increased for the reason that h_{F_2} is greater in summer than in winter. Hence most long and medium distance transmission during the summer is by way of the E layer. The frequent occurrence of sporadic E reflections during the summer, both by day and by night, increases the likelihood of such transmission. In general it should be noted that the probability of E layer transmission over long distances is greater than over short distances of a few hundred kilometers, other things being equal.

The F_2 layer is capable of reflecting higher frequencies during the winter day than at any other time. This condition exists for a period of seven or eight hours, centered at about 1300 local time at the place where the wave strikes the layer. The most favorable time for transmission to the west is thus later than for transmission to the east. In the summer, however, the F_2 layer can reflect higher frequencies for a period of seven or eight hours around sunset at the place where the wave strikes the layer than at any other hour of the day. The period of lowest f_F and consequent lowest maximum frequencies which can be reflected from the F layer occurs about an hour before sunrise, both summer and winter. Because of the slow decrease of f_F during the late summer evening, F transmission of higher frequencies is more likely then than during the late winter evening.

Normal E transmission will take place at the highest frequencies around noon local time. Sporadic E reflections are especially useful for transmission in the summer morning and evening.

The F_1 layer is normally useless for transmission save for short distances and for a very limited band of frequencies, and does not need to be considered from a transmission standpoint. The reason for this is that f_{F_1} is not sufficiently above f_E for a wave to penetrate the E layer and be reflected from the higher F_1 layer, at least at fairly large angles of incidence.

For single reflection transmission the controlling portion of the ionosphere is halfway between the terminal points. For multireflection transmission the ionosphere along the entire path, except for that portion within several hundred kilometers from the terminal points, must be considered.

From the critical frequency graphs of Figs. 1 to 15, the year-to-year ratios of useful transmission frequencies as well as the ratios of normal incidence critical frequencies for each month may be obtained. The long-time increase is apparent for all the regions, and is believed to be associated with the eleven-year sunspot cycle. When allowance is made for the seasonal variations, f_E and f_{F_1} are seen to have increased by a factor of about 1.3, during the period of these observations. During the same period the f_{F_2} increased by a factor of about 1.9. The effect of the general increase in critical frequencies is to raise the maximum usable frequencies proportionally and also to increase the absorption on the medium high frequencies. This means that the most effective frequencies for transmission have increased along with the increase in sunspot activity and may be expected to continue to increase until the sunspot maximum is reached. The sunspot minimum was during the winter of 1933–1934 and the next maximum is expected about 1939.

It should be emphasized that these results are averages and represent data taken systematically and over a long period of time at Washington, D.C. Reports[6] from Watheroo, Australia, and Huancayo, Peru, indicate that ionosphere conditions are different in the southern hemisphere. Much more comprehensive data will have to be obtained from other latitudes, especially from higher latitudes, before a world-wide picture of the ionosphere may be found. For purposes of transmission, however, the ionosphere may be considered as essentially uniform, at least over a range of latitude somewhat exceeding that of the United States.

It is believed that current information on ionosphere conditions is of sufficient interest to warrant publication of the future data monthly. It is planned to do this in the form given in Figs. 13 to 15 inclusive.

VI. Transmission Irregularities

Two types of transmission irregularities, which are not shown on the average curves, have been observed.

The first type has occurred during fairly severe magnetic storms when the $f^x_{F_2}$ has been observed to be lower, the h_{F_2} higher, and absorption greater than normal during the night of and the day following the local magnetic disturbance.[7,8] During a period of such magnetic dis-

[6] L. V. Berkner, H. W. Wells, and S. L. Seaton, "Characteristics of the upper region of the ionosphere," *Terr. Mag.*, vol. 41, p. 173; June, (1936).

[7] S. S. Kirby, T. R. Gilliland, E. B. Judson, and N. Smith, "The ionosphere, sunspots and magnetic storms," *Phys. Rev.*, vol. 48, p. 849; November 15, (1935).

[8] S. S. Kirby, T. R. Gilliland, N. Smith, and S. E. Reymer, "The ionosphere, solar eclipse and magnetic storm." *Phys. Rev.*, vol. 50, p. 258; August 1, (1936).

turbances the maximum usable frequency was much less than during a magnetically quiet period. A second type of irregularity is the "fade-out,"[9,10,11] a sudden wiping out of practically all high-frequency sky-wave transmission for periods of a few minutes to about an hour. This is caused by a sudden increase in absorption in the lower regions of the ionosphere—the E layer or below—due to a sudden increase of ionization. This effect is accompanied by a sudden brief disturbance of the earth's magnetic field. The cause of these phenomena is a burst of radiation from a sudden solar eruption. No relation has been observed between this effect in the lower ionosphere and the magnetic storm effect in the higher ionosphere, as entirely different regions of the ionosphere are concerned.

VII. Conclusions

The general form of the diurnal and seasonal variations of the critical frequencies and virtual heights has recurred from year to year. The daytime critical frequencies of the E and F_1 regions were symmetrical about noon reaching a diurnal maximum at noon and a seasonal maximum in midsummer. The diurnal maximum of $f^x_{F_2}$ occurred at about 1300 local time in the winter and at about sunset in the summer. The diurnal maximum in winter was much greater than in summer. The diurnal minimum in both winter and summer occurred about one hour before sunrise. The critical frequency decreased much more rapidly during the winter evening than during the summer evening.

In addition to the seasonal variations there has been a continuous long-time increase of critical frequencies associated with the eleven-year sunspot cycle. It was pointed out that this effect increased the upper limit of useful transmission frequencies determined by penetration of the ionosphere and also increased the lower limit of useful transmission frequencies determined by absorption in the lower ionosphere.

Finally, for practical applications, it should be emphasized that the absorption, virtual heights, and critical frequencies of all portions of the ionosphere traversed by the waves must be considered in determining transmission conditions over a given path.

[9] J. H. Dellinger, "Confirmation of cosmic phenomenon," *Science*, vol. 82, p. 548; December 6, (1935).

[10] J. H. Dellinger, "High-frequency fadeouts continue," *QST*, vol. 20, p. 37; June, (1936).

[11] J. H. Dellinger, "Direct effects of particular solar eruptions on terrestrial phenomena," *Phys. Rev.*, vol. 50, p. 1189; December 15, (1936).

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A MULTIPLE UNIT STEERABLE ANTENNA FOR SHORT-WAVE RECEPTION*

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Summary—*This paper discusses a receiving system employing sharp vertical-plane directivity, capable of being steered to meet the varying angles at which short radio waves arrive at a receiving location. The system is the culmination of some four years effort to determine the degree to which receiving antenna directivity may be carried to increase the reliability of short-wave transatlantic telephone circuits. The system consists of an end-on array of antennas, of fixed directivity, whose outputs are combined in phase for the desired angle. The antenna outputs are conducted over coaxial transmission lines to the receiving building where the phasing is accomplished by means of rotatable phase shifters operating at intermediate frequency. These phase shifters, one for each antenna, are geared together, and the favored direction in the vertical plane may be steered by rotating the assembly. Several sets of these phase shifters are paralleled, each set constituting a separately steerable branch. One of these branches serves as an exploring or monitoring circuit for determining the angles at which waves are arriving. The remaining branches may then be set to receive at these angles. The several receiving branches have common automatic gain control and thus provide a diversity on an angle basis. To obtain the full benefit of the angular resolution afforded by the sharp directivity, the different transmission times, corresponding to the different angles, are equalized by audio delay networks, before combining in the final output.*

The experimental system, located at the Bell Telephone Laboratories' field laboratory near Holmdel, New Jersey, is described. This system comprises six rhombic antennas extending three quarters of a mile along the direction to England. Two receiving branches, in addition to a monitoring branch, are provided. Experience obtained with this system since the spring of 1935 is discussed. The benefits ascribable to it are (1) a signal-to-noise improvement of seven to eight decibels, referred to one of the six antennas alone, and (2) a substantial quality improvement due jointly to the diversity action and the reduction of selective fading.

While a three-quarter-mile short-wave antenna system is an unusually long one, the steerability feature permits the employment of considerably more directivity, afforded by further increasing the length. A system two miles long is believed to be practicable and desirable. It could be expected to perform more consistently better than the three-quarter-mile trial installation, and should yield a signal-to-noise improvement of twelve to thirteen decibels referred to one rhombic antenna. With the object of predicting the performance of larger systems, the performance of the experimental system is examined in great detail and compared with theory.

I. Introduction

FOR more than a decade, point-to-point short-wave radio services have employed directional antennas both in transmitting and receiving. Transmitting antenna directivity results in increased field intensity at the receiving location and receiving antenna directiv-

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ity discriminates against noise. Both directivities improve the signal-to-noise ratio of a given circuit and permit operation under more adverse transmission conditions. Arrays of simple antennas as well as extensive configurations of long wires have been used to produce these directivities in both the vertical and the horizontal planes.

Antennas in present use on the longer circuits, such as the New York-London telephone facilities represent about the limit of fixed directivity. Further increase or "sharpening" of the directivity would seriously encroach upon the angular range of directions which are effective in the propagation of waves from transmitter to receiver. The vertical angle range useful in transmitting and receiving short waves is considerable. The horizontal range is appreciable although considerably less than the vertical range. To confine the principal antenna response to only a portion of these ranges penalizes the circuit when that portion is ineffective.

Much experience and considerable statistical data have been obtained which determine this useful range of directions for the New York-London circuits, and antennas have been designed in conformity with these results. However, too much weight must not be given to statistical results which indicate, for instance, that ninety per cent of the time the effective angles are, say, in the range from ten to twenty degrees. For, if the remaining ten per cent includes much of the time that has been lost with existing facilities, an antenna designed for a ten- to twenty-degree response may really be of no value, or even detrimental as a means of extending the usefulness of the circuit. Owing to the great variability in conditions on the north Atlantic path and to the relatively small amount of significant data which has been accumulated during times when gain is most needed it might be detrimental to carry fixed directivity further than present practice has adopted.[1]

If, however, the directivity can be varied or "steered" to meet the various conditions imposed by nature, a new field is opened in which a new order of antenna sharpness and gain is possible. In addition to the gain in signal-to-noise ratio afforded by directivity, a reduction in selective fading is possible if the sharpness is increased to the point where a separation of differently delayed waves is achieved. As early as 1927, Edmond Bruce[2,3] found remarkable reductions in short-wave

[1] One way of attacking the problem of obtaining increased antenna gain has been proposed by John Stone Stone in U. S. Patent 1,954,898. This patent relates to fixed antennas but has certain features, such as delay equalization, in common with the system to be described in this paper.

[2] E. Bruce "Developments in short-wave directive antennas," Proc. I.R.E., vol. 19, pp. 1406–1433; August, (1931).

[3] E. Bruce and A. C. Beck "Experiments with directivity steering for fading reduction," Proc. I.R.E., vol. 23, pp. 357–371; April, (1935).

fading by using a receiving antenna having an extremely sharp directional pattern. The successful employment of sharp directivity is, of course, predicated upon considerable stability of wave directions. The experiments reported by R. K. Potter[4] in 1930 suggested that short waves are propagated in a more or less orderly manner and that stable wave directions might exist. Later experiments,[5] made in co-operation with the British Post Office, using pulse transmission to resolve angles in time, gave confirming data and demonstrated clearly the physical facts upon which is based the system to be described in the present paper. These fundamental facts, outlined in the paper describing the experiments just mentioned, are recapitulated here because a clear understanding of their nature and significance is an essential introduction to the subject in hand. In the pulse tests it was found that:

"1. To the extent that we have been able to resolve the propagation into separate (vertical) angles, the separate angles are found not to be erratic; they vary slowly.

"2. There appears to be at least a qualitative relation between angle and delay; the greater the delay the greater the angle above the horizontal.

"The existence of the many waves of different delay, which is known to make fading selective with respect to frequency, greatly impairs the quality of a short-wave radiotelephone circuit. . . . The experimental facts, tentatively established, that individual wave angles are fairly stable and that waves of different delay invariably possess different vertical angles, make this problem hold considerable promise.

"The simple antennas described . . . are suitable for angle determination because of their ability to reject a single wave but they are not in general suitable for quality improvement. For such studies it would be preferable to construct a more elaborate antenna whose directional pattern has a single major lobe which is steerable in the vertical plane. Such an antenna would aim to select a narrow range of angles in which occur waves of substantially the same delay."

The present paper describes a steerable antenna receiving system of the general character suggested by the above quotation, and which has been in experimental operation at the Holmdel, New Jersey, field laboratory of the Bell Telephone Laboratories for the past two years. Certain other important features are incorporated in the system, notably an arrangement whereby individual wave groups arriving at different vertical angles are received separately and, after separate delay equalization, combined, thereby incorporating a unique form of

[4] R. K. Potter "Transmission characteristics of a short-wave telephone circuit," Proc. I.R.E., vol. 18, pp. 581–648; April, (1930).

[5] Friis, Feldman, and Sharpless "The determination of the direction of arrival of short radio waves," Proc. I.R.E., vol. 22, pp. 47–78; January, (1934).

diversity. Another important feature possessed by the system is its frequency range which permits operation on all of the frequencies used in short-wave transatlantic services.

II. Principles of Steering Antenna Directivity

An old and elemental type of steering of receiving antenna directivity is found in direction finders. The steering of a directional lobe as distinguished from the steering of a null has been accomplished in recent years. Schelleng[6] reported a moderate degree of horizontal plane steering, accomplished by means of phase shifters. Jansky[7] has obtained horizontal steering by bodily rotating an entire broadside array.

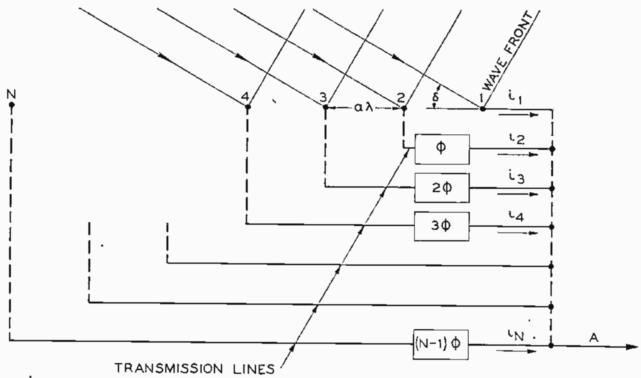


Fig. 1—A steerable antenna array using variable phase shifts ϕ, 2ϕ, 3ϕ, etc. The transmission lines indicated by broken lines are assumed to be of zero length. a is the spacing in free space wave lengths.

Bruce and Beck[3] obtained vertical steering by varying the shape of a rhombic antenna by means of ropes, and demonstrated the value of steering in the reduction of selective fading. The present authors[5] have employed rotatable phase shifters to steer the nulls in the directional patterns of two spaced antennas. In that work the value of the rapid adjustments possible with phase shifters was very apparent. In the linear end-on MUSA[8] system to be described rotatable phase shifters are again employed to steer the vertical response.[9]

In Fig. 1 is shown a schematic representation of a linear end-on array of N equally spaced unit antennas in free space. The antennas are indicated by the numbered points. For simplicity it is assumed, in the

[6] J. C. Shelleng "Some problems in short-wave telephone transmission," Proc. I.R.E., vol. 18, pp. 913–938; June, (1930).

[7] K. G. Jansky "Directional studies of atmospherics at high frequencies," Proc. I.R.E., vol. 20, pp. 1920–1932; December, (1932).

[8] The word MUSA is coined from the initial letters of "multiple unit steerable antenna."

[9] U. S. Patent No. 2,041,600.

following preliminary analysis, that the antennas are spaced far enough to be substantially isolated from each other. Choosing antenna No. 1 for reference and considering a plane wave arriving at an angle δ with the axis of the array, it is clear that the output of No. 2 will add in phase with that of No. 1 if the phase advance ϕ is made equal to $2\pi ac/v - 2\pi a \cos \delta$, where c = velocity of light and v = the phase velocity of the transmission lines. Similarly, the output of No. 3 will add to that

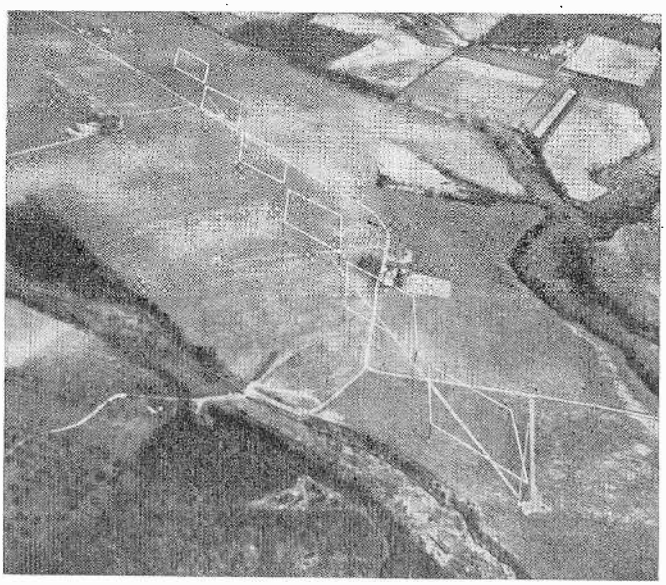


Fig. 2—Airplane view of the three-quarter-mile experimental MUSA on the receiving laboratory site located near Holmdel, New Jersey. The white line beneath the antennas is the newly filled trench in which coaxial transmission lines are buried. The building appearing in the right-hand foreground houses the receiving apparatus. The ground is flat to within ± 4 feet.

of No. 1 and No. 2 if its phase is advanced 2ϕ, etc. If the spacing, $a\lambda$, is sufficient there will be other angles for which the N outputs add in phase; at intermediate angles the outputs interfere with the result that zeros and minor maxima occur. By properly designing the unit antenna the undesired maxima may be suppressed.

In the Holmdel experimental system the unit antennas are of the rhombic type. An aerial view of the six antennas, which are located on the great circle through England, is shown in Fig. 2. These six antennas, combined as in Fig. 1, yield polar directional patterns such as those shown at the top of Fig. 3. The solid line pattern and the dashed line pattern correspond to different values of the phase shift ϕ. The multiple phase shifts of Fig. 1 are obtained by gearing the phase shifters to a common shaft which enables the directional pattern to be steered simply by rotating the shaft.

Thus far we have discussed the problem of sharp steerable directivity from the point of view of a single plane wave, whereas it is well known that multiple ionosphere reflections usually produce several

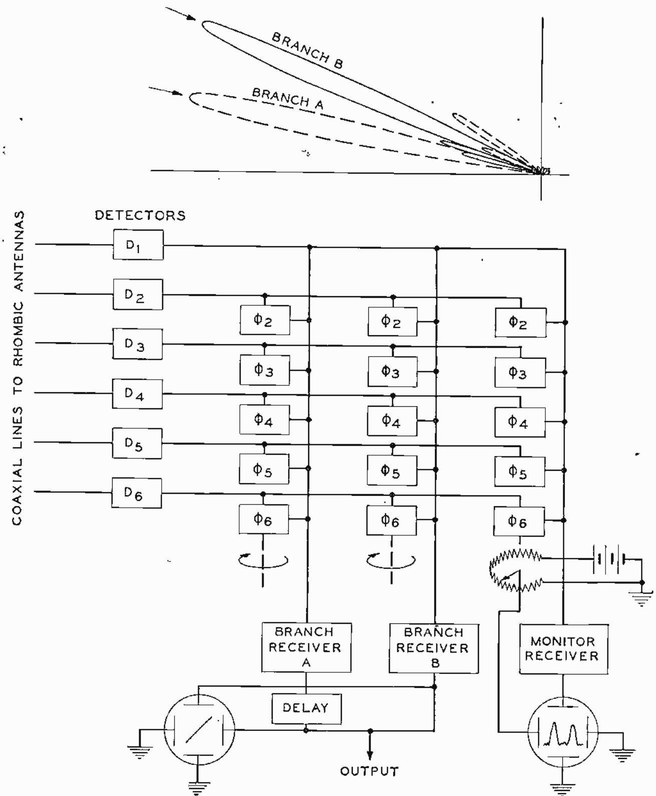


Fig. 3—Schematic diagram of the experimental MUSA receiver. The five phase shifters ϕ_2, ϕ_3, etc., of each branch, are geared to a shaft to provide the phase shifts ϕ, 2ϕ, 3ϕ, etc., of Fig. 1. The inset at the top shows the directional patterns of the two branches when steered at angles of 12 and 23 degrees, at a wave length of 25 meters.

more or less discrete waves, or bundles of waves, having different vertical angles and different transmission delays. To obtain the maximum advantage, however, requires that all of the several wave bundles be separately received and suitably combined after the transmission delays have been equalized. The achievement of this objective not only yields the ultimate gain in signal-to-noise ratio but at the same time *reduces the distortion associated with selective fading.*

The method of obtaining sharp steerable directivity by combining the output of fixed antennas through phase shifters makes it possible to use the same antennas and transmission lines to provide several separately steerable lobes each of which is in effect an independent MUSA.[10] In the experimental system, shown schematically in Fig. 3, the antenna outputs are combined at intermediate frequency, and the separately steerable lobes are obtained by branching each of the six first detectors into three phase shifters and combining the outputs of the phase shifters to form three steerable branches. One branch is used continuously to explore the angle range to determine at which angles the waves are arriving. The other two branches are set accordingly and their outputs are "received" by conventional receivers, with common automatic gain control. The demodulated audio outputs are equalized for difference in transmission time and then combined. A cathode-ray oscilloscope displays the output of the exploring or monitoring branch. It plots amplitude (provided by a linear rectifier) as the ordinate, against phase shift ϕ_2 (corresponding to ϕ in Fig. 1). The screen of the oscilloscope is of the retentive type and thus displays several consecutive sweeps at once. A pattern corresponding to two waves is illustrated. The other cathode-ray oscilloscope is used in the adjustment which equalizes the delay of the two waves. Delay is added to the low angle branch until the oscilloscope shows a line (or compact elongated figure) which oscillates between the two axes as the two waves fade differently. This means that all of the audio frequencies of one branch are combining in phase with those of the other.

The above brief description was introduced to acquaint the reader with the essentially simple features of the MUSA system. Before describing the details and the results obtained with the experimental system, a more comprehensive analysis of steering principles will be given.

Returning to Fig. 1, it is assumed, of course, that the transmission lines are terminated in their characteristic impedance at the receiving terminal[11] (the phase shifters of Fig. 1) so that the phase is distributed linearly along the lines. Neglecting line loss (or equalizing it), the N currents, equal in magnitude and different in phase, are

$$\left.\begin{aligned} \dot{i}_1 &= I\epsilon^{j\omega t} \\ \dot{i}_2 &= I\epsilon^{j\{\omega t+\phi-2\pi a(v-\cos\delta)\}} \\ \dot{i}_3 &= I\epsilon^{j\{\omega t+2[\phi-2\pi a(v-\cos\delta)]\}} \\ &\cdots\cdots\cdots\cdots \\ \dot{i}_N &= I\epsilon^{j\{\omega t+(N-1)[\phi-2\pi a(v-\cos\delta)]\}} \end{aligned}\right\} \tag{1}$$

[10] R. K. Potter, U. S. Patent No. 2,030,181.

[11] Noncharacteristic terminations at the receiving ends of the lines are permissible if all terminations are identical and if the antennas are matched to the characteristic line impedance. Conversely, characteristic terminations at the receiving ends suffice if the antenna impedances are merely identical.

where,

i = instantaneous current in exponential notation
ω = angular frequency
N = total number of unit antennas
a = spacing in free space wave lengths
$\upsilon = c/v$ = the ratio of the velocity of light to that of the transmission line.

The sum of the N currents is

$$A = I\epsilon^{j\omega t}\left\{1 + \epsilon^{j[\phi - 2\pi a(\upsilon - \cos\delta]} + \cdots + \epsilon^{j(N-1)[\phi - 2\pi a(\upsilon - \cos\delta)]}\right\}. \quad (2)$$

This exponential series may be evaluated with the aid of the identity[12]

$$1 + \epsilon^{j\theta} + \epsilon^{j2\theta} + \cdots + \epsilon^{j(n-1)\theta} \equiv \frac{\sin\frac{n\theta}{2}}{\sin\frac{\theta}{2}}\epsilon^{j\frac{(n-1)\theta}{2}}.$$

Using this summation we have

$$A = I\frac{\sin\frac{N}{2}[\phi - 2\pi a(\upsilon - \cos\delta)]}{\sin\frac{1}{2}[\phi - 2\pi a(\upsilon - \cos\delta)]}\epsilon^{j\{\omega t + (N-1)/2[\phi - 2\pi a(\upsilon - \cos\delta)]\}}. \quad (3)$$

The amplitude of A in (3) is the array directional pattern or array factor. It is zero when the numerator alone is zero, i.e., when

$$\frac{1}{2}[\phi - 2\pi a(\upsilon - \cos\delta)] \neq 0, \pm\pi, \pm 2\pi \cdots \text{ and simultaneously}$$

$$\frac{N}{2}[\phi - 2\pi a(\upsilon - \cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

It attains its maximum value of NI when the denominator and numerator are zero simultaneously, i.e., when

$$\frac{1}{2}[\phi - 2\pi a(\upsilon - \cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots \text{ and}$$

$$\frac{N}{2}[\phi - 2\pi a(\upsilon - \cos\delta)] = 0, \pm\pi, \pm 2\pi \cdots.$$

[12] This identity may be deduced by substituting $\epsilon^{j\theta}$ for r in the well-known formula for the sum of a geometrical progression

$$1 + r + r^2 + r^3 + \cdots + r^{n-1} \equiv \frac{r^n - 1}{r - 1}.$$

Plots of (3) for ten unit antennas ($N=10$) spaced five wave lengths ($a=5$) are shown in Fig. 4 for two arbitrary values of ϕ. The same array used at twice the frequency ($N=10$, $a=10$) has the directional patterns shown in Fig. 5. The abscissas are labeled earth angle although nothing has been said thus far concerning the disposition of the N antennas with respect to the earth. In order that the simple multiple phase shifts of Fig. 1 shall suffice to steer the array, reflection from the ground must affect the phase of all antenna outputs identically. This is assured by constructing the array over, and parallel to, a flat expanse of ground. Since the angle δ measures the direction of the wave referred to the direction of the array axis the array factor represents a surface of revolution. Figs. 4 and 5 show merely axial cross sections which, for a horizontal array, may be considered vertical plane patterns.

Equation (3), as well as Figs. 4 and 5, shows that the sharpness of the principal lobe depends upon the total length of the array in wave lengths, i.e., upon Na, while the angular spacing of adjacent principal lobes depends inversely upon the spacing "a." Thus, a single lobed pattern results if the array consists of a large number of closely spaced units.

A single lobed pattern is desirable, but to obtain it by using a large number of unit antennas[13] with separate transmission lines and phase shifters would be a rather extensive undertaking. Provided a restricted range of steering is permissible, a simpler solution is to employ comparatively few large unit antennas and to let their directional pattern suppress the undesired principal lobes of the array pattern. Useful angles for transatlantic circuits are confined to the range from zero, or some low undetermined limit, to some higher limit. In what follows let δ_m represent an angle a little above the useful range so that a null may be located at δ_m without imposing an excessive loss. The array may then be designed so that when the first principal lobe is steered at zero angle the second falls at δ_m or beyond. The question of whether the array design permits the construction of a suitable unit antenna in the length $a\lambda$ allotted to it is considered in the following paragraph. As a matter of fact, this analysis closely follows the actual steps in the development of the MUSA system.

Turning back to the ideal system comprising a very large number of closely spaced unit antennas, which yields the single lobed pattern, let us divide the antennas into N groups with n antennas in eaeh group.

[13] The reader may observe that the reduction of the spacing would, if carried so far as to make "a" a fraction of a wave length, violate the assumption that there is negligible reaction or coupling between unit antennas. As stated, this assumption is made in the interest of simplicity. It is theoretically possible to compensate for coupling between antennas so that (1), (2), and (3) still hold.

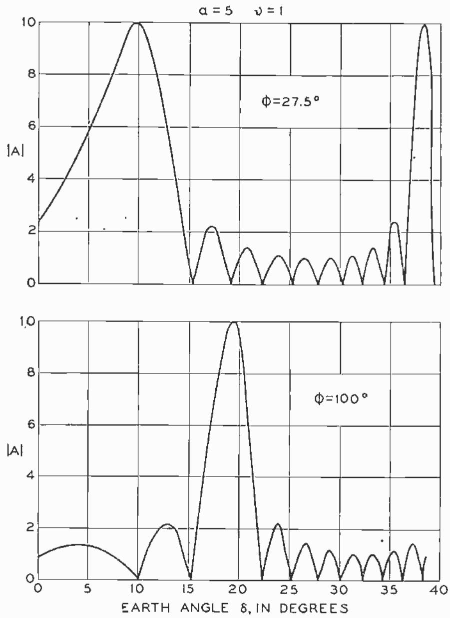


Fig. 4—Plots of the array factor for a 45-wave length horizontal end-on array.

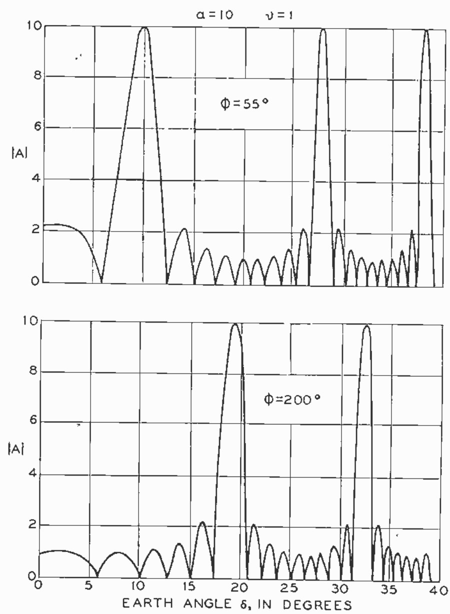


Fig. 5—Plots of the array factor for a 90-wave length array; that of Fig. 4 used at twice the frequency.

Calling the group spacing "a" and the phase shift between adjacent antennas ϕ the application of (3) gives, dropping the exponential factor,

$$A = \frac{\sin \frac{nN}{2}\left[\phi - 2\pi \frac{a}{n}(v - \cos\delta)\right]}{\sin \frac{1}{2}\left[\phi - 2\pi \frac{a}{n}(v - \cos\delta)\right]}. \tag{4}$$

Multiplying numerator and denominator by

$$\sin \frac{n}{2}\,[\phi - 2\pi \frac{a}{n}\,(v - \cos\delta)]$$

results in

$$A' = \frac{\sin \frac{n}{2}\left[\phi - 2\pi \frac{a}{n}(v - \cos\delta)\right]}{\sin \frac{1}{2}\left[\phi - 2\pi \frac{a}{n}(v - \cos\delta)\right]} \times \frac{\sin \frac{N}{2}\,[n\phi - 2\pi a(v - \cos\delta)]}{\sin \frac{1}{2}\left[n\phi - 2\pi a(v - \cos\delta)\right]}. \tag{5}$$

Equation (5), which appears as the product of two array factors, is merely another way of writing the array factor for the large number (Nn) of unit antennas. The first factor represents an array of n "sub-unit" antennas of spacing a/n and phase shift ϕ. The second represents the array of these arrays with a spacing of $a\lambda$ and a phase shift $n\phi$. We now proceed to treat these two factors independently and assign the values ϕ_f and ϕ_v to replace ϕ and $n\phi$, respectively. Fig. 6 depicts such an array of arrays. If now we regard the array of n subunits as constituting a fixed unit antenna and adjust it to receive at zero angle (by putting $\phi_f = 2\pi a/n(v-1)$ in accordance with the lower limit of the useful range, we obtain

$$A'' = \frac{\sin \frac{n}{2}\left[2\pi \frac{a}{n}(1 - \cos\delta)\right]}{\sin \frac{1}{2}\left[2\pi \frac{a}{n}(1 - \cos\delta)\right]} \times \frac{\sin \frac{N}{2}\,[\phi_v - 2\pi a(v - \cos\delta)]}{\sin \frac{1}{2}\,[\phi_v - 2\pi a(v - \cos\delta)]}. \tag{6}$$

The first factor in (6) represents the pattern of the unit antenna. It is a relatively broad single lobed pattern with maximum response at $\delta=0$. It drops to zero at $\delta=\cos^{-1}(1-1/a)$. For higher angles nothing but minor maxima occur since "a" is small and n is large. The second factor represents the steerable array pattern of the N unit antennas. With ϕ_v adjusted for maximum response at zero angle (this makes $\phi_v=n\phi_f$) this system is identical with the array of Nn subunits. In this case, all principal lobes of the array factor for the N units, excepting the first, coincide exactly with nulls of the array factor for the n subunits, and the familiar tapered distribution of minor maxima associated with the array of Nn subunits results. As ϕ_v is varied to steer

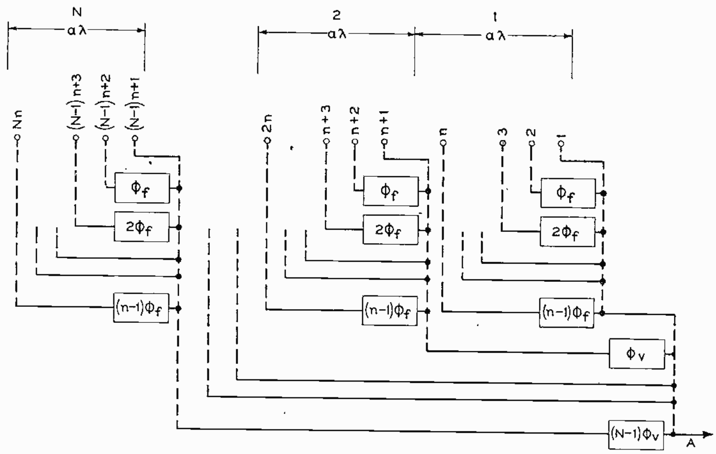


Fig. 6—A steerable array formed by dividing the antennas of Fig. 1 into N groups of n each. The subscripts "f" and "v" refer to fixed and variable phase shifts.

for other angles than $\delta=0$, the coincidence of nulls and undesired principal lobes no longer occurs. Since, however, the fixed unit antenna has only minor response beyond its first null, those undesired principal lobes are adequately suppressed, and the array may therefore be steered anywhere within the range from $\delta=0$ to $\delta\doteq\cos^{-1}(1-1/a)$, with single lobed response. As the principal lobe is steered away from $\delta=0$ the maximum amplitude falls off in comparison with that of the array of Nn subunits. This represents a loss of signal-to-noise ratio and is to be regarded as a penalty for compromising to the extent of using fixed arrays as unit antennas. The loss is appreciable, however, only if the array is steered near the upper cutoff angle of the unit antenna. It remains but to select "a" so that $\cos^{-1}(1-1/a)$ represents the upper limit of the range, δ_m.

For a fixed physical spacing, "a" varies inversely with the wave length, which results in an increasing steering range with increasing wave length. Since the critical angle of reflection from the ionosphere increases with wave length the upper limit of the range of useful angles can be expected to increase also. By selecting the proper spacing, the steering range and the critical angle can be made to agree satisfactorily. Fig. 7 shows a plot of $\delta = \cos^{-1}(1-1/a)$ against wave length for the unit antenna spacing of 200 meters which was adopted for the experimental MUSA system to be described. The points denote upper limits of earth angles obtained from measurements made during the years 1933–1936 on signals from Rugby[5] and Daventry, England.

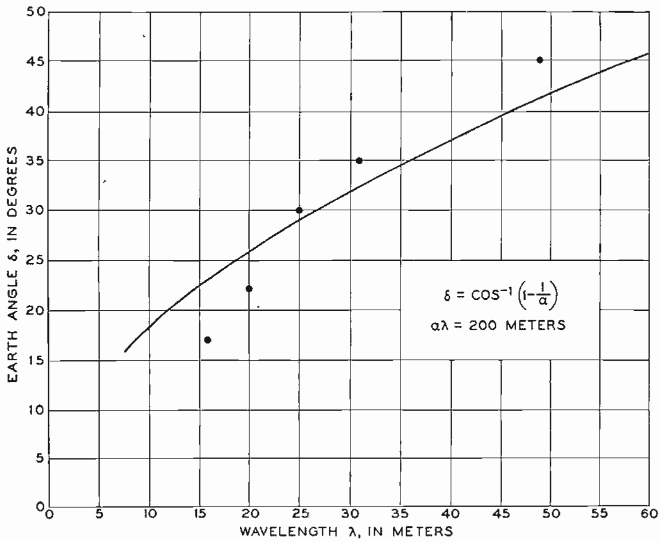


Fig. 7—Measured upper limits of vertical angles as a function of wave length, compared with the upper limit of the array depicted in Fig. 6. The measured values represent the highest angles observed; usually stronger waves of lower angles predominate.

The foregoing analysis shows that

(1) A MUSA system may be so proportioned that the upper limit of its steering range follows, with fair accuracy, the upper limit of the range of useful angles, as the wave length is varied.

(2) It is theoretically possible to construct a suitable unit antenna in the space provided for it when (1) is satisfied.

III. Description of the Experimental MUSA System

Antennas and Transmission Lines

Any type of unit antenna whose directional pattern suppresses the undesired principal lobes over the required wave length range is basically suitable for use in a MUSA system. The rhombic antenna[14] does not fulfill this requirement as well as the linear array of subunits

[14] Bruce, Beck, and Lowry "Horizontal rhombic antennas," Proc. I.R.E., vol. 23, pp. 24–46; January, (1935).

discussed in the preceding section. It was, however, selected on account of its advanced state of development. The manner in which it fits into the MUSA array factor will be discussed later.

The coupling or "cross talk" between antennas need not be of negligible magnitude in a MUSA system. For, to a first approximation, the coupling is confined to adjacent antennas and is similar for all pairs so that only the *end* antennas could be expected to fail to combine properly with the others. At the ends, "dummy" antennas, not connected with the receiver but terminated like the others, could be erected to supply the coupling necessary to make all antennas alike. Measurements made on the experimental MUSA (Fig. 2) indicated that the cross talk is small enough to be neglected, however, so that dummy antennas ahead of or behind the six regular ones were considered unnecessary. The performance of the system in subsequent tests corroborates this conclusion.

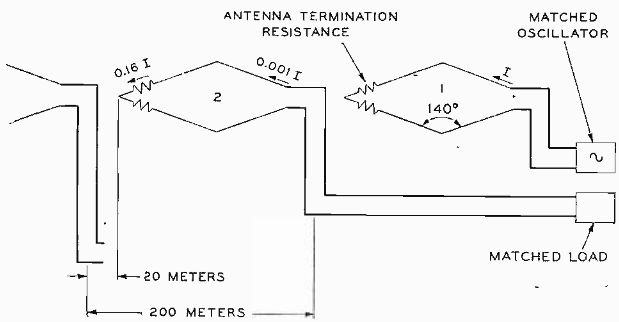


Fig. 8—Measurements of cross talk between adjacent antennas in the MUSA as made from the transmitting point of view.

The cross talk measurements yielded the results indicated on Fig. 8. The small amount of cross talk current (0.001 I) measured at the transmission line end of the forward antenna (No. 2) and the larger current (0.16 I) at the other end reflects the fact that the rhombic antenna is "unidirectional." To a first approximation the current in such an aperiodic antenna accumulates progressively towards the output end. Therefore, the "effective" cross talk current is probably less than $(0.16\ I+0.001\ I)/2=0.08\ I$; i.e., the effect upon the field radiated in the principal lobe will be altered by less than ten per cent due to the parasitic excitation of the antenna ahead. Antennas farther ahead as well as those behind contribute relatively nothing.

Since, by the reciprocal theorem the directional pattern of any antenna is the same for transmitting and receiving, the cross talk should likewise result in less than 10 per cent effect in the receiving case.

The measurements of Fig. 8 were made at 18 megacycles. At this frequency the rhombic antennas are proportioned to give maximum radiation approximately end-on. At lower frequencies the cross talk is probably less.

The coaxial transmission lines are constructed of 60-foot lengths of one-inch copper plumbing pipe spliced with screw type plumbing unions. The inner conductor is one-fourth inch in diameter and is supported by isolantite insulators. The characteristic impedance of the lines is 78 ohms. The lines extend up the poles where they are connected to the antennas through balanced-to-unbalanced matching transformers.[14] At the receiving building the lines terminate on a special jack strip. Nitrogen pressure is maintained in all lines to exclude moisture.

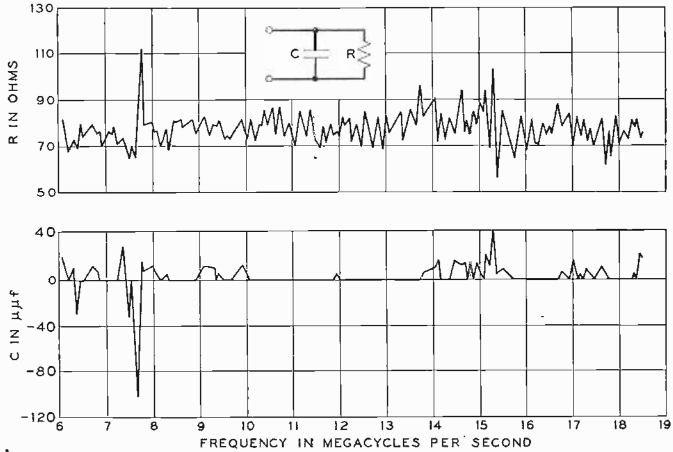


Fig. 9—Impedance measurements made upon the 1000-meter line terminated in a resistance of 78 ohms. The reactance is expressed as shunt capacitance, negative values meaning an inductive reactance numerically equal to the corresponding capacitive reactance.

In order to operate the MUSA system it is not essential that the velocity of the transmission lines be known. The velocity must be known accurately, however, in order to determine the angle of the waves as they are selected by the steerable lobe. Accordingly, the velocity was calculated (taking the insulators into account) and also measured. The calculated ratio of the line velocity to the velocity of light is 0.941; measurements yielded 0.933 ± 0.004. Using the value of 0.933, angles less than zero have occasionally been measured. A value of 0.937 would have made the lowest indicated angle just zero.

The longest line is about 1000 meters in length. Its impedance measured at one end when the other end is terminated by a resistance of 78 ohms shows some variation as the frequency is varied. In Fig. 9 are shown the results of impedance measurements made by substituting for the line an equivalent parallel combination of resistance and reactance. The two notable variations occurring at approximately 7.7 and 15.4 megacycles are believed to be caused by a slight irregularity at each joint, which adds a shunt capacitance of the order of 1.8 micro-microfarads. When spaced regularly at 60-foot intervals these capacitances have a somewhat cumulative effect at frequencies for which 60 feet (18.3 meters) is a multiple of the half wave length. Sixty feet, when increased by the line velocity ratio, corresponds to 7.7 and 15.4 mega-

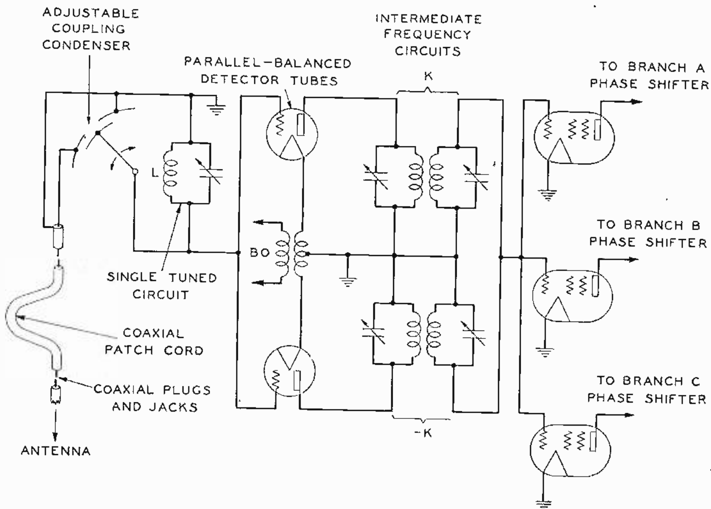


Fig. 10—Input circuit, first detector, and first intermediate-frequency tubes.

cycles. Clearly, line sections which are not short compared with the shortest wave length should be made unequal so that joint irregularities will not be harmful. The smaller variations of the order of ± 10 ohms may be due to random eccentricities produced by slight buckling of the inner conductor between insulators. With the possible exception of the two large variations this line is sufficiently smooth for use in a MUSA, as both theory and subsequent experience indicate.

Input Circuit and First Detectors

The MUSA system imposes requirements upon the input circuits and detectors which do not apply to conventional receivers. These requirements are as follows:

(1) The circuits must suppress standing waves on the transmission lines.[15]

[15] This requirement was more easily met than the alternate requirement nentioned in footnote (11).

(2) The phase shift from the transmission line to the phase shifter stage must be alike in all six circuits, independent of wave length.

In order to simplify the experimental job it was decided to dispense with the selectivity afforded by high-frequency amplifiers and to use the simple circuits shown in Fig. 10. The capacitive coupling to the

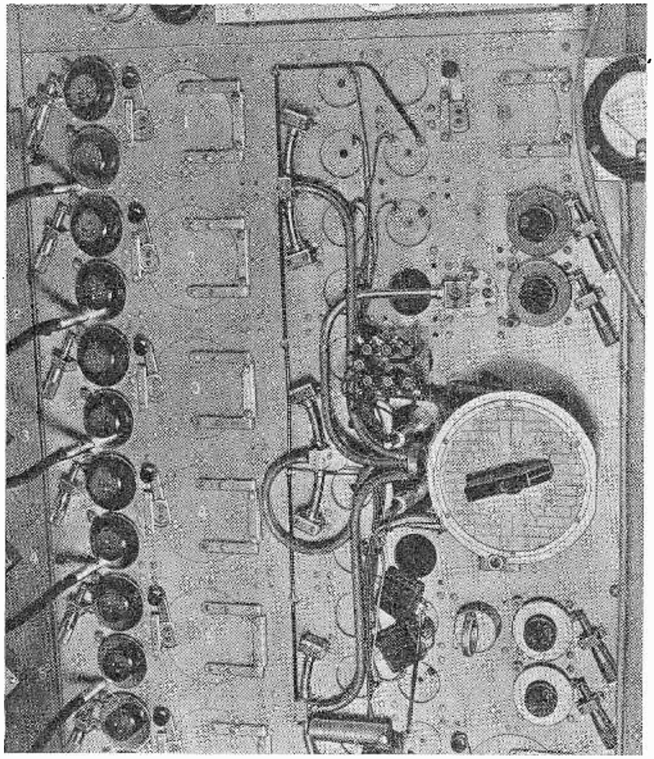


Fig. 11—Close-up view of high-frequency panel with cover removed. The beating oscillator supply line originates in the upper right-hand corner. It supplies the six detectors with equiphase and equiamplitude voltages. Plug-in coils fit into the compartments covered by the six circular doors. Micrometer heads which are used to adjust the six tuning condensers appear. The coaxial patch cords appear at the extreme left.

transmission line is a convenient means of matching the low impedance lines to the high impedance circuits. Plug-in coils (L) are used to cover the range from 4.5 to 22 megacycles.

The first detectors are of the two-tube balanced type which suppresses interference from two signals differing by the intermediate frequency and isolates the beating oscillator supply from the input circuits. The latter prevents cross talk between the six inputs, and assures independence in the tuning of the input circuits. The beating oscillator voltage is introduced, at low impedance, between cathodes[16] by means of the distributing system of equal length coaxial lines shown in Fig. 11. This distributing system gives equiphase beating oscillator inputs to all detectors and makes requirement (2) attainable by having nominal similarity in the remaining parts of the six circuits.

Requirement (1) is met by feeding a test oscillator of 78 ohms impedance into the first circuit jack and adjusting the tuning condenser

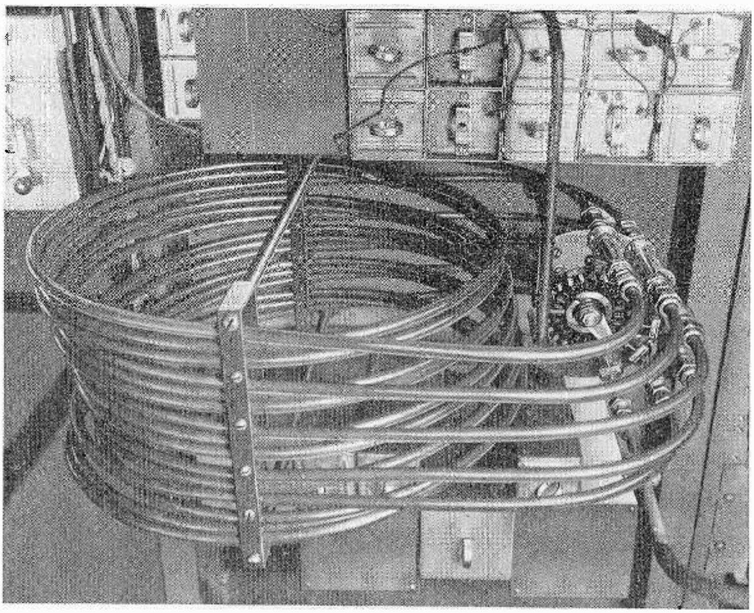


Fig. 12—The standing wave detector comprising 50 feet of 3/8-inch coaxial line, which may be used to test the correctness of the input circuit adjustment.

and the coupling condenser (Fig. 10) alternately until the maximum signal voltage appears on an indicating meter in one of the three intermediate-frequency branches. The three-terminal coupling condenser is an aid in this procedure since varying the coupling imposes only a slight variation in the capacitance across the coil. When the indicating instrument is a square-law vacuum tube voltmeter with the main current balanced out and the remainder indicated by a 30-microampere meter, the sensitivity is more than sufficient to tune the circuits correctly.

[16] W. A. Harris "Superheterodyne frequency conversion systems," Proc. I.R.E., vol. 22, pp. 279–294; April, (1935).

The criterion of correct tune is the degree of suppression of standing waves on the transmission lines. To determine whether or not the maximizing adjustment insures an adequate standing wave suppression, a standing wave detector was incorporated in the experimental design. This is shown in Fig. 12. It consists of about 16 meters of 78-ohm coaxial line arranged in a coil and terminated by the first circuit to be tested. It is fed at the other end by a test oscillator. Six capacitively coupled taps are brought to the low capacitance switch shown in the photograph. The selector arm connects the taps to an auxiliary receiver with a high input impedance. The absence of standing waves is shown

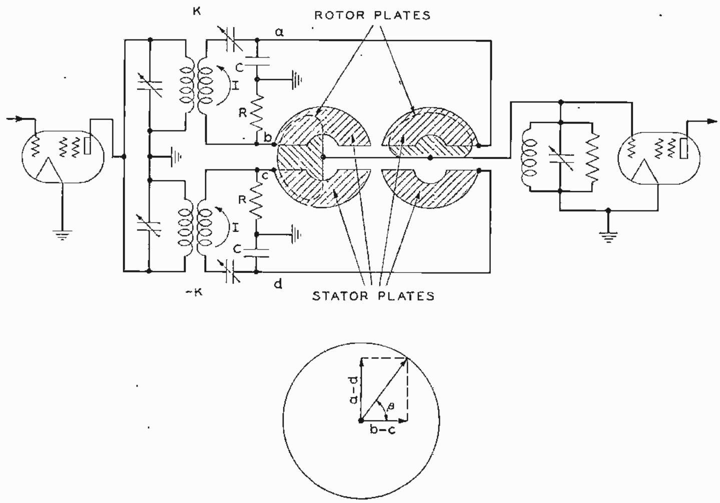


Fig. 13—Circuit diagram and vector diagram of the phase shifter. The rotor plates are especially designed to give a phase shift proportional to shaft angle.

by equal readings at the six positions. It was found that the maximizing adjustment results in a standing wave with less than ten per cent total variation which represents nearly as much suppression as the smoothness of the line allows. With nominally correct resistance termination standing waves of five per cent usually occur. For standing waves not exceeding ten per cent the accompanying phase distribution along the line does not depart more than a few degrees from the desired linear distribution. The use of the standing wave detector in routine operation was therefore not required.

Phase Shifters

Of the numerous methods of shifting phase the method[17] illustrated in Fig. 13 is the one chosen for the 18 circuits (3 branches, 6 antennas)

[17] L. A. Meacham, U. S. Patent No. 2,004,613.

of the experimental MUSA. Here points a, b, d, and c have voltages to ground 90 degrees apart. The potential of point b is IR; that of c is $-IR$; that of a is $jI/\omega C$; that of d is $-jI/\omega C$. The resistance R and reactance $1/\omega C$ are made equal at the mid-band frequency so that four equal voltages, distributed equally over 360 degrees of phase appear on the four stators of the special condenser. A photograph of this condenser appears in Fig. 14. Two specially shaped eccentric rotors mounted in quadrature to each other on the same shaft comprise the output terminal. It will be noted that voltages of opposite phase are connected to adjacent stators. Thus, with the rotors in the position shown dotted in Fig. 13 the output comes from point a since d is not coupled

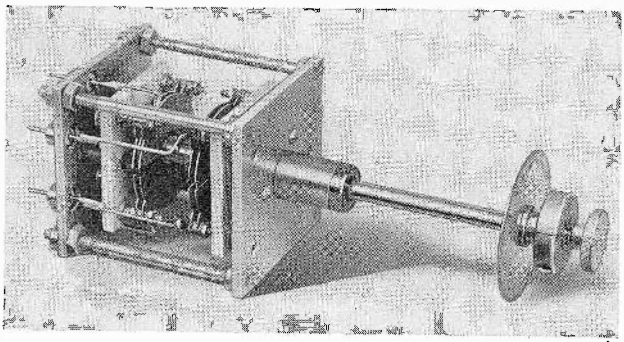


Fig. 14—The phase shifting condenser.

and b and c cancel each other. By shaping the two rotors so that the difference in exposure to opposite stator plates is proportional, respectively, to the sine and cosine of the angle of shaft rotation, the total current flowing from the two rotors will be constant and of phase proportional to the shaft angle. This is illustrated by the vector diagram in Fig. 13 in which β is the shaft angle and vectors $a-d$ and $b-c$ are the quadrature rotor outputs proportional to $\sin\beta$ and $\cos\beta$.

These phase shifters vary in output by less than ± 5 per cent as the shaft is rotated. The departure from linearity of phase shift is correspondingly small; i.e., less than ± 5 degrees.

The useful band width of this type of phase shifter is fundamentally limited by the fact that $1/\omega C$ varies with frequency while R does not. However, this limitation does not appear in the Holmdel MUSA in which the percentage band width is small because the phase shifters operate at the intermediate frequency of 396 kilocycles.

The phase shifters are connected to the steering shaft with helical gears of multiple ratios as shown in Fig. 15. The phase shifter shafts may be slipped with respect to the main shaft. After they have been aligned so that locally supplied equiphase inputs to all detectors add in phase at the point where the phase shifter outputs are combined they are locked. This adjustment is independent of signal frequency. Provision is made for adjusting the gain of each of the six phase shifter circuits so that the differences in transmission-line loss may be compensated and any other desired amplitude adjustments made. The

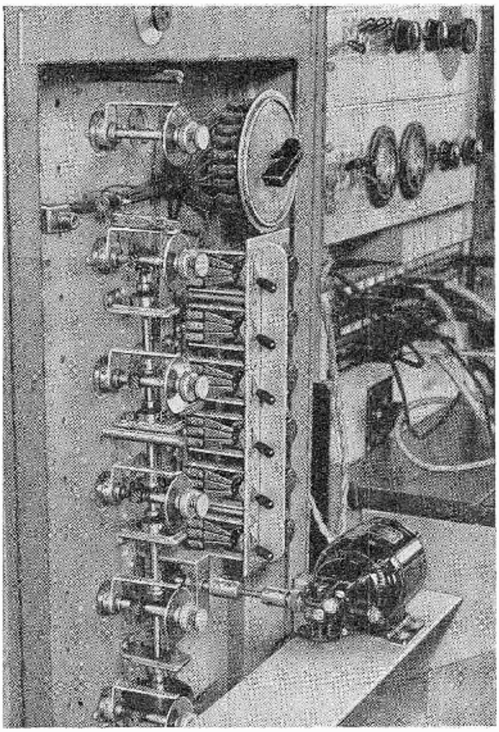


Fig. 15—Phase shifting panel of the monitoring branch. Only five of the six phase shifters are rotated for steering purposes. They are geared to the steering shaft in ratios of 1 : 1, 1 : 2, 1 : 3, 1 : 4, and 1 : 5.

photograph of Fig. 15 shows the monitoring or exploring branch whose steering shaft is motor driven at one revolution per second.

Before leaving the subject of phase shifting it may be well to distinguish between phase shift and delay as here used. All electrical networks, except for certain highly distortive ones, possess a phase-frequency characteristic which is such that higher frequencies have their phases retarded with respect to lower frequencies. The ratio of the increment of phase retardation to the increment of frequency, i.e., the slope of the phase characteristic, is the delay. It is sometimes called the group delay or group transmission time as distinguished from the "phase time."[18] The delay is the only time which can be measured. It does not determine the phase shift of a particular frequency nor is it determined by the phase shift. A phase shifter applied to the network merely moves the phase curve intact up or down on the phase axis.

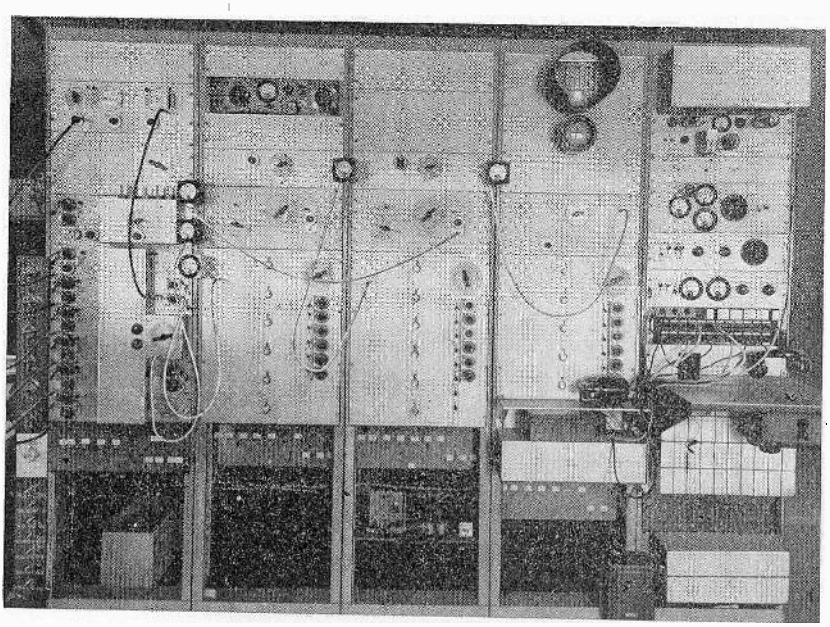


Fig. 16—Front view of the MUSA receiving equipment. The high-frequency bay is at the left and the audio-frequency bay at the right. The branch receivers are the panels directly above the phase shifting panels. The pulse receivers appear above these. At the top of the bay containing the monitoring branch equipment are the two oscilloscopes referred to in Fig. 3. The large tube with the ruled face is the monitoring oscilloscope.

General Description of the System

The preceding paragraphs have described features which distinguish the MUSA system from conventional receiving systems. There remain to describe several auxiliary features and to present a unified picture of the whole.

[18] This distinction is brought out by J. C. Schelleng in a "Note on the determination of the ionization of the upper atmosphere," Proc. I.R.E., vol. 16, pp. 1471–1476; November, (1928).

A general discussion of delay distortion (phase distortion) is to be found in a symposium appearing in the *Bell Sys. Tech. Jour.*, vol. 14, July, (1930).

The experimental system was designed for double side-band reception and all of the results reported in this paper refer to double side-band. There has recently been completed equipment which may be substituted for the double side-band equipment for the reception of reduced carrier single side-band signals. The new equipment may also be used to select, with crystal filters, one side band of double side-band signals.

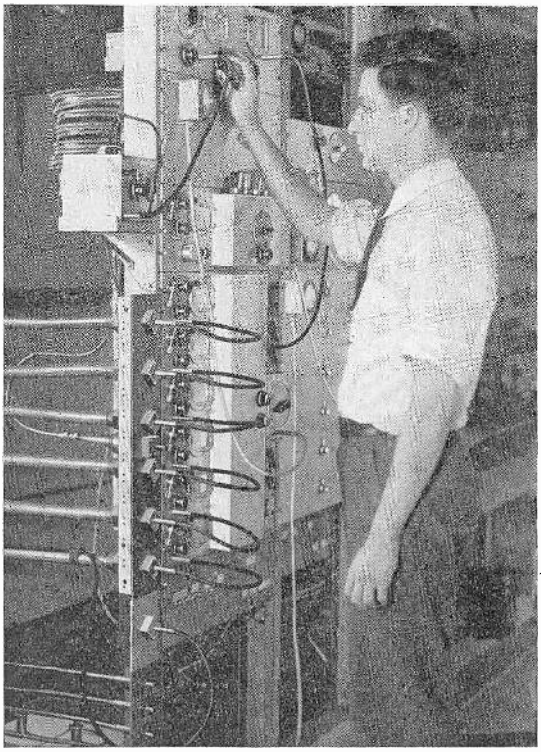


Fig. 17—View showing the six transmission lines and coaxial patch cords. The beating oscillator is mounted upon the shelf and is connected to the power amplifier (which is being adjusted by Mr. Edwards) at the top of the bay.

The delay to be inserted in the low angle branch as indicated in Fig. 3 is obtained electrically from an audio-frequency delay network. The delay could theoretically be provided at the intermediate frequency but no advantage would result. The audio-frequency delay network is a special artificial line composed of forty sections and terminated by its characteristic impedance. Each section has a delay of 68 microseconds. A special switch is arranged to tap a high impedance output circuit across any desired section thus providing a delay of 2.7 milliseconds variable in 0.068-millisecond steps. A special equalizing network[19] which makes the transmission loss the same for all steps and which also equalizes the frequency-loss characteristic so that the response is flat to 5000 cycles for all steps is automatically controlled by this switch. The forty delay sections appear in Fig. 16 just under the

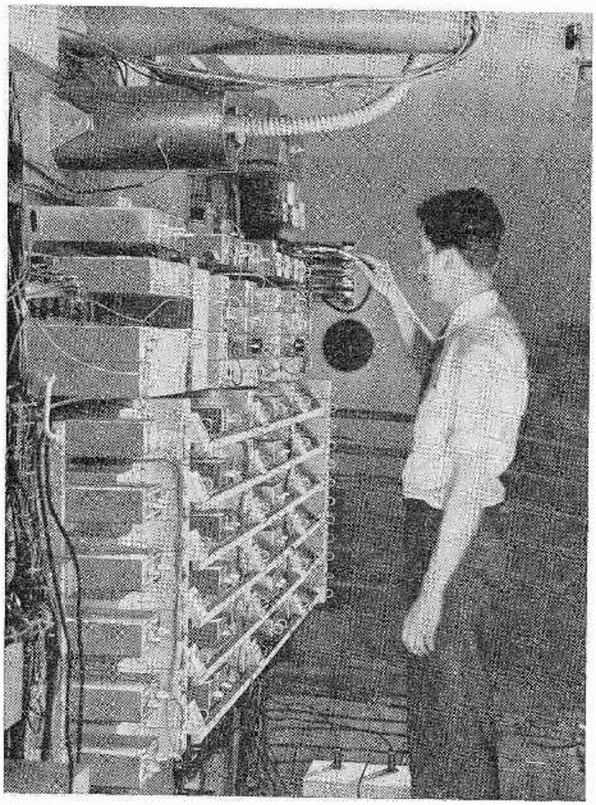


Fig. 18—Rear view of the receiving equipment. The six detector outputs feed the three branches via the square transmission lines.

shelf on the right-hand bay. The maximum delay which has been required in actual operation is 2.5 milliseconds.

Both linear rectifiers and square-law detectors are provided for final demodulation and either may be switched into service as desired. The automatic gain control for use with either demodulator is obtained

[19] This network and the delay sections were designed by P. H. Richardson of Bell Telephone Laboratories, Inc.

from linear rectifiers but a different diversity connection is made for each type of demodulator, in the interest of output volume constancy. A choice of time constants of 0.06, 0.5, and 4 seconds is provided.

Keys are provided, whose ganged manipulation makes it possible, among other things, to compare (1) the MUSA output versus any one of the six antennas connected to one branch receiver, and (2) any pair of antennas in ordinary diversity using both branch receivers, versus one antenna using one receiver.

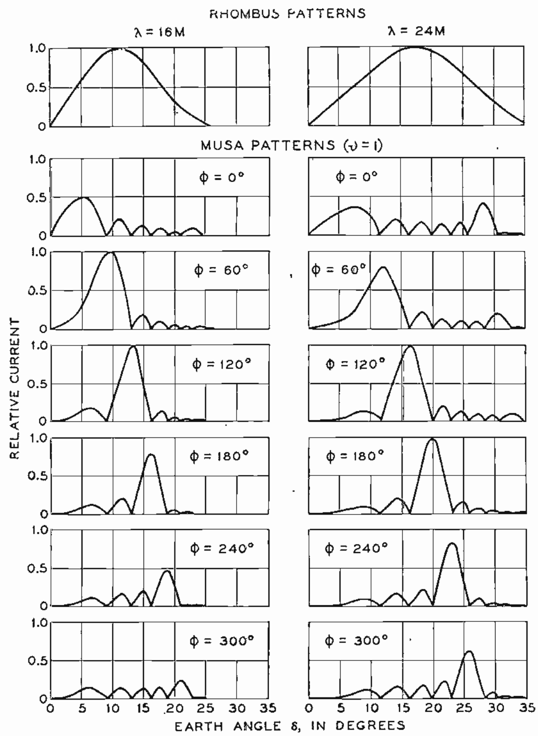


Fig. 19—Vertical directional patterns of the experimental MUSA.

In addition to the regular branch receivers with a 12-kilocycle band width and the monitoring branch receiver with a 2.5-kilocycle band width, two other receivers are provided in the experimental system. These receivers have a 30-kilocycle band width and are used for pulse reception. They are bridged across the inputs of the two regular branch receivers and are connected to a cathode-ray oscilloscope through a commutator.[5]

Various photographs of the MUSA receiver appear with explanatory captions in Figs. 16, 17, and 18.

A family of calculated directional patterns of the experimental MUSA is shown in Figs. 19 and 20. At the top of each column is shown the principal lobe of the vertical directional pattern of the unit rhombic antenna, calculated in the median plane. Beneath are shown six vertical patterns of the MUSA, which are obtained by multiplying the array factor[20] by the unit antenna pattern. The upper pattern corresponds to phasing for zero angle. The remaining ones are plotted for increments of 60 degrees of phase.

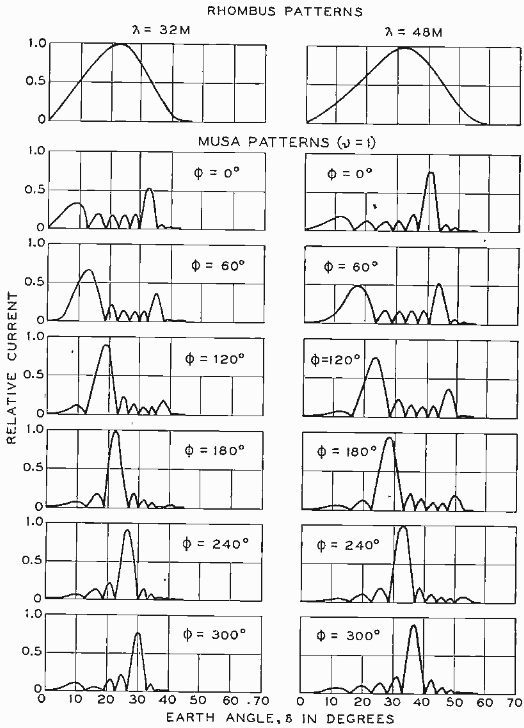


Fig. 20—Vertical directional patterns of the experimental MUSA. Note that the angle scale is half of that in Fig. 19.

These patterns fall short of the "ideal," which the reader may have visualized while reading Section II, in two ways. First, the unit antenna does not suppress the second lobe of the array factor as well as could be desired. By design, it does so for the short waves but inherently fails to do so for the longer waves. Second, the principal lobe of the unit antenna shifts bodily towards higher angles with increasing wave length, whereas it is desirable to have only the upper cutoff move

[20] Calculated from (3) putting $v=1$.

upward while retaining low angle response. Both of these shortcomings restrict the steering range through which the MUSA is essentially single lobed. The upward shift with wave length of the unit antenna response is in fair agreement with the way in which the mean angle of arrival has been found to vary with wave length and is, on that account, not altogether objectionable. The Holmdel MUSA employing such unit antennas represents, however, a considerable departure from present antennas of fixed directivity designed from statistical data, and approaches the ideal MUSA steerable over the entire useful angle range.

The curves as plotted assume that the differences in transmission line loss for the various line lengths have been equalized in the intermediate-frequency circuits. By slightly tapering the amplitudes so that the antennas in the middle of the array contribute more than those near the ends a reduction of the minor lobes has been obtained at the cost of slightly widening the principal lobe. As a result of this, the directional discrimination of the experimental MUSA has been improved. All data and photographic records reported in this paper, however, were obtained before this improvement was introduced.

IV. Tests and General Evaluation[21]

Tests and Experience

Numerous experiments and tests had been carried out on the various parts of the MUSA system before it was first tuned to a transatlantic signal. Despite the fact that all tests concurred in predicting that the system would perform as designed, it was with considerable gratification that a pattern was observed on the monitoring oscilloscope, during one of the early trials, which was almost exactly as calculated for a single wave. Patterns corresponding to two or more waves in various degrees of resolution were observed from time to time. To increase the angle resolution, for test purposes, pulses were transmitted by the British Post Office on several occasions. Turning the steering shaft during these tests clearly showed the principal lobe sweeping through the angle range. When fairly discrete pulses were received the minor lobes could be readily identified. In Fig. 21 is shown a sample of motion picture oscillograms of pulse reception. Two principal waves or, more accurately, wave bundles, occurred and were separated by the two MUSA branches as shown. For details of the pulse technique employed in these tests the reader is referred to a previous publication.[5]

[21] The theory and test results of the signal-to-noise advantage are considered together in Part V.

Before exhibiting sample motion pictures of typical patterns displayed by the angle monitoring oscilloscope and the delay indicator

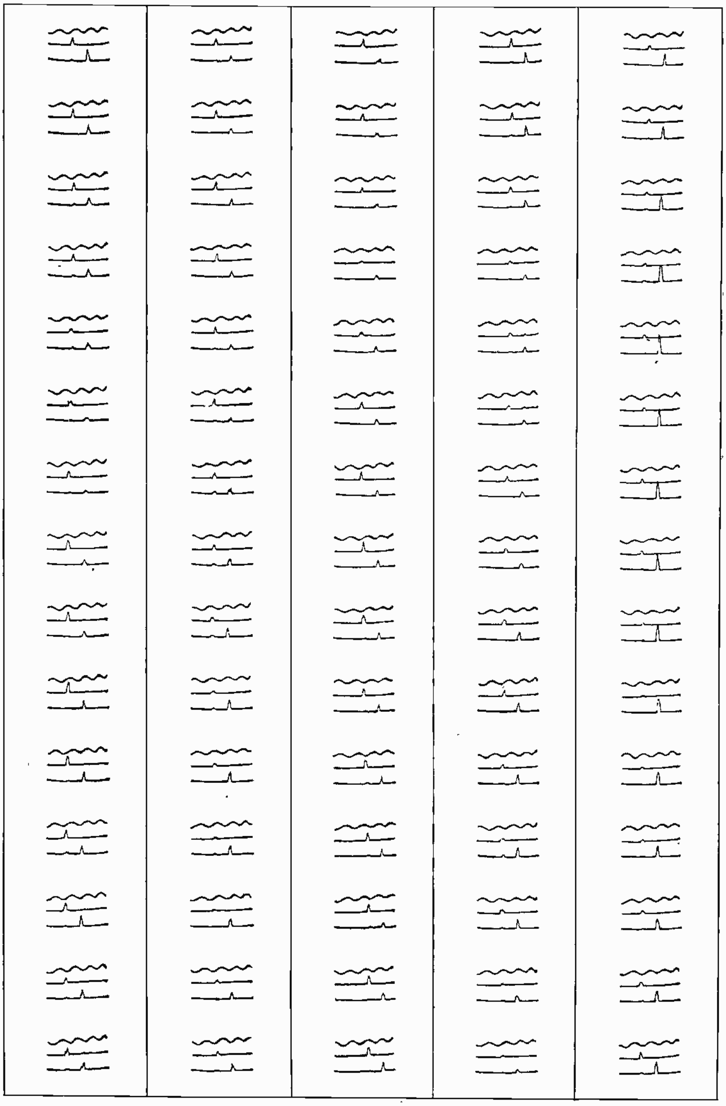


Fig. 21—This retouched plate shows pulses received with MUSA. On each frame time advances from left to right and is measured by the thousand-cycle timing wave. The center trace shows the output of one MUSA branch steered at 25 degrees. The bottom trace shows the output of the second MUSA branch steered at 32 degrees. Wide band amplifiers for pulse reception are bridged in parallel with the speech band intermediate-frequency amplifiers. The transmitted pulses are about 200 microseconds long. GCS (9020 kilocycles) Rugby, February 25, 1936, at 4:11 P.M., E.S.T.

oscilloscope, further discussion of the former is desirable. The photographs of Fig. 22 show the monitoring oscilloscope pattern with a locally produced equiphase, equiamplitude input supplied to each detector. This figure illustrates the manner in which the pattern is built from the six components after the manner of a Fourier synthesis. The vertical and horizontal axes visible on the monitoring oscilloscope in Fig. 16, but which do not appear naturally on the photographs, were drawn in Fig. 22. As mentioned previously, the oscilloscope sweep axis represents one revolution of the "fundamental" phase shifter so

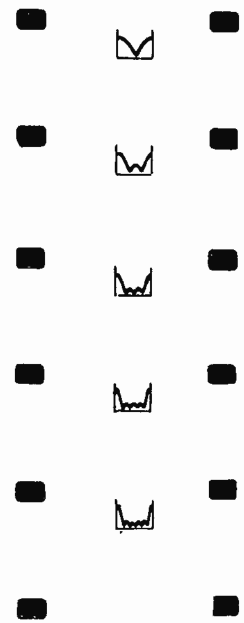


Fig. 22—These five frames show the angle monitoring pattern when a local signal is used to simulate a wave. The bottom frame shows the ideal MUSA pattern for one wave. The remaining frames show the effect of reducing the number of antennas from six (1-2-3-4-5-6) to five (2-3-4-5-6) to four (3-4-5-6) to three (4-5-6) to two (5-6). These films were taken before the amplitude tapering was introduced. Tapered amplitudes reduce the minor lobes to about half of the amplitudes shown.

that the beginning and end of the sweep represent the same condition. The ends of the sweep are arbitrarily fixed to represent zero (or 360) degrees of phase shift referred to the output of the first antenna, whose phase is not varied. Consequently equiphase inputs result in a principal lobe half of which appears at each end. This would correspond to a wave of zero angle if the velocity of the transmission lines was equal to that of light. For a lesser velocity, zero angle may occur at any point on the phase axis, depending upon the wave length. (See Fig. 28 for a sample angle calibration curve.) The principal lobe as well as the four minor lobes of the monitoring oscilloscope represent the output from one wave as the MUSA is steered through its entire

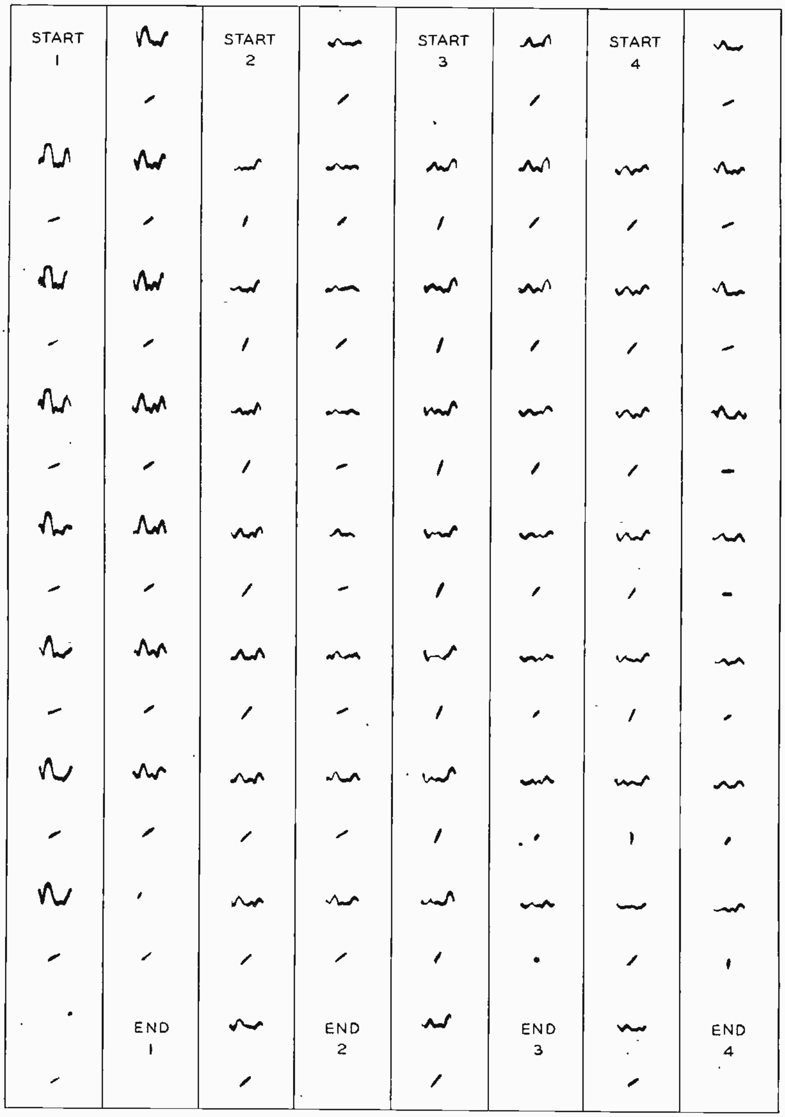


Fig. 23—Pictures of the angle monitoring oscilloscope and the delay indicator tube. The right-hand end of the sweep of the monitoring tube represents zero phase. The indicated angles are 8.5 and 20.5 degrees. The MUSA branches were set at these angles ($\phi_A = 240°$, $\phi_B = 30°$) using 950 microseconds delay. GSE (11,860 kilocycles) Daventry, February 21, 1936, 11:05 A.M., E.S.T. Musical program.

range. The oscilloscope pattern, unlike the directional pattern, does not appear sharper for short wave lengths than for long wave lengths; the principal lobe is always 120 degrees wide and the minor ones 60 degrees wide on the phase axis. One degree of phase difference, however, represents a difference in steering angle which depends upon the wave length and the earth angle.

The samples of motion picture film shown in Fig. 23 represent fairly typical "two-path" patterns. The camera was focused to include both oscilloscopes and was manipulated by means of a special step-by-step crank. The operator endeavored to expose each frame during one sweep of the monitoring tube. The delay indicator tube shows a continuous pattern produced by the audio frequencies. A correct delay setting is indicated by a straight line. Here, with the two branches steered at the indicated angles of 8.5 and 20.5 degrees, a delay of 950 microseconds was required to produce the straight line. The diversity action is apparent in the tilting of this line. When the low angle wave, which corresponds to the left-hand peak on the monitoring tube, is predominant the delay indicator line becomes horizontal and, conversely, when the high angle wave is predominant the line approaches the vertical axis. Automatic gain control is used on the branch receivers supplying the speech outputs but is not used on the monitoring branch.

Fig. 24 shows, in samples 1 and 2, reception of two waves which are just separable by the directivity present in the Holmdel MUSA. The angles are 15 and 22 degrees and the wave length is 31.6 meters. The delay used is 400 microseconds. In samples 3 and 4 a third wave of 26 degrees is present. One branch was steered at this wave; the other was steered at the 15-degree wave and a delay of 1000 microseconds was used.

It is of interest to compare these samples showing the manner in which the MUSA branch outputs combine, with the samples in Fig. 25 which were obtained with a two-antenna space diversity setup. Six antennas were retained in the monitoring branch but five were cut out of each receiving branch leaving one antenna to supply each branch. In samples 1 and 2, antennas 1 and 6 (1000 meters apart) were retained. In samples 3 and 4, adjacent antennas (Nos. 1 and 2) 200 meters apart were used. These records were obtained about 15 minutes later than those of Fig. 23 and show the same two waves at 8.5 and 20.5 degrees. No delay was used. Note that the outputs combine in phase only when one wave predominates. Inserting delay in either branch is, of course, not effective in improving the audio combination. To do so would impair the addition when one wave is predominant and would not be beneficial when both waves are comparable.

Fig. 24—Pictures of the angle monitoring oscilloscope and the delay indicator tube. In films 1 and 2 the indicated angles are 15 and 22 degrees. The MUSA branches were set at these angles ($\phi_A = 240°$, $\phi_B = 340°$) and a delay of 400 microseconds was used. The time was 3:20 P.M., E.S.T. Films 3 and 4 were taken at 3:15 when a third wave of 26 degrees was present. One branch was sterred at this wave ($\phi_B = 50°$); the other at 16 degrees ($\phi_A = 250°$). A delay of 1000 microseconds was required. GSB (9510 kilocycles) Daventry, March 10, 1936.

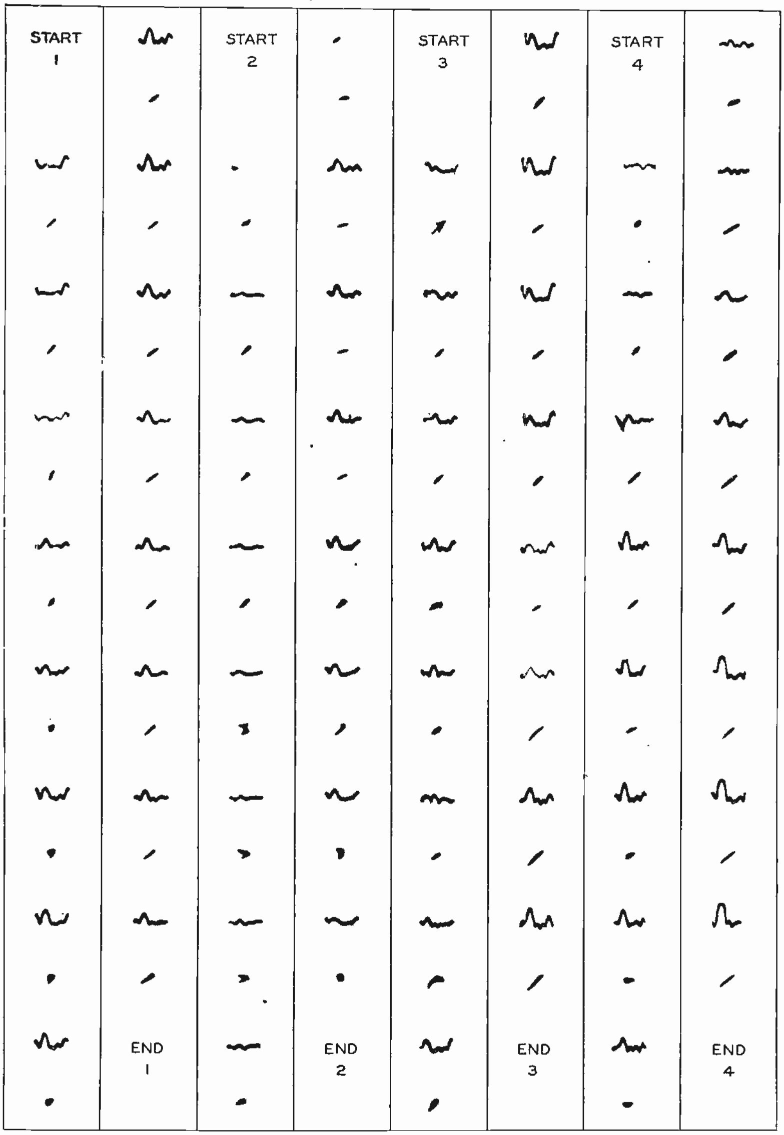


Fig. 25—This plate, made immediately following that of Fig. 23 shows for comparison the manner in which the audio outputs add in two-station space diversity. The angle monitor shows the 8.5- and 20.5-degree waves as before. Films 1 and 2 taken at 11:15 A.M., E.S.T., were obtained with rhombic antennas 1 and 6 (40 wave lengths apart). Films 3 and 4 taken at 11:20 were obtained with antennas 1 and 2 (8 wave lengths apart). Note the second harmonic in film 2 particularly. GSE (11,860 kilocycles) Daventry, February 21, 1936. Musical program. Zero delay.

Fig. 26 shows, in samples 1, 2, 3, and 4, how the delay indicator tube pattern is affected by the delay adjustment. The two branches were steered at the same angle thus making both branch outputs

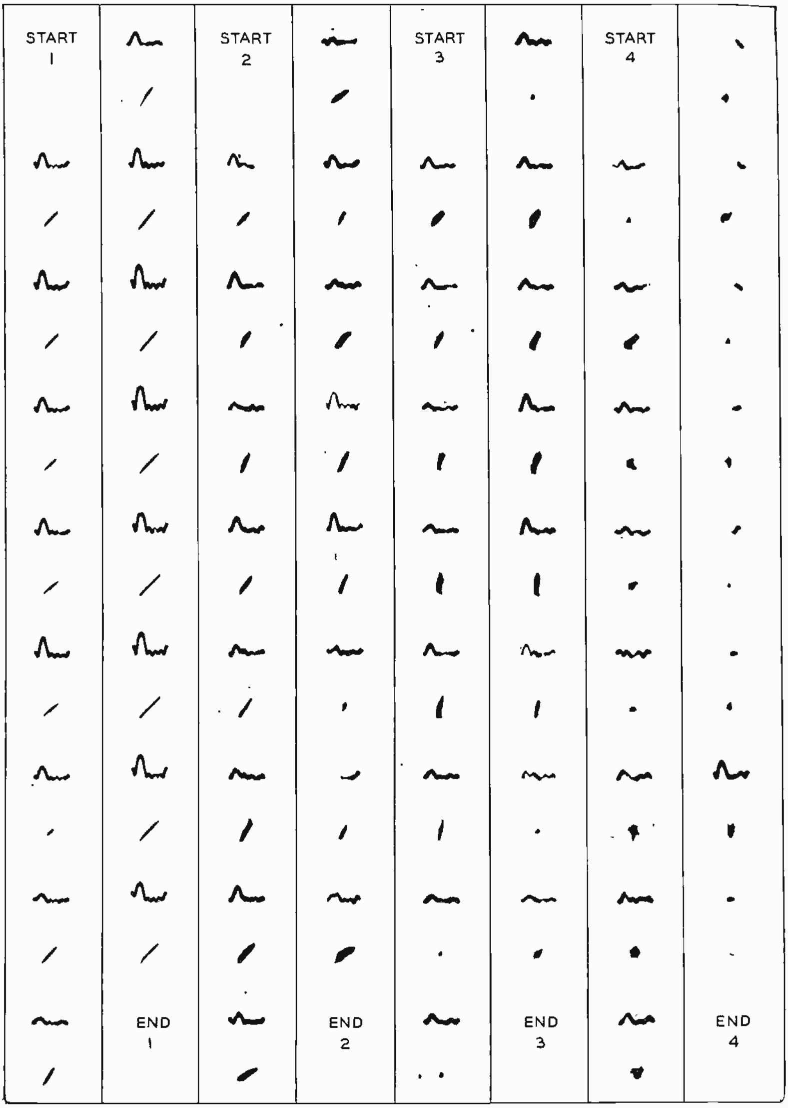


Fig. 26—Film showing the effect upon the audio addition, of unequalized delay. Both MUSA branches were steered at the same angle,—that of the major wave shown. Film 1 shows no delay added and since each branch receives the same wave the audio outputs add perfectly. Films 2, 3, and 4 show the effect of adding 340, 680, and 2700 microseconds delay, respectively.

identical so that perfect delay adjustment occurs with zero delay. This is the condition depicted in sample 1. In samples 2, 3, and

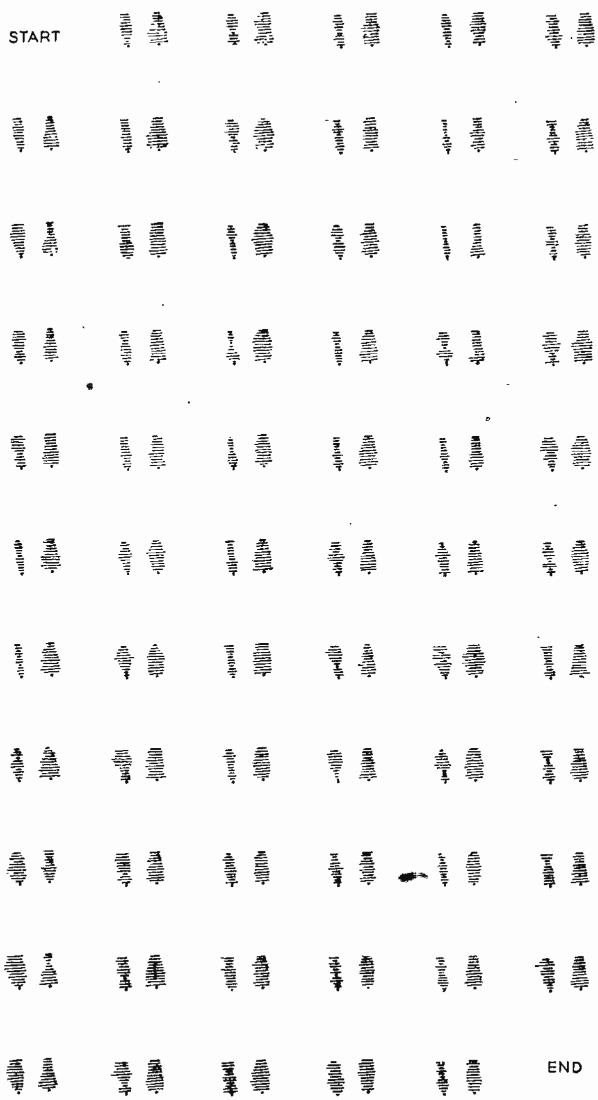


Fig. 27—This is a cathode-ray "multitone" record comparing the MUSA output with that of a horizontal half-wave antenna. The tones on the right-hand side of each frame are the MUSA output; those on the left are the output of the horizontal half-wave antenna. The two MUSA branches were steered at 15 and 22.5 degrees. A delay of 470 microseconds was used to equalize the transmission time. GCS (9020 kilocycles) Rugby, February 24, 1936, at 3:54 P.M. E.S.T.

4 the delays are 340, 680, and 2700 microseconds, respectively.

A number of tests were carried out with the co-operation of the British Post Office in which twelve tones were transmitted. These tones were nonharmonically related. They were separated at the output of the receiver by means of filters, and commutated to appear successively on an oscilloscope. The reader is referred to a paper[4] by R. K. Potter describing this technique. Fig. 27 shows a sample of motion pictures made of the oscilloscope patterns. Two receiving systems are compared; the right-hand pattern shows the output of the MUSA while the left shows the output of a conventional receiver connected to a horizontal half-wave antenna. The tones trace the horizontal lines in sequence from top (425 cycles) to bottom (2125 cycles). After one pattern is executed the commutator switches from one receiver to the other. The twelfth tone is omitted to provide time for the switching. The complete double pattern is traced in about one sixth of a second and the camera is operated at a speed which exposes each frame a little longer than one sixth of a second.

In Fig. 27 the MUSA branches were steered at 15 and 22.5 degrees and employed an equalizing delay of 470 microseconds. While the MUSA output is not perfect it is vastly superior to that of the doublet. The tone frequencies and filters are such as to suppress harmonic distortion with the result that the patterns show mainly the selective fading of the fundamental audio frequencies. Note that the fundamental output nearly disappears in the doublet receiver. In practice this would correspond to violent harmonic distortion of speech or music.

In addition to the tests and experiments illustrated by the motion picture reproductions in the preceding paragraphs a series of experiments were conducted using broadcast transmission on 49 meters from a station at Halifax, Nova Scotia. In these experiments angles and delay differences were measured and compared with multiple reflection theory. The agreement between measured and predicted values is not only interesting as a study of the ionosphere but constitutes a unique and valuable test of the performance of the MUSA system.

Observations on VE9HX, Halifax

During the course of reception experiments with GSL (BBC, Daventry, 6110 kilocycles) performed as a part of the routine operating program for the MUSA system, a broadcast station appeared on GSL's frequency. This station carried the programs of CHNS, Halifax, Nova Scotia, and was subsequently determined to be an experimental station with the call letters VE9HX located hear Halifax and nearly on the great-circle path from New York to London. The transmitting antenna is a half-wave horizontal, one-quarter wave above ground and oriented to radiate in the direction of New York.

The first experience with this station showed two stable transmission paths capable of being separated by the two branches of the MUSA. The delays could be accurately equalized and rather definite correlation was obtained with the multiple "hop" propagation picture. This fact and the additional reason that propagation from England on the same frequency might be compared with the simpler phenomena encountered with Halifax led to the measurements described in the following paragraphs.

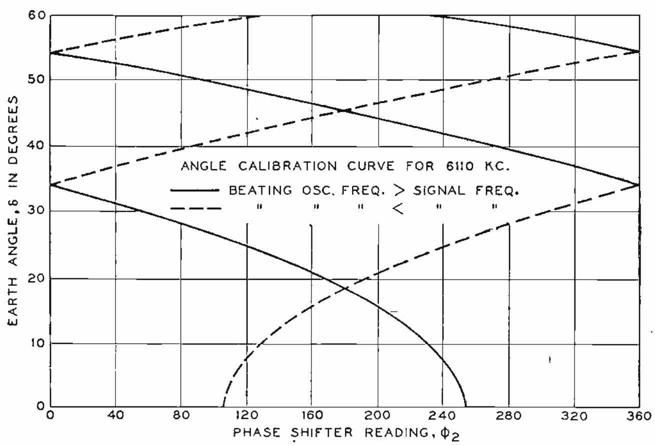
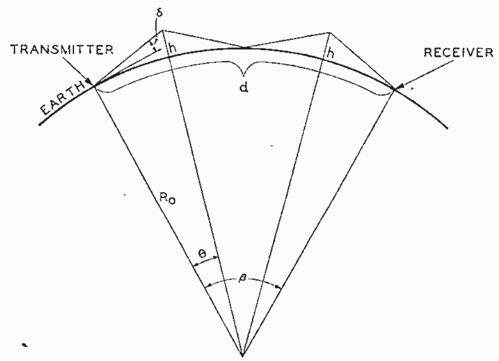


Fig. 28—Calibration curves of the Holmdel MUSA for 49.1 meters, giving the angle of the principal lobe as a function of phase advance ϕ_2 (Fig. 3). Note that the sense of the phase shift depends upon the beating oscillator frequency. The curves are calculated for a velocity ratio $v=1/0.933$.

About eleven hours of observation, distributed over fifteen days, are included. The log aimed to record all changes which occurred during an observation period. The procedure was as follows: The two branches of the receiver were steered at the angles indicated by the monitoring oscilloscope. Delay was added to the lower angle branch until the two audio outputs added. The delay setting was usually critical to one section of the network (67.5 microseconds) and always to two sections. The angles were determined from the calibration curve reproduced in Fig. 28. The phase readings observed on the monitoring oscilloscope were recorded to within ± 10 degrees and the earth angles determined by them are liable to be in error by one degree (possibly 1.5 degrees) apart from the ambiguity due to the multiple lobe characteristics of the MUSA. At this wave length, the major lobe of the unit rhombic antennas is broad, the first null occurring at 58 degrees, so that two angles had to be considered possible.



$$\text{DELAY} = \frac{2nR_0 \sin\theta}{c\cos(\delta+\theta)} - \frac{d}{c}\,;\; 1 + \frac{h}{R_0} = \frac{\cos\delta}{\cos(\delta+\theta)}\,;\; 2n\theta = \beta$$

Fig. 29—Delay and angle relations for multiple reflection from a uniform reflecting surface. The number of ionosphere reflections is designated by n.

The multiple hop picture is illustrated in Fig. 29. Here the delay referred to the ground wave is expressed in terms of earth angles δ

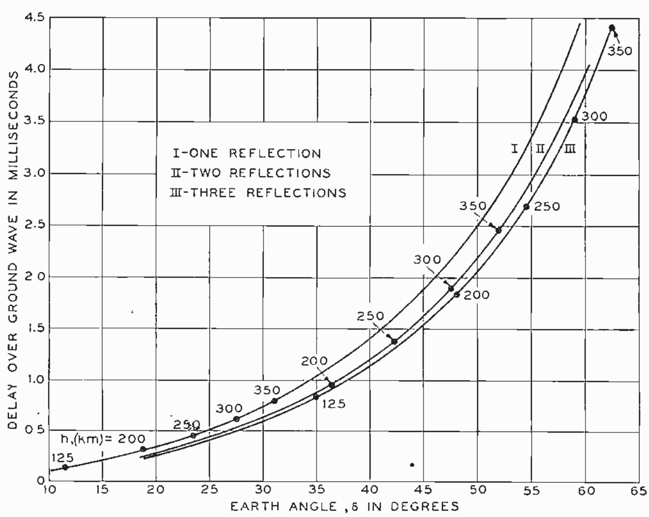


Fig. 30—Curves giving the delay-angle relations for multiple reflection on the Halifax-to-Holmdel path.

and n, the number of hops or ionosphere reflections. The height h and angle δ are also related through n as shown in Fig. 29. Using the first relation, the curves of Fig. 30 were drawn; using the second relation, points corresponding to various heights were located on the curves. For the Holmdel-Halifax circuit d is 643 miles (1030 kilo-

TABLE I
OBSERVATIONS ON VE9HX, HALIFAX, NOVA SCOTIA
6110 kilocycles 49.1 meters

	E.S.T.	Date	$\delta_1°$	$\delta_2°$	Relative Delay milliseconds		Virtual Height kilometers			Estimated		Field decibels above $1\mu v/m.$
					meas.	calc.	1st	2nd	3rd	1st	2nd	
		1935										
	P.M. 5:00	11–25	18.2	38	1.01	0.77	195	215				
	P.M. 4:45	11–26	24.5	42	1.01	0.85	260	250				
	P.M. 4:40	12–17	26.4	44	0.95	0.97	290	270				27
	P.M. 4:41	12–17	24.5	43	0.95	0.95	265	255				
	P.M. 5:01	12–17	24.5	42	0.95	0.85	265	250				
	P.M. 4:20	12–18	25.5	44	0.95	1.05	275	270				27
	P.M. 4:25	12–18	24.0	42.5	0.95	0.90	250	250				
A	P.M. 4:40	12–18	23.0	42	—	0.90	245	250				
	P.M. 4:30	12–23	24.5	44	0.95	1.05	265	270				25
	A.M. 10:29	12–26	28.0	44	0.95	0.90	305	270				−14
	A.M. 10:46	12–26	28.0	44	0.81	0.90	305	270				
	A.M. 10:52	12–26	29.5	44	0.78	0.85	330	270				
	P.M. 4:33	12–26	24.5	44	0.88	1.05	265	270		242	245	18
	P.M. 4:49	12–26	24.5	42	0.95	0.85	265	250				
	P.M. 4:58	12–26	24.0	42.5	0.88	0.90	250	250				
	A.M. 10:07	12–27	25.5	43	0.95	0.95	275	255				−14
	A.M. 10:57	12–27	29.5	42	0.68	0.65	330	250		130	243	
	A.M. 11:03	12–27	31.0	42	0.88	0.70		250	100			
	A.M. 11:20	12–27	<8.0	45.5	1.28	1.6+	<120	280				
B						1.5+	<120		185			
	A.M. 11:48	12–27	8.0	47.5	1.28	1.8+	<120	300				
						1.7	<120		195			
	A.M. 11:56	12–27	8.0	45.5	1.28	1.6+	<120	280		130	247	
						1.5+	<120		185			
C	P.M. 4:32	12–27	25.5	44	0.88	1.05	275	270				14
	P.M. 4:59	12–27	27.0	43	0.88	0.85	295	255				
D	A.M. 10:45	12–31	31.0	42	0.50	0.55	350	250				0
	A.M. 11:45	12–31	8.0	35.5	0.71	0.8+	<120	195				
		1936										
	A.M. 10:30	1–2	24.5	42	0.88	0.85	265	250				− 2
	P.M. 6:05	1–14	20.5	42	1.01	1.00	215	250				8
E	P.M. 6:35	1–14	18.4	38	1.01	0.77	200	215				
	P.M. 6:15	1–15	23.0	42	1.08	0.90	245	250				22
	P.M. 6:20	1–15	24.0	42	1.11	0.85	250	250				
	P.M. 6:40	1–16	25.5	42	1.08	0.85	275	250				14
	P.M. 7:21	1–16	24.5	43	1.18	0.95	265	255				
F	P.M. 8:39	1–16	31.5	37	0.27	0.20	355	205				
	P.M. 9:35	1–16	26.4	37	0.47	0.42	290	205				27
	P.M. 5:50	1–21	24.5	42	0.95	0.85	265	250		267	247	22
G	P.M. 6:10	1–21	26.4	44	1.01	0.97	290	270				
	P.M. 6:16	1–21	22.0	40	0.95	0.80	235	230		232	245	
	A.M. 10:40	1–22	24.5	43	0.95	0.95	265	255				− 2
	A.M. 11:05	1–22	24.5	34	0.41	0.35	265	185				
						0.30	265		120			
H	A.M. 11:09	1–22	34.0	43	0.60	0.60	185	255				
						0.65		255	120			
	A.M. 11:30	1–22	24.5	43	0.95	0.95	265	255				
	A.M. 11:35	1–22	24.5	34	0.41	0.35	265	185				
						0.30	265		120			
I	P.M. 6:45	1–24	18.4	38	0.74	0.77	200	215				2

meters) making $\beta = 9°21'$. Corresponding to each measured angle there is a delay (referred arbitrarily to the ground wave which, of course, was not received) and a layer height, for each of the modes or orders.

Both angles together yield a delay difference which is to be compared with the measured value.

In Table I the virtual heights are deduced from the curves for the assumed hop orders. The calculated relative delay is the delay difference corresponding to these heights. All angles below 60 degrees were considered and all combinations of hop orders were considered for each angle, subject to the experimental knowledge of the sense of the delay. The values shown in the table are the ones which give the best agreement with the measured delay. In most instances there was no question concerning the interpretation; in a few doubtful cases two possibilities are presented (December 27 and January 22).

Examination of the table shows that except near noon, the propagation comprises the first and second reflections from the F region of the ionosphere. Groups A, C, E and G illustrate this. In the majority of instances the agreement is excellent; these cases constitute strong evidence that the MUSA performs correctly.

The discrepancies in the table between layer heights for the first and second hops and between measured and calculated delay are not entirely experimental error. Assuming errors in measured angles sufficient to make the delays agree will, in some cases, increase the discrepancy in heights. An interpretation one might make of this is that the ionosphere is not uniform over the circuit and the regular reflection basis of calculating is not strictly in accord with facts. However, there are other theoretical explanations for discrepancies in height. Under usual conditions, the second reflection height should be slightly greater than the first but for certain ionizations in the E region, the first F reflection may be retarded more than the second F reflection in passing through the E region. Thus the heights may differ in either direction without demanding horizontal nonuniformity. The discrepancies between measured and calculated delay may be explained by horizontal nonuniformity in the ionosphere. For an essentially nondissipative atmosphere of ions having any vertical distribution but no horizontal gradient, and neglecting the earth's magnetic field, the group delay is identical with that calculated from triangular paths coinciding with the initial earth angles. Breit and Tuve showed this in their 1926 paper. With horizontal variations in the ionosphere such as tilting layers, no kind of agreement could be expected; the waves might even travel via other than great circle routes.

During three days of our observations W. M. Goodall made measurements of virtual height and of critical frequency which enabled him to predict the results we might be expected to observe. His estimates are shown in the next to the last column of the table.

The data for December 27 (B) are interesting in that after 11 o'clock the first F reflection apparently disappeared. Instead, a first reflection from the E layer is indicated. This was predicted by Mr. Goodall on the basis that the E region ionization at noon became so great that 24-degree waves should be reflected. For completeness the table shows an alternative interpretation of a first E reflection and a third reflection from a 185- to 195-kilometer height. The first E reflection and second F reflection are perhaps more likely. The 11:03 record is not explained.

Something similar appeared to happen on December 31 (D). On January 22 (H) normal first and second F reflections occurred with angles of 24.5 and 43 degrees. In addition a third wave of 34 degrees appeared. Two interpretations of this are shown but neither seems very plausible.

As a general rule propagation from Halifax is simpler than from Daventry on the same wave length. In particular GSL waves received by the two MUSA branches are definitely less discrete and include sufficient delay differences in themselves to prevent the nicety of equalization possible with VE9HX. If multiple reflection takes place, which we have no reason to doubt, it is generally so distorted by non-uniformity over the path or by other factors as to be unrecognizable. In view of the occasional complexity of the Halifax circuit, only one sixth as long, this is perhaps to be expected.

The absence from these observations on Halifax of any third reflections from the F layer is likely due to the fact that they would fall in the neighborhood of the first null of the rhombic antenna and would have to be much stronger in space in order to appear comparable with the second or first. There have been momentary appearances of waves which might have been third reflections but they did not persist long enough to work with.

When single waves were present, which was not unusual in the later evening hours, the angle more often corresponded with the first F reflection rather than the second.

Additional Numerical Data on Reception with the MUSA

The data shown in Fig. 31 are submitted to supplement the rather meager numerical data on transatlantic reception thus far presented. Here, relative delays and angles taken from the MUSA operating log are shown in plots A, B, and C. Only the end points of the lines are significant; they denote by their abscissas the angles at which the two receiving branches were set. The ordinates of the upper end points denote the equalizing delay. The lines merely connect coexistent points. The data shown were selected from the rather extensive log to present a fair cross section of conditions, omitting, however, all cases in which both branches were steered at the same wave bundle. They cover winter and summer and were obtained with frequencies appropriate to the time and season. Most of the observations were made on transmission from Daventry, the remainder on transmission from Rugby. In D are shown the results of pulse measurements made before the MUSA was in use. Here the angles were measured by the two antenna null method and the delays were observed directly on the oscilloscope time axis.[5] Although as many as five points, each denoting

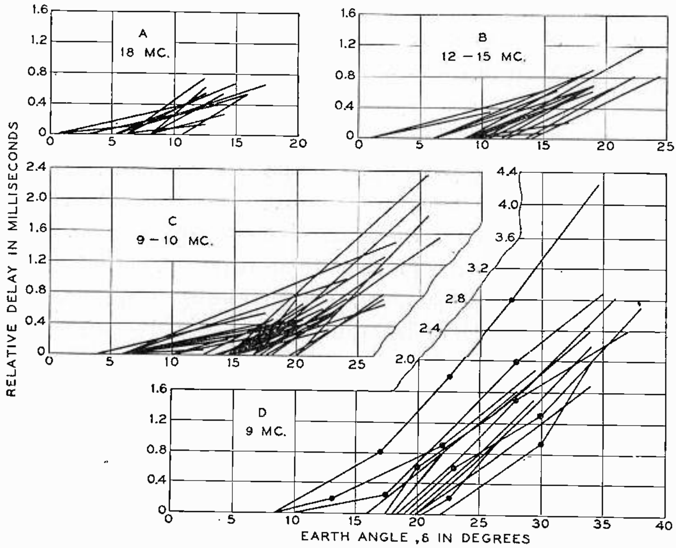


Fig. 31—Pairs of measured angles and relative delay denoted by the end points of the line segments. The data in *A*, *B*, and *C* were obtained with the MUSA; that of *D* was obtained by the use of pulses.

a wave bundle, are shown, generally not more than three were important at once. These measurements were made on transmission from Rugby.

It will be noticed that all four groups of data show that the relative delay per degree of angle difference is small at low angles and increases with the angle, roughly as the multiple reflection theory indicates. (This characteristic is distinctly favorable to the performance of the MUSA since its angle resolving power falls off at very low angles.) The scattering of the data indicates that an equalizing delay determined by the angle settings would not be successful; i.e., the delay must be capable of adjustment to meet the various transmission conditions.

Quality Improvement with the MUSA

The distortion of speech and musical quality which characterizes short-wave circuits is due entirely to the interference of differently delayed waves each of which individually is fundamentally free from all kinds of distortion except nonselective fading. This conclusion is almost self-evident and is corroborated by the results of several years of pulse investigation[5] made in co-öperation with the British Post Office.

A MUSA system can be expected to select one out of several multiple reflections. However, these reflections suffer more or less scattering with the result that they appear as bundles of waves of various degrees of compactness. These bundles possess a small spread of both angle and delay. The delay interval included in a bundle of waves is rarely less than 100 microseconds. Double refraction or "magnetoionic splitting" occurring in the ionosphere doubtless accounts for the existence of a small minimum delay. A delay interval of fifty microseconds or so may be detected even in the unusually compact bundles represented by the pulses of Fig. 21. Transmission from Halifax appears to include a delay interval of this order, also. With transatlantic propagation it is not uncommon to have a bundle containing numerous weaker components extending over several hundred microseconds. On rare occasions these have extended over two milliseconds, masking any multiple reflections which may have been present.

The quality associated with one MUSA branch which selects one out of several bundles of waves is thus not perfect. The effect of a delay interval of a few hundred microseconds is scarcely noticeable, however, except during deep carrier fades. Therefore, if diversity action between two branches steered at the low and high angle parts of the same bundle is employed, deep fades are avoided to a large extent, and the quality is almost perfect. When more than one wave bundle is present diversity action between branches steered at the principal bundles accomplishes this escape from deep fades. It is desirable to utilize all of the principal bundles in diversity in order to preserve the discrimination of the MUSA. For, one of the bundles, if not provided with a branch to receive it, would cross talk into the other branches when it momentarily became strong and those provided with branch receivers became weak. Signal-to-noise ratio considerations discussed in Section V constitute an equally important (and related) reason for utilizing all principal bundles.

As distinguished from selective fading, which is greatly reduced by the rejection of all but one wave bundle, general fading is by no means eliminated. The reader may expect, however, that when the MUSA selects one wave bundle from several it restricts the waves accepted to those which have traveled more nearly a common path, and for a given degree of turbulence in the ionosphere, the fading should be slower, since only relative changes among the several waves result in interference fading. Such a tendency no doubt exists and has been noticed occasionally in the operation of the MUSA but rarely has there been a marked effect (excepting certain cases of flutter fading to be described later). This will be understood when it is recalled that even a fifty-microsecond delay interval means that a difference of 500 wave lengths is involved for a wave length of thirty meters. In order that the fading rate be sharply reduced it is required that the ionosphere shall preserve this difference, to within a half wave length, more effectively than it does if larger differences are involved. Since a half wave length is only 0.1 per cent of 500 wave lengths a rather high degree of balance is thus required. Evidently, the turbulence of the ionosphere usually prevents such a balance.

Using broadcast signals (double side band) from Daventry a thousand or more comparisons were made of the MUSA versus a single antenna and receiver, using the switching arrangement mentioned in Section III. Remarkable improvements were sometimes observed and some improvement was almost always noted. The exceptions were the instances when distortion was not detectable using one antenna, and the rare occasions when particularly violent flutter fading occurred.

Space diversity reception using two antennas showed a substantial improvement, usually, but failed ever to show the order of improvement demonstrated by the two-branch MUSA when two or more wave bundles of comparable amplitude occurred. Figs. 23 and 25 suggest, by the way in which the audio outputs are seen to combine, that the distortion with MUSA reception is slight compared with that with diversity reception.

The increased naturalness which results from reducing the distortion is, of course, pleasing to the ear and has some value in telephone circuits on account of the subscribers' satisfaction. In addition, it increases the intelligibility particularly when considerable noise is present. It is impossible to evaluate the increased intelligibility definitely but, in certain cases at least, it permits the signal-to-noise ratio to be two or three decibels lower. From the point of view of picking up short-wave broadcasts for rebroadcasting, a more substantial value can be attached to the MUSA quality improvement.

To a considerable extent, the magnitude of the quality improvement ascribed to the MUSA in the preceding paragraphs depends upon the fact that double side-band signals were employed. For, with double side-band signals the selective fading caused by the interference of the differently delayed waves results not only in selective fading of the audio output, but also produces nonlinear distortion when the carrier fades selectively. This nonlinear distortion sounds much like overmodulation, and when it occurs in its more violent forms it completely ruins the quality and intelligibility. With single side-band transmission it is possible to demodulate with such a strong carrier that nonlinear distortion is virtually eliminated. The fading of the audio output is sometimes more selective than with double side-band but the resulting quality is substantially better.

Single side-band transatlantic signals were not available during the trial of the MUSA system. However, as mentioned in Section III, receiving equipment was available which rejects one side band and reduces the percentage modulation by a factor of ten or more. It was found that this equipment, applied to the one antenna system, resulted in substantially reduced nonlinear distortion and that the quality could be still further improved by the reduction of selective fading afforded by the MUSA. With MUSA reception there was apparently no quality improvement in going from double to single side band.

Summarizing Discussion

In this section the general performance of the experimental MUSA has been described in a necessarily qualitative manner. Motion picture oscillograms were shown to illustrate the performance under fairly typical transatlantic conditions. An investigation of propagation from Halifax in which the MUSA was employed to identify ionosphere reflections was included to supplement the rather fragmentary evidence available in motion picture oscillograms. The improved quality obtained with MUSA reception was discussed from several points of view. The evaluation of the MUSA has been general; it serves partly to introduce the following section which deals specifically with the signal-to-noise ratio evaluation.

Before closing this section it is appropriate to discuss conditions with which the experimental MUSA could not adequately cope.

On numerous occasions the fact that only two branches are provided has definitely handicapped the performance. More often, however, the need for greater angular discrimination or resolving power has been apparent. Except on infrequent occasions a MUSA two to three times the length of the experimental one and equipped with three branch receivers could be expected to perform as well as the experimental one now performs at its best. The occasions when it might not are the infrequent times when violent flutter fading occurs.

At least one type of flutter fading appears to be associated with a pronounced scattering which results in a kind of shower of erratic waves arriving over a wide range of directions. Receiving antenna directivity has been found definitely helpful in all except the most violent cases. Apparently when improvements due to directivity occur they occur principally by selecting a more or less normally propagated wave bundle and rejecting the shower of erratic scattered waves. When, in the most violent cases, no reduction of the flutter can be achieved the reason may be that the unit antenna accepts too wide a horizontal range to permit the MUSA to discriminate sufficiently against the shower. (It will be remembered that the MUSA array factor is of the form of a semiconical shell and thus the MUSA will, in general, accept as wide a horizontal range as the unit antenna permits.

V. The Signal-to-Noise Improvement of the MUSA Receiving System

Because of the complicated nature of short-wave transmission and also because of the uncertain state of noise measuring technique, it is not a simple matter to give a satisfactory answer to the question: "What is the signal-to-noise improvement of a MUSA system?" In this section an attempt has been made to simplify the problem by separating the various factors involved. The section begins with an analysis of the problem assuming simple types of wave transmission. This is followed by experimental studies and discussions.

In discussing the signal-to-noise advantage of a MUSA it is understood that a reference receiving system must be adopted, and for this purpose one of the unit antennas connected to an automatic gain controlled receiver was chosen. Other types of antennas as, for instance, a simple vertical or horizontal doublet might have been used but other factors not significant to the MUSA would then have been involved.

Simple Analysis of the Signal-to-Noise Ratio Improvement

The MUSA differs from other directional antennas in that it is an array of antennas between which there is negligible electromagnetic coupling. This allows (but does not require) a different point of view, not explicitly involving directivity, in considering the signal-to-noise advantage of the array. The following analysis is made from this point of view. In Figs. 32 to 34 antennas are represented by signal generators, e_s, static generators, e_a, and resistances R_A. The input circuits of the receivers are matched to the antennas.

In Fig. 32, N spaced antennas are shown connected in parallel. The root-mean-square noise voltage, E_n, at the input to the receivers represents the thermal noise originating in the receiver input circuits. For the matched condition this noise is constant and independent of the number of antennas. A single wave is assumed and the signal outputs of the antennas are phased by means of the phase shifters ϕ. The maximum signal power obtainable from N antennas obviously is

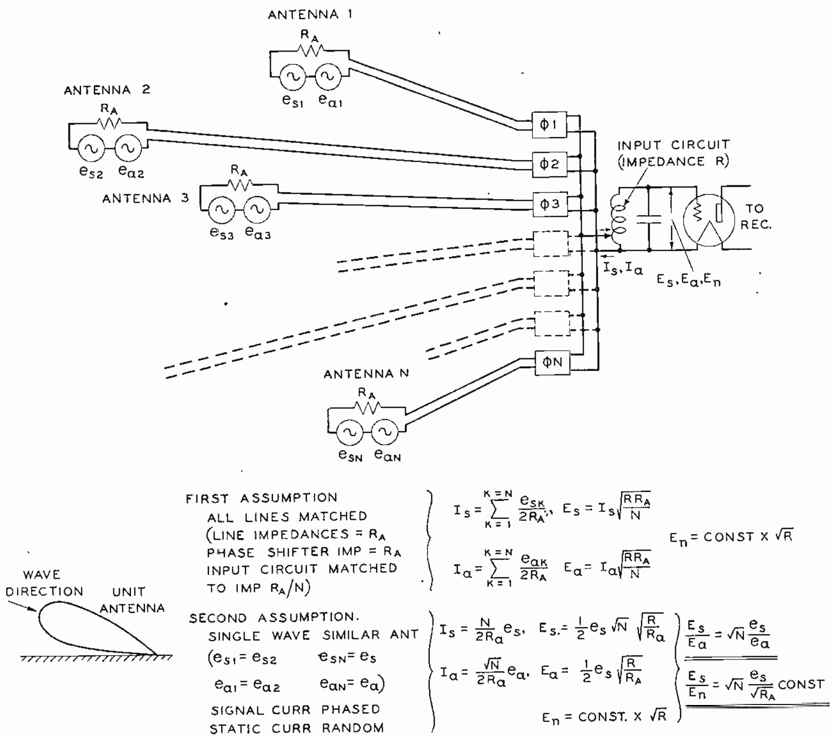


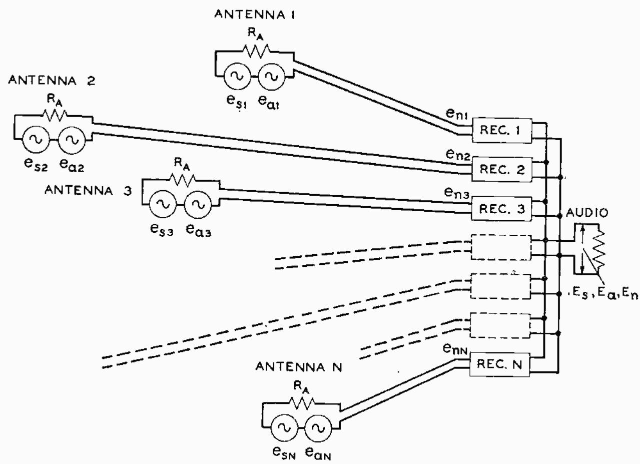
Fig. 32—Simple signal-to-noise analysis of a system of N spaced antennas. Signal currents are phased and combined at the incoming frequency. The summation signs include addition on the power basis.

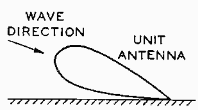
N times that obtainable from one antenna. In terms of receiver noise, e_n, the improvement in signal-to-noise ratio is 10 log N decibels referred to one antenna. If, instead of receiver noise, static is the predominating noise, the signal power received is not significant but the same improvement is realized for the general case in which the static is distributed randomly among the N antennas.[22] In that case the N signals are

[22] If static comes from all directions simultaneously, its distribution is random among the ideal unit antennas discussed in Section II. This is deduced from calculations which show that gain (signal-to-noise ratio) is proportional to the length of the system; i.e., to the number of unit antennas. The assumption

phased to add on a current basis while the N noise sources add on a power basis. Analogous arguments apply to a series connection of N antennas and result in the same improvement of 10 log N decibels.

The system described above has been shown mainly to introduce the system shown in Fig. 33. This diagram shows the audio addition of the outputs of N receivers fed by N antennas. Note that this system has no high-frequency phase shifters in the transmission lines. It is in fact similar to the diversity receiving system described by H. H.





SINGE WAVE. SIMILAR ANT.

$e_{s1} = e_{s2} = \cdots\cdots e_{sN} = e_s$

$e_{a1} = e_{a2} = \cdots\cdots e_{aN} = e_a$

$e_{n1} = e_{n2} = \cdots\cdots e_{nN} = e_n$

AUDIO SIGNALS THEN IN PHASE

$E_s \propto N e_s$, $E_a \propto \sqrt{N}\, e_a$, $E_n \propto \sqrt{N}\, e_n$

$\frac{E_s}{E_a} = \sqrt{N}\frac{e_s}{e_a}$, $\frac{E_s}{E_n} = \sqrt{N}\frac{e_s}{e_n}$

Fig. 33—Simple signal-to-noise analysis of a system of N spaced antennas Signal currents are combined at audio frequency.

Beverage and H. O. Peterson.[23] For a *single wave* this is seen to be equivalent to the phased addition at carrier frequency shown in Fig. 32.

The signal-to-noise improvements shown on Figs. 32 and 33 were easily calculated because a single nonfading wave was assumed. In

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of randomness requires that the spacing of unit antennas having a certain angular discrimination must be equal to or greater than the antenna length required to produce that discrimination in the simple linear end-on type of unit antenna.

That static is, on the average, distributed randomly among the rhombic antennas of the experimental MUSA is shown by measurements described later in this section.

[23] "Diversity receiving system of RCA communications, Inc.," Proc. I.R.E., vol. 19, pp. 531–561; April, (1931).

actual practice several fading waves are involved and it is then difficult, if not impossible, to make significant calculations. Later in this section, however, some of the general features of the system shown in Fig. 33 will be discussed from the point of view of several waves.

The MUSA system is characterized by the ability to separate waves and it is therefore possible to analyze it in a simple manner for

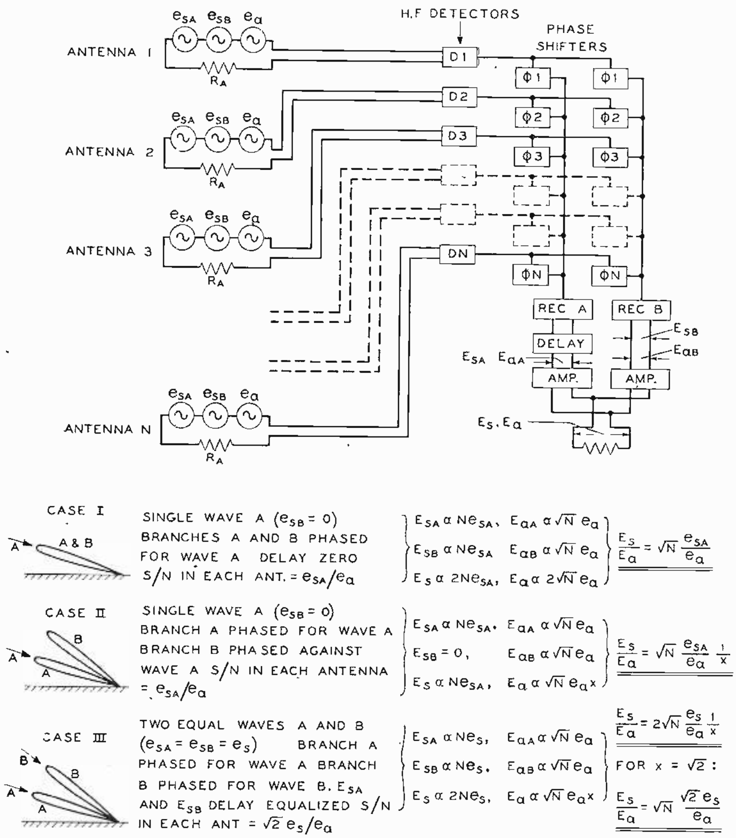


Fig. 34—Simple signal-to-noise analysis of the MUSA system.

cases of more than one wave. The arrangement in Fig. 34 corresponds to the Holmdel MUSA. The signals from the equally spaced antennas are here phased at the intermediate frequencies. Since random static and first circuit noise give identical results the analysis is given for static only.

As shown in Case I, if only one wave is present and both branches are phased for it the system functions as in Fig. 33 and it yields the same improvement of 10 log N decibels. If as shown in Case II the second branch is not phased for it (i.e., if the wave falls upon a minor lobe or a minimum of the MUSA directional pattern) less than the full improvement occurs. On the basis of linear audio detectors the reduction of improvement is 20 log x where x lies between 2 and $\sqrt{2}$. This quantity refers to the manner in which the noise from sources 1, 2, $\cdots N$ in Branch A adds with the noise *from the same sources* after having been phased differently and perhaps delayed differently in Branch B.[24] This involves the audio-frequency band width and method of noise measurement. As will be shown later x is usually not much different from $\sqrt{2}$. Taking $x=\sqrt{2}$ the loss in Case II is three decibels. If an audio detector is used which does not demodulate noise when the signal is absent (a square-law detector accomplishes this for practical purposes) this loss disappears, and branches may be phased for temporarily nonexistent waves without incurring a penalty. Case III is the important one. It assumes two equal waves. Branch A is phased for one; Branch B for the other. Again taking $x=\sqrt{2}$, the improvement referred to e_s/e_a is 10 log $N+3$ decibels. Here e_s/e_a denotes the signal-to-noise ratio in each antenna due to one wave. Referring the improvement to the signal-to-noise ratio of one antenna receiving both waves, assumed to add randomly, increases the reference by three decibels and reduces the improvement to 10 log N decibels.

This analysis may be expanded to include K waves in which case *K branches* would be required to obtain the gain of *10 log N decibels* referred to one unit antenna.

It has been tacitly assumed in the foregoing analysis of Fig. 34 that the audio outputs of the several branches are delay equalized to add and that there is no diversity action (all of the waves are assumed to remain equal). The influence of fading is difficult to predict and will be discussed later in connection with experimental results.

Some readers, not concerned with details, may omit reading the following subsections and find it sufficient to read only the Summarizing Discussion of this section.

Test Method

From a practical point of view the best way of testing a MUSA system would seem to be to operate it on transatlantic telephone signals and compare its output with that of the reference system. Speech volume and noise could then be measured in the conventional manner. So far as the signal-to-noise improvement is concerned it would be a laborious and lengthy task to get satisfactory data because so often,

[24] The case of $x=2$ (in-phase addition) arises only when the phasing and delay of the two branches are alike.

during the test period,[25] static and receiver noise is masked by transmitted noise, interfering signals, and other man-made noise. To test the experimental MUSA, therefore, a different method was selected which gave significant data in a shorter time.

Since the success of the MUSA is related so fundamentally to the nature of the arriving signal the important thing to be determined by the measurements is how well the MUSA is able to cope with the various conditions of wave arrival. For instance, in the case of a single bundle of arriving waves how close does the actual signal-to-noise improvement come to the 10 log N decibel calculated for Case I (Fig. 34) in which a single nonfading wave was assumed? Likewise, for the case of two-wave bundles do the calculations of Case III agree with measurements?

For these purposes the signal-to-noise measurements would have to be free from directional static, interference, and transmitted noise; otherwise the measured improvements would be distorted. To insure uniform and desirable noise conditions it was decided to use thermal noise originating in the receiver input circuits[26] instead of whatever noise might be present on the radio channel. This was accomplished by inserting resistance pads in the antenna transmission lines to reduce the signal (and external noise) to a level where thermal noise greatly exceeded other noise. Signal-to-noise ratios in the range between fifteen and forty decibels were obtained in this manner, free of interference and directional static, and of transmitted noise.

Substituting thermal noise for external static may at first seem far-fetched. Except for the fact that static is sometimes sufficiently directional to be received with different intensity as the MUSA is steered differently, the substitution is sound. In general, the static output does not vary with steering, as the measurements described later indicate but to avoid the distortion of results which would occur when this is not so, it was desired specifically to substitute nondirectional noise. Studies of the characteristics of static and thermal noise have shown that both are alike so far as the effect of band width upon average and effective values is concerned, and have indicated that both consist of extremely short, randomly distributed pulses which overlap when received and detected by receivers of ordinary band widths. In a given band width, the envelope of the currents produced by static sources is highly irregular in comparison with that produced by thermal agitation. It appears, however, that the *character* of either

[25] Transmission conditions during 1935 were comparatively undisturbed.

[26] A portion of the noise originates in the plate circuit of the first detector. For the present purposes this is equivalent to first circuit noise.

envelope is not sensibly affected by the number of antennas combined nor by the manner in which the branch outputs are combined, so that both give the same improvement figures using any arbitrary noise measuring method.

There were several possibilities with respect to the signal to be employed in these tests. A single tone, a large number of tones distributed throughout the audio band and other special signals were considered. A simple method requiring no modulation was finally adopted. It consisted in alternately connecting the output of the antenna to be tested and that of the reference antenna to the same receiver. Assuming that the automatic gain control of this receiver would maintain a constant audio output level the signal-to-noise advantage is the ratio of the noise levels. The automatic gain control of the MUSA receiver did not, of course, hold the output level absolutely constant but a correction was easily made for the small variations in level.

The circuits of the measuring equipment are shown in Fig. 35. The rectified carrier appearing in the linear speech rectifier is taken to be proportional to signal and is measured simultaneously with the noise demodulated in the rectifier. When the keys are thrown to position 2 (by a gang arrangement) the signal meter shows the sum of the two rectified carriers and the noise meter reads the combined noise in the output of the diversity mixing amplifiers. Using the sum of the two rectifier currents to represent the signal implies that actual audio outputs from the two branches could be delay equalized to add arithmetically. As applied to a MUSA system this assumption is justified, in general. When the keys are switched to position 1, the rectified carrier of branch B alone appears on the signal meter and noise from branch B appears alone on the noise meter. At the same time the diversity connection is broken and all except one of the six-phase shifter amplifiers in branch B are biased to cutoff; i.e., only one unit antenna is used. The pad "L" is adjusted to give the same audio gain from rectifier B to the noise meter for connection 1 as for connection 2.

By manipulating the keys which control the cutoff biases on the phase shifter tubes the "1" to "2" switchover may also be used to compare one antenna (one receiver) with two antennas in ordinary space diversity or one antenna with all six in a single branch.

The use of receiver noise as a noise source depends upon (1) having the noise equal in all six circuits and (2) upon having it originate ahead of the point where the gain is varied. In well-designed receivers the noise should approach the thermal noise limit of the first circuit. It was found possible to have the signal-to-noise ratio, for a given signal

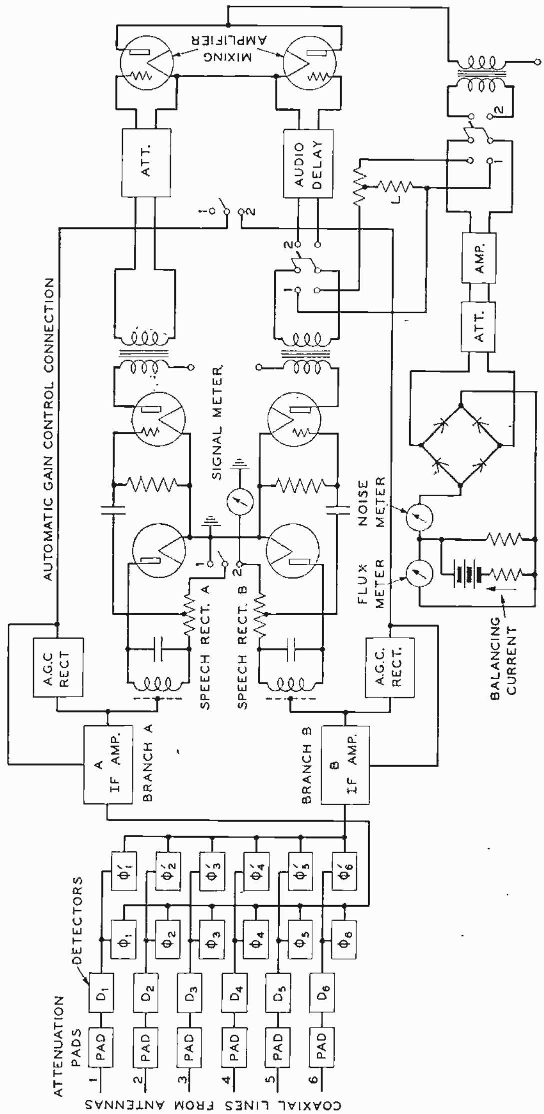


Fig. 35—Circuit used in measuring the signal-to-noise improvement of the experimental MUSA system.

level, of all six high-frequency input circuits equal to within ± 0.5 decibel and within a few decibels of the thermal limit.

The first tests were made with a local oscillator supplying the signal. They really constituted tests of the measuring set up. All six input circuits were fed simultaneously through 80-ohm pads giving equiphase and equiamplitude signals on each detector grid. This corresponds to receiving a single steady wave, and one branch was "steered" as if to receive such a wave. When the multiple switch was manipulated as to compare one antenna with the steered branch the indicated signal-to-noise improvement was usually between seven and eight decibels, compared with the theoretical value of 7.8 decibels (10 log 6).

Such a local test using the switchover with all associated equipment was made before and after every transatlantic test. Corrections based upon 7.8 decibels were made to the data in cases where the local tests showed a slightly different improvement factor. In all of the work the gains of the phase shifters were adjusted to equalize the difference in line loss. The effect of this is, however, trivial.

In measuring on transatlantic waves with automatic gain control the noise variation, corresponding nearly to the reciprocal of fading, rendered visual noise readings too rough to be suitable. A Weston high speed DB meter (copper-oxide bridge type) having a calibrated range of 16 decibels was used as a noise meter. To this instrument was added a fluxmeter (Fig. 35) of low restoring torque which automatically averaged the variations of the meter pointer over the 15-second periods of observation used in these tests. The fact that the noise meter rectifier is linear means that the noise current is averaged arithmetically along the time axis. (A discussion of other ways of averaging will be given later.) To permit the maximum time interval during which the restoring torque had negligible effect a balancing current was applied. A telechron motor marked time intervals of 15 seconds with a bell. The switchover between "1" and "2" (Fig. 35) was made and the fluxmeter restored to zero reading at the ring of the bell. The signal meter reading (calibrated in decibels) was maintained fairly steady with the automatic gain control, and could be averaged accurately by eye.

Test Results

The first measurements on transatlantic signals were made on 16 meters in September, 1935. Tests were made on the British Post Office Station GAU (18,620 kilocycles) between noon and 2 P.M., E.D.S.T., on September 16, 17, 18, and 19. At our request the transmitter operated on reduced power, presumably fifteen decibels less than normal. The propagation during these tests was characterized by low angles and slow fading. The angular discrimination of the MUSA for these low angles is so slight that it was decided to use only one branch and defer the question of diversity in these first tests.

Owing to the power reduction and to the fact that the period from September 15 to 18 inclusive was disturbed some of the data had to be obtained without antenna pads. Table II summarizes the results of the measurements.

TABLE II
ONE BRANCH
GAU 18,620 kilocycles

Date	Test No.	Pads in Ant. db.	Reference Antenna	Number of Readings	S/N Improvement db	Group Average db
1935						
9–16	1	20	1	19	3.7	
9–17	6	20	1	18	3.0	
9–17	10	20	1	16	3.0	3.3
9–16	2	20	6	20	8.8	
9–17	7	20	6	20	11.0	10.0
9–16	4	0	1	17	6.2	
9–17	9	0	1	11	6.5	
9–19	11	0	1	18	6.0	
9–19	13	0	1	28	5.6	
9–19	15	0	1	20	8.0	6.4
9–16	5	0	6	30	6.4	
9–17	8	0	6	17	7.9	
9–19	12	0	6	20	5.0	
9–19	14	0	6	29	6.1	6.4

The apparent line loss is 6.7 db (4.3 calculated).
The equivalent improvement obtained from the data with pads is 7.3 db; without pads, 6.4 db. Average 6.9 or 7 db.

When thermal noise is a contributing or predominating factor, the signal-to-noise ratio of the six-antenna branch must be compared with both No. 1 and No. 6 antennas in order that the line loss may be accounted for. With thermal noise predominating, the difference between the improvements referred to No. 1 and No. 6 should of course equal the line loss of No. 6. It may be shown that the arithmetic means of the two improvement ratios (voltage) should give very closely the improvement corresponding to random static ($10 \log 6 = 7.8$ decibels). In Table II the arithmetic means of the improvement ratios is, therefore, called the equivalent improvement.

During these tests the indicated angle of arrival was from one to three degrees (such low angle determinations are not trustworthy within perhaps two degrees) and the receiving branch was set correspondingly and not altered during a test. The fading on No. 1 and No. 6 antennas was usually but not always unlike. Adjacent antennas always showed substantially synchronous fading.

A sample of the plots from which the figures in the table were obtained is shown in Fig. 36. This shows the noise readings reduced to a constant signal meter reading for Test 13. Each horizontal line segment represents one 15-second fluxmeter period (the actual period was 14 seconds, one second being required for switching). The arithmetic averages of the segments are shown by dashed lines. It is to be emphasized that the scattering of improvements taken from adjacent readings is not experimental error but is due to the fact that pairs of

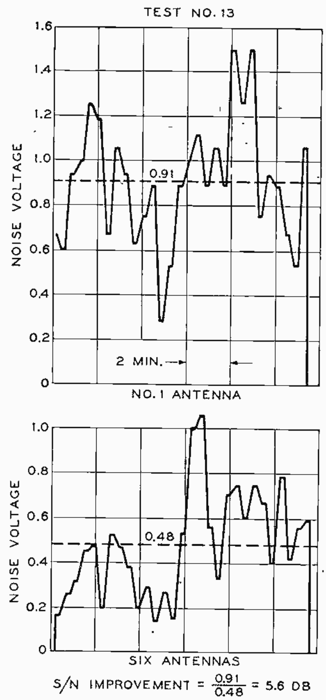


Fig. 36—Sample of measured noise plotted against time. GAU (18,620 kilocycles) Rugby, September 19, 1935.

adjacent readings were obtained at different stages of the fading cycle. Two separate systems (receivers and antennas and measuring equipment) permitting simultaneous measurements would not help this situation, since fading would not be synchronous on two systems. Evidently a considerable number of readings must be taken to insure that all stages of fading are equally represented in both of the systems being compared.

Returning to Table II the discrepancy between the apparent line loss and the calculated value (the loss could really be five decibels perhaps) suggests that insufficient data were obtained with the pads. There is a possibility that the measurements without pads involve directional static. However, taking the data as they stand yields an average of seven decibels which is less than one decibel below the value 10 log $N=7.8$ decibels calculated for the nonfading wave of Case I, Fig. 34. (The fact that only one branch was used in the measurements instead of the two branches of Case I does not affect the situation since the idle branch was disconnected and so contributed no signal and no noise.) A reduction of the order of one decibel from the calculated improvement could be expected since all of the waves of one bundle cannot fall on the apex of the directional pattern. It was encouraging to find that no more loss occurred; i.e., to find that the waves in a single bundle may be phased so effectively.

Before leaving these tests, the results for September 18 should be mentioned. On this day the signal-to-noise ratio was so low, even without antenna pads, that measurements could not be made. The noise on this day was first taken to be thermal noise but was found during the course of experimentation to be external noise[27] some ten decibels higher than thermal noise, as received on a single rhombus. At the end of the test the operator at Rugby keyed the transmitter with tone, advising us that the schedule was completed and wishing us "good night." With one antenna the signal was hopelessly lost in noise; with the six antennas the code was readable.

More comprehensive measurements were made on GBW (14,440 kilocycles) and a few on GCW (9790 kilocycles), using the two branches. Since an unmodulated carrier was used, rectified carrier being taken to represent signal, there was no criterion for setting the audio delay. Accordingly, it was kept at zero and a correction introduced later. The results are shown in Tables III and IV.

The data in the tables are classified roughly according to whether two bundles or one bundle of waves were present. In the latter case the two branches were steered, one on each side of the bundle, a few degrees apart. During these tests slight adjustments in steering were made when indicated by the angle monitoring tube, as in normal operation of the system. The large amount of data taken with GBW makes the results in Table III particularly reliable. This is reflected in the close agreement between measured and calculated line loss. Before discussing the results further the effect of delay needs to be analyzed.

[27] This noise, which was directive to the extent that four-decibel variation occurred with steering the MUSA, was doubtless a sample of the "star static." It was encountered also on 31 meters in October. See footnote (32).

TABLE III

Two Branches
GBW 14,440 kilocycles

Date	Test No.	Pads in Ant. db	Reference Antenna	Number of Readings	S/N Improvement db	Group Average db	Number of Wave Bundles
1935							
10–2	21	40	1	20	2.7		1
10–2	23	40	1	16	5.3		1
10–2	24	40	1	16	4.4		1
10–8	29	40	1	20	6.3		1
10–10	37	40	1	20	4.4		1
						4.7	
10–2	20	40	6	19	6.9		1
10–2	22	40	6	20	8.4		1
10–2	25	40	6	16	9.0		1
10–8	28	40	6	17	10.9		1
10–9	30	40	6	38	8.0		
						8.5	
9–30	17	40	1	22	3.4		2
9–30	19	40	1	14	4.1		2
10–2	26	40	1	16	4.6		2
10–10	33	40	1	19	2.0		2
						3.5	
9–30	16	40	6	17	8.0		2
9–30	18	40	6	17	7.9		2
10–2	27	40	6	20	6.7		2
10–10	34	40	6	20	7.3		2
						7.4	

The apparent line loss is 3.8 and 3.9 db for the one-wave and two-wave groups, repectively. The calculated loss is 3.8 db.

The equivalent improvement for one-wave group is 6.8 db to which may be added the later determined correction of 1.2 db for the effect of delay, giving *8.0 db.*

The equivalent improvement for two-wave groups is 5.7 db to which may be added 0.8 db for the effect of delay, giving *6.5 db.*

TABLE IV

Two Branches
GCW 9790 kilocycles

Date	Test No.	Pads in Ant. db	Reference Antenna	Number of Readings	S/N Improvement db	Group Average db	Number of Wave Bundles
1935							
12–13	39	40	1	15	4.8		2
12–13	40	40	1	14	4.7		2
						4.7	
12–13	38	40	6	14	7.9		2
12–13	41	40	6	13	6.7		2
						7.3	

The apparent line loss is 2.6 db. The calculated loss is 3.1 db.

The equivalent improvement is 6.1 db to which may be added 0.9 db for the effect of delay, giving *7.0 db.*

Correction Due to Delay

The effect upon the noise, of delaying one audio output, is shown in Fig. 37. The curves were obtained with the circuit shown in Fig. 35 using thermal noise. The equiphase, equiamplitude signal source mentioned previously was used to supply the inputs. Branch A was kept phased so that the six signals added, and branch B was varied. The curves show the effect of delay upon noise in a 250- to 2750-cycle audio band, as measured with the Weston DB meter, for various differences in steering. The curves are labeled in terms of the difference in the phase settings of the two branches. The 40-degree or 80-degree curves correspond in practice to steering on each side of a single bundle of waves. The 160-degree curve typifies steering at two separate wave bundles. The use of 100 microseconds (or more) delay is generally advantageous for the audio addition when steering at one bundle. Since this amount of delay makes the audio noise addition nearly random and for widely different steering the addition is also random the assumption that the noise from the two branches adds on a power basis, made in reference to Fig. 34 ($x=\sqrt{2}$), is justified.

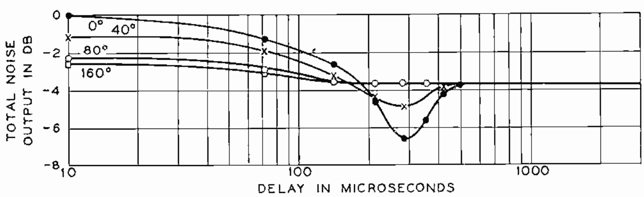


Fig. 37—The effect of delay and phasing upon noise output of the MUSA receiver.

The effect of delay is to produce an interference pattern in the audio noise spectrum. This accounts for the dip in the noise curve for a delay of 300 microseconds which locates the first interference minimum at about the center of the audio band. The asymptotic approach to 3.5-decibel reduction corresponds more nearly to a reduction ratio of $2/\pi$ than to $1/\sqrt{2}$ due to the fact that the Weston DB meter is nearer linear than square law in response.

In obtaining these curves it was desired to simulate the reception of two waves for which the corresponding branches were phased to add. It was not convenient to set up locally such a two-wave case but the single wave input should give identically the same results provided phases were avoided which resulted in a signal at the second detector too low to demodulate the noise. A signal level so high that further increase did not affect the noise output was used for all points. The real purpose of the signal was to insure that the demodulated noise was not dependent upon the intermediate-frequency bands and that the results would be unaffected by possible differences in intermediate-frequency bands.[28]

As mentioned, noise has been measured with an unweighted 250- to 2750-cycle frequency band. Had a weighting network[29] which emphasizes frequencies in the vicinity of 1000 cycles been used the dips

[28] This precaution was subsequently found to be unnecessary; i.e., similar results were obtained with no input signal.

[29] Barstow, Blye, and Kent "Measurment of telephone noise and power wave shape," *Elec. Eng.*, vol. 54, pp. 1307–1315; December, (1935).

in the curves marked 0° and 40° would have been deeper and would have occurred in the vicinity of 500 microseconds delay.

Returning now to Tables III and IV the measured improvements were corrected to correspond to the effect of the delay which would probably have been used to obtain the best audio addition for the signal. The 1.2-decibel correction for the one-bundle case represents the reduction of noise obtained with 60-degree phase difference with the addition of 100 or 150 microseconds delay. The 0.8- or 0.9-decibel correction for the two-bundle case corresponds to any large delay and a large phase difference, say 160 degrees. These corrections would not have been much different if a weighting network had been used.

The measured difference of 1.5 decibels, shown in Table III, between the one-wave bundle and the two-wave bundle measurements is probably real and due to the fact that when the branches are steered at two separated bundles some loss is incurred when one wave disappears for a few minutes. This loss could have been at least partly recovered by using square-law detectors. Tests showing the advantage of square-law detectors over linear detectors are described later in this section. Employing square-law detectors would justify a correction of about one decibel to be added to the two-bundle improvement measurements in Tables III and IV. Applying this correction we summarize the results in Table V.

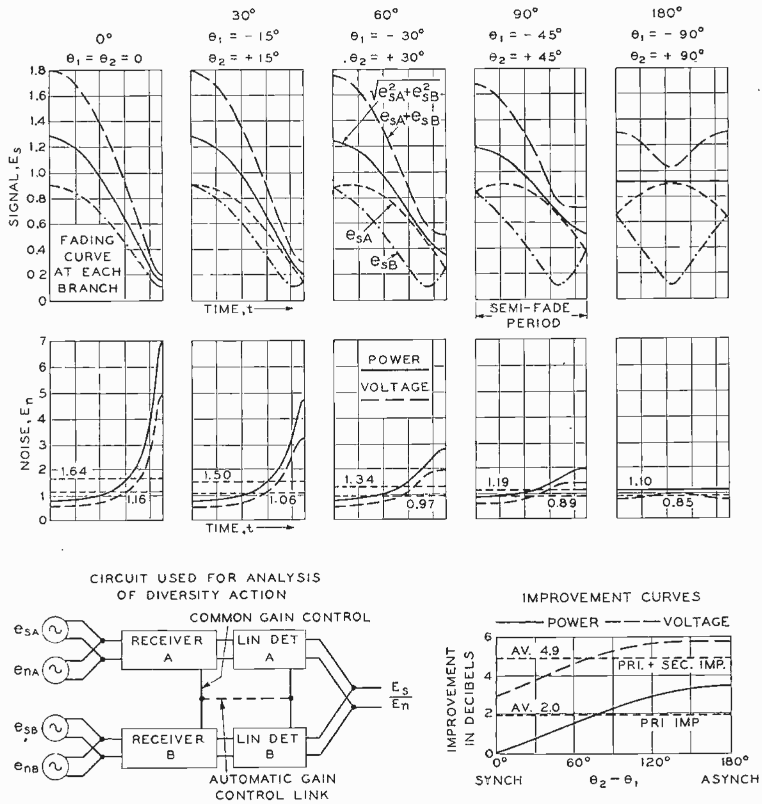
TABLE V
SUMMARY OF SIGNAL-TO-NOISE MEASUREMENTS

One Bundle of Waves		*Two Bundles of Waves*
One Branch only	*Two Branches*	*Two Branches*
7 db (Table II)	8 db (Table III)	7.5–8 db (Tables III and IV)

These improvement figures for two branches as they stand are approximately equal to 10 log 6 = 7.8 decibels as calculated for nonfading waves, and leave nothing to be ascribed to diversity action. Since a loss of perhaps one decibel occurs in the case of one branch (Table II), the recovery of that one decibel with two branches is to be ascribed to diversity action. Originally, considerably more was expected of the angle diversity. It appears however from theoretical and experimental evidence that one decibel is about what should be expected for the case in hand. It seems appropriate to include this study of diversity here.

Diversity Action

The first attempt to analyze diversity action was made with a graphical approach to the problem. On Fig. 38 is shown a schematic diagram of the system to be analyzed. Two receivers A and B with linear audio detectors may be regarded as fed from two angle branches of a MUSA. The noise generators e_{nA} and e_{nB} are assumed to be of equal power but of random phase. The signal generators e_{sA} and e_{sB} are assumed to fade according to the equations shown beneath the dia-



$$e_{sA} = \sqrt{1 + 2 \times 0.8 \cos(2\pi t/T + \theta_1) + (0.8)^2}$$

$$e_{sB} = \sqrt{1 + 2 \times 0.8 \cos(2\pi t/T + \theta_2) + (0.8)^2}$$

Fig. 38—Graphical analysis of diversity action as it relates to signal-to-noise ratio.

gram. They represent the carrier amplitude but since fading is assumed to be essentially nonselective in each branch they also represent the side bands. This type of fading might result from interference between two waves of small relative delay whose amplitude ratio is 0.8, such a pair being received by each branch. The automatic gain control is assumed to be perfect; i.e., the audio output, E_S, is maintained constant.

By definition, diversity in fading occurs when the fading of the two branches is not synchronous. If all degrees of asynchronism are equally probable the diversity is random. This is the case considered. In Fig. 38 five stages in the cycle of variation from synchronous to asynchronous fading are used for calculation. In each of these, fading curves corresponding to the two assumed waves are shown displaced from each other by 0, 30, 60, 90, and 180 degrees. With "ideal" automatic gain control, the two receiver gains, always equal, will be proportional to the reciprocal of the resultant of e_{SA} and e_{SB}. For "ideal" linear detectors the noise output of the receivers will be proportional only to the gain. The noise curves plot the noise variation on this basis. Two cases of signal addition are considered—voltage and power addition. The corresponding noise curves differ only as the reciprocal of the resultant signal curves differ. These noise curves are averaged (with a planimeter) and the resulting average signal-to-noise ratios are used to plot the improvement curves shown in the figure. The improvement curve for power addition of signal is located on the improvement axis so that zero improvement is shown for synchronous fading. The curve for voltage addition of signal is located three decibels higher at synchronous fading. These curves are again averaged over the cycle from synchronism to asynchronism (by averaging noise voltage). The improvements are 2.0 decibels and 4.9 decibels.

Power addition of the two signals corresponds in practice to the case in which the delay is unequalized and sufficient to cause the audio outputs of each branch to combine on a power basis like noise. The two-decibel improvement might appropriately be called the primary improvement since it is due solely to the diversified fading. The additional improvement of 2.9 decibels found with voltage addition of the signals is due to favorable discrimination in the addition of signal and of noise and might be called the secondary improvement. The secondary improvement occurs in reception with the MUSA; it has already been included in the 10 log N decibel improvement calculation.

In practice, it would be undesirable to use the "ideal" automatic gain control assumed in the above analysis; the action must be smoothed out with, for instance, a capacitance-resistance network. The effect of this is to reduce the primary gain since the noise peaks, whose avoidance by diversity action results in the primary improvement, are reduced. An analysis of diversity action without automatic gain control was made. In this case the signal was averaged while the noise remained constant. The results are included in the table shown in Fig. 39 which is introduced later.

This treatment of diversity action has been made from the point of view of MUSA reception but is applicable to ordinary space diversity using two stations or antennas. In the case of a single bundle of waves no modification of the analysis need be made; the signal generators then represent the spaced antenna outputs which are fading randomly. In this case voltage addition of the audio outputs may be expected to occur since a single bundle will typically include only a small delay interval. In the general case of two or more wave bundles the signal generators must be interpreted to represent not the carrier but the side-band average, for fading will then be essentially selective and the audio output will not be proportional to carrier as was assumed in the analysis. If this interpretation is made the signal-to-noise ratio in each receiver becomes proportional to the generator amplitudes e_{sA} and e_{sB}, and the analysis of Fig. 38 is applicable. In this case voltage addition does not occur since the audio outputs are essentially different owing to the selective fading.[30] They add, in general, to a value intermediate between the power and voltage sum, although for the more complicated conditions they combine on a power basis.

The above analysis has been based upon simple two-wave interference and the results might not be applicable to the more complicated and changing conditions of actual transmission. Accordingly, R. L. Dietzold has made a statistical analysis for other types of fading and for three stations as well as for two. The results appear in Fig. 39 together with the results of the above graphical analysis for two-wave interference fading. The time sequence of amplitude in the more complicated types of fading encountered in practice is not significant; the percentage distribution determines the results. The "four-wave" distribution curve corresponds to four equal waves of random phase. The quadratic distribution curve was deduced experimentally by R. S. Ohl. Except that these different distributions were assumed, the assumptions were the same as those of Fig. 38. The improvements are expressed in decibels referred to the signal-to-noise ratio for one station or branch with ideal automatic gain control.

The small effect upon the results of assuming different time distributions lends significance to these calculations. The averaged round numbers are probably about right.

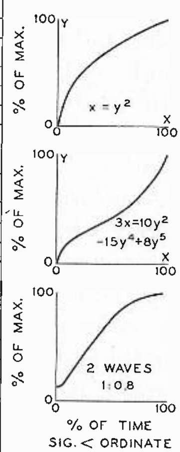
With no automatic gain control (or with one which acts slowly compared with the fading) there is little or no primary gain. With infinitely fast and stiff gain control action there is a 2- and 2.5-decibel primary gain for two and three stations, respectively.

[30] This refers to speech signals; in the case of telegraph signals the frequency band is so narrow that fading is always essentially nonselective, and voltage addition occurs.

A few measurements were made at Holmdel on two-station diversity (antennas 1 and 6 of the MUSA). The thermal noise and rectified carrier technique was used. The results appear in Table VI.

NO. OF STATIONS OR BRANCHES	$E_s=\sqrt{e_{sA}^2+\cdots e_{sK}^2}$ $E_n=\sqrt{e_{nA}^2+\cdots e_{nK}^2}$ PRIMARY IMPROVEMENT		$E_s=e_{sA}+\cdots e_{sK}$ $E_n=\sqrt{e_{nA}^2+\cdots e_{nK}^2}$ PRI. + SEC. IMPROVEMENT	
K	NO AGC	AGC*	NO AGC	AGC
QUADRATIC DISTRIBUTION				
1	2.5	0	2.5	0
2	2.8	2.2	5.5	4.8
3	2.9	2.5	7.3	6.8
FOUR WAVE DISTRIBUTION				
1	3.4	0	3.4	0
2	—	—	6.4	5.2
3	—	—	8.2	7.5
TWO WAVE NEAR-SINUSOIDAL DISTRIBUTION 19 DECIBEL FADE				
1	2.8	0	2.8	0
2	3.2	2.0	5.8	4.9
3	—	—	—	—
AVERAGED RESULTS				
1	3	0	3	0
2	3	2	6	5
3	3	2.5	8	7

ASSUMED DISTRIBUTION CURVES



* AUTOMATIC GAIN CONTROL

Fig. 39—Summary of results of diversity analysis.

The measuring technique was exactly the same as used in obtaining the data for Tables III and IV in which voltage addition of the signal was assumed. A 3-decibel improvement is therefore included in the 3.6-decibel figure. This leaves only 0.6 decibel (possibly one

TABLE VI
ANTENNAS 1 AND 6 IN DIVERSITY
GBW 14,440 kilocycles

Date	Test No.	Pads in Antennas db	Reference Antenna	No. of Readings	S/N Improvement db	Average
1935						
10–9	32	40	1	19	1.7	
10–10	35	40	1	20	2.2	2.0
10–9	31	40	6	14	4.9	
10–10	36	40	6	20	5.2	5.1

The apparent line loss is 3.1 db. The calculated loss is 3.8 db.
The equivalent improvement is 3.6 db.

decibel or even 1.5 decibels since the measurements are too meager to be reliable to better than one decibel) for primary gain compared with a possible 2.0 decibels. We are inclined to use about one decibel for primary gain. The time constant on the automatic gain control was of the order of 0.06 second in this and all signal-to-noise comparisons. That this time constant was not fast enough to produce the high noise peaks corresponding to the inverse of fading is shown by the transcribed motion picture record of the signal and noise meter variations, shown in Fig. 40. Note the signal fades.

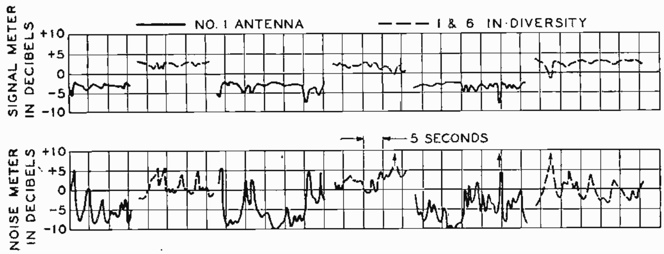


Fig. 40—Sample of signal and noise variations occurring in diversity tests. The arrows indicate noise levels beyond the scale of the meter. GBW (14,440 kilocycles) Rugby, October 10, 1935. 1920 G.M.T.

A secondary improvement of 3 decibels is too high for two-station space diversity; i.e., the signals do not add on a voltage basis.[30] Oscilloscope observations of the diversity combinations of the audio outputs of two spaced antennas (No. 1 and No. 6 of the Holmdel MUSA) indicate, however, that on the average the secondary improvement is appreciable and probably about 2 decibels for two antennas and 3 decibels for three antennas. This improvement depends upon the number of wave bundles, their angular separation, their relative delays, the spacing of the antennas and the frequency band occupied by the signal. For a single compact wave bundle the secondary improvements will be nearly 3 decibels and 4.8 decibels for two- and three-antenna systems, respectively, but for several bundles of large relative delay the secondary improvement may disappear.

The results of some recent tests of a three-antenna diversity system on trial at Netcong, N. J., carried out under the direction of F. A. Polkinghorn, showed a signal-to-noise improvement of 3 to 3.5 decibels. Assuming a 3-decibel secondary improvement there remains something of the order of 0.5 decibel for the primary improvement. This is plausible in view of the time constant of one second used on the automatic gain controls. Linear audio detectors were used in these tests. As will be discussed later the employment of square-law detectors could be expected to add 0.5 decibel to this figure. Linear detectors are to be preferred, however, on the basis of quality distortion. Table VII is based upon the theoretical and experimental study of diversity action and gives typical results for space diversity systems.

TABLE VII
SUMMARY OF SPACE DIVERSITY IMPROVEMENTS

Number of Antennas	Primary Improvement in db Automatic Gain Control		Secondary Improvements in db Number of Wave Bundles		
	0.06 Sec.	1 Sec.	1	2	3–5
2	1	0.5	3	2	1
3	1	0.5	4.5	3	1.5

Add 0.5 db to primary improvement when square-law detectors are used.

Table VII shows that on the average the secondary improvement is larger than the primary improvement. In other words, the advantage which accrues from the similarity of the antenna outputs exceeds that which accrues from their diversification. This result had not been expected.

It should be emphasized here that the improvements summarized in Table VII for space diversity systems and in Table V for a MUSA system refer to signal-to-noise ratios only; i.e., quality improvement is not included.

An important advantage of a MUSA system over a space diversity system is its ability to maintain its improvement when more than one wave bundle occurs, and since two or more bundles are common, the advantage is distinctly real. A further advantage not discussed thus far relates to interfering signals as distinguished from static. Unless the interfering signals fall upon the principal lobe of the MUSA array pattern when it is steered to receive the desired signal, important directional discrimination against the interference occurs. Little or no discrimination against interference can occur in a space diversity system since it lacks the phasing which produces directional discrimination.

The Time Constant of the Automatic Gain Control

Thus far no comments have been made on the improvement figures relating to "no automatic gain control" shown in the table of Fig. 39. This table shows that the signal-to-noise ratio for one antenna ($K=1$) is from 2.5 to 3.5 decibels higher when no automatic gain control is used; i.e., perfect automatic gain control penalizes the signal-to-noise ratio to that extent.[31] The advantage of automatic gain control is a

[31] The action of the automatic gain control does not change the instantaneous signal-to-noise ratio. Interpreting signal-to-noise ratio as *average signal* divided by *average noise* rather than the average of the *signal divided by the noise* results in this difference.

constant output volume. In practice, a compromise is effected by retarding the action of the control. A time constant of 0.5 or one second is usually used. (This compromise is influenced by quality considerations as well as noise considerations.)

In the MUSA system signal-to-noise ratio measurements the time constant of the automatic gain control circuit (0.06 second) was not changed during the switchover from the MUSA to the single antenna. If a time constant of 0.5 second had been used with the MUSA and a one-second time constant with the reference receiver, the measured improvement would probably have been reduced by a little less than one decibel.

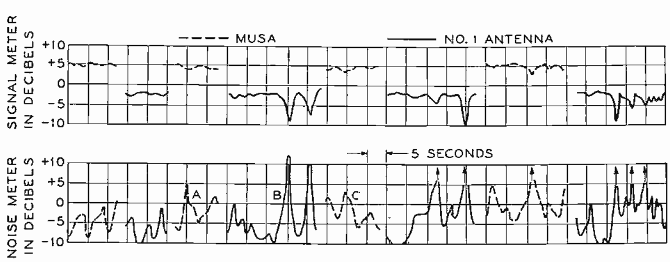


Fig. 41—Sample of signal and noise variations occurring in MUSA tests. The arrows indicate noise levels beyond the scale of the meter. This record was obtained five minutes before that in Fig. 40.

Method of Averaging Noise

In all of the signal-to-noise measurements and in the diversity analysis noise voltage has been averaged arithmetically along the time axis. Owing to a rather marked reduction of noise peaks with the MUSA compared with a unit antenna different improvements would result if different ways of measuring it had been adopted. To investigate this, motion pictures were made of the signal meter and noise meter variations for the MUSA and for the single antenna. The transcribed records appear in Fig. 41. Some calculations have been carried out for the noise distributions marked A, B, and C in Fig. 41. If the noise ratio of B/A measured by arithmetically averaging noise voltage is called 0 decibels, it becomes +2.4 decibels by averaging power arithmetically. The corresponding figures for B/C are 0 and +2.7 decibels. Thus, if noise power is averaged instead of noise voltage the measured primary diversity improvement is substantially increased.

From the point of view of the interfering effect upon speech it is not clear which method of averaging is more significant. This matter is probably related too closely to the distortion which incidentally accompanies the noise peaks to be considered alone.

In the light of the discussion presented in the preceding pages it appears that the signal-to-noise improvement of the experimental MUSA can be expressed as 8 ± 1 decibels.

Square-Law Detectors

In the discussion of the signal-to-noise measurements it was stated that the measured improvements would have been higher had square-law audio detectors been used instead of linear rectifiers. For the two-bundle MUSA measurements one decibel was allowed for this and for

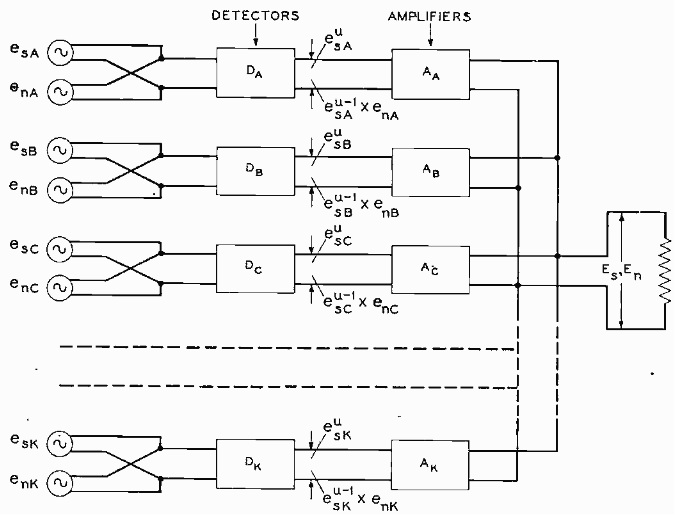


Fig. 42—Circuit employed in the analysis of the effect of detector characteristics upon signal-to-noise ratio.

the three-antenna diversity measurements at Netcong 0.5 decibel was allowed. These figures are based upon tests to be described in the following paragraphs. First, however, an analysis will be made of the effect upon the signal-to-noise ratio of various types of detectors in a MUSA system. Fig. 42 is a schematic representation of the system to be analyzed, comprising K branches. The K signal generators e_{sA}, e_{sB}, $\cdots$ e_{sK} represent the various wave bundles as received by the steerable branches. The noise generators e_{nA}, e_{nB}, $\cdots$ e_{nK} are equal in amplitude but random in phase. The detectors are generalized to the extent that the audio output is proportional to the u power of the input.

Assuming that $e_s >> e_n$ the audio outputs are proportional to e_{sA}^u, e_{sB}^u, $\cdots$ e_{sK}^u. The noise outputs are then proportional to $e_{nA}e_{sA}^{u-1}$, $e_{nB}e_{sB}^{u-1}$, $\cdots$ $e_{nK}e_{sK}^{u-1}$ since the signal-to-noise ratio in each branch must be independent of u. Assuming the signals to be delay equalized, the signal-to-noise ratio of the final output is

$$\frac{E_s}{E_n} = \frac{e_{sA}^u + e_{sB}^u + \cdots + e_{sK}^u}{e_n\sqrt{e_{sA}^{2u-2} + e_{sB}^{2u-2} + \cdots + e_{sK}^{2u-2}}}. \tag{7}$$

Maximizing this expression with respect to u shows that the maximum occurs for $u=2$ (square law) and is

$$\frac{E_s}{E_n} = \frac{\sqrt{e_{sA}^2 + e_{sB}^2 + \cdots + e_{sK}^2}}{e_n}. \tag{8}$$
$$(u = 2)$$

That this expression represents the maximum signal-to-noise ratio may also be concluded by observing that it is proportional to the square root of the total energy.

For linear detectors $u=1$ and the signal-to-noise ratio becomes

$$\frac{E_s}{E_n} = \frac{e_{sA} + e_{sB} + \cdots + e_{sK}}{e_n\sqrt{K}}. \tag{9}$$
$$(u = 1)$$

If the branch signals are all equal, i.e., if $e_{sA}=e_{sB}= \cdots =e_{sK}$, (8) and (9) give the same result, but for unequal amplitudes there is an advantage in using square-law detectors.

This analysis shows that square-law detection introduces just the correct amount of emphasis upon the stronger waves and that any additional expansion or contractions of the differences among the waves is detrimental. This means that the gains in all branches should be equal. It also indicates that any arrangement in which the stronger of the several waves is automatically switched in and the remaining ones switched out is inferior.

The experimental MUSA receiver is equipped with both linear and square-law detectors, and some signal-to-noise ratio comparisons were made using locally generated signals. Fig. 43 shows schematically the essential parts of the test circuit. The noise generators represent the thermal noise originating in the receiver input circuits. The input signal e_s was modulated with a tone. The calculated curves shown in the figure are obtained from (8) and (9) which reduce to

$$\frac{E_s}{E_n} \propto \sqrt{1 + \left(\frac{e_{sB}}{e_{sA}}\right)^2} \tag{10}$$
$$u = 2$$

and to

$$\frac{E_s}{E_n} \propto \left(1 + \frac{e_{sB}}{e_{sA}}\right). \qquad (11)$$

$$u = 1$$

The equation for the square-law detector is sound and was verified by the measurements. The equation for the linear detector should apply only over a certain range of signal and noise levels. The measurements indicate this.

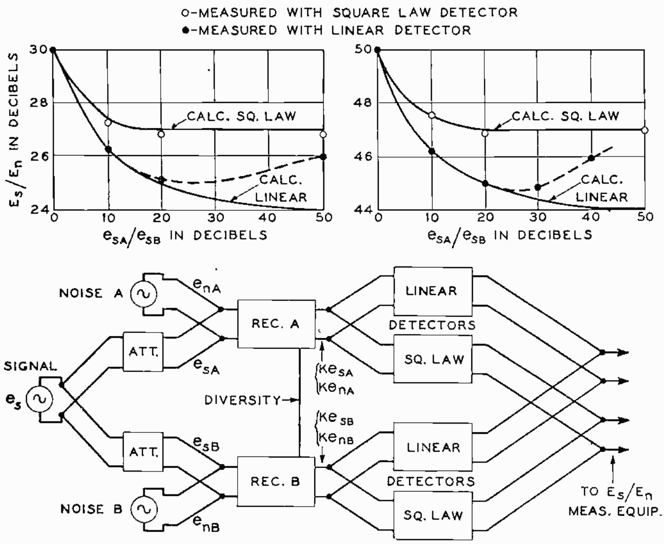


Fig. 43—Test circuit and experimental results of the study of detector characteristics.

Automatic gain control was not used in these tests since the two gain controls could not be relied upon to "track" sufficiently well. To make the measurements significant manual gain control was used to maintain the receiver gains equal and the output normal. It may be pointed out here that in receiving actual radio signals with linear detectors accurate equality of gains is not required. Moderate differences in gain (of a few decibels) can be depended upon to be beneficial as often as detrimental. With square-law detectors no departure from equality can be beneficial.

The curves of Fig. 43 show that 10- and 20-decibel differences in signal level give the square-law detector an advantage of one and two decibels, respectively. In receiving two bundles of waves the branch outputs commonly fade in and out with the result that their average ratio is of the order of 10 decibels. Such were the conditions, as well as could be estimated, during the two-bundle tests in Tables III and IV. The one-decibel correction applied to those results in Table V is therefore justified. In the one-wave bundle measurements, the percentage of time during which the branch outputs were substantially different was so small that no correction was applied in Table V. In the case of space diversity the correction is also small; about 0.5 decibel seems reasonable.

From the point of view of distortion in receiving double side-band signals linear detectors are superior to square-law detectors and this compensates their inferiority in signal-to-noise ratio. The principal reason for using linear detection in the signal-to-noise ratio tests of the MUSA was, however, their experimental advantage in simplicity and accuracy (Fig. 35).

Random Addition of Static

In analyzing the spaced antenna systems at the beginning of this section it was assumed that the static outputs of the antennas add on a power basis. An experimental study of this was made by measuring the static output of one unit antenna and comparing it with the static output of the six antennas combined as one MUSA branch. The circuit shown in Fig. 35 was used for these experiments. The results are tabulated in Table VIII.

TABLE VIII

Date	GMT	f_{mc}	Type of Static	Addition Max. db	Addition Min. db	Thermal Noise db	QRM	Method
1935								
9–19	1530	18.6	star	8.5		−12	light	Rdg. DB Meter
10–15	1500	9.51	star	8.0				Rdg. DB Meter
10–16		9.51	distant	7.5		− 6		Rdg. DB Meter
10–22	1500	9.51	crash	8		−20	none	Vary I-F gain
10–23	1500	9.51	distant	8		− 9	light	Vary I-F gain
	1820	11.86	distant	8.5			light	Vary I-F gain
10–24	1500	9.51	star	11.4	5.4	−12	light	Vary I-F gain
	1510	9.51	star	11.0	6.0	−12	light	Vary I-F gain
	2045	9.51	crash	7.5		−30	light	Vary I-F gain
11–1	1450	9.51	distant	9.0		− 8	none	Vary I-F gain
	1830	9.51	distant	8.0		− 7	—	Vary I-F gain
1936								
1–7	1500	9.51	distant	7.5		− 8	light	Vary I-F gain
	1505	9.51	distant	8		− 8	light	Vary I-F gain
1–14	0300	4.82	crash	8.2	7.3	−20	none	Fluxmeter
1–15	0300	4.82	crash	6.8	3.0	−30	none	Fluxmeter
		Average		8.0				

The column headed f_{mc} indicates the frequency to which the receiver was tuned. The MUSA was tuned to a desired station which possessed a comparatively clear channel, and, following the signoff of the station, static was measured without a demodulating carrier.

The receiver was, of course, operated with manual instead of automatic gain control. Care was taken to insure that overloading did not occur. The column headed "addition" gives the ratio in decibels of the static output of the six-antenna branch to that of one antenna. Where figures are entered in the middle of the column no effect of steering was noticed. (Effects of the order of one decibel could have been overlooked, however.) The column headed thermal noise gives the ratio in decibels of receiver noise originating in one of the first circuits (measured with a resistance replacing the antenna) to the total noise measured with the unit antenna connected. It shows that thermal noise was negligible.

The star static[32] was steady and therefore accurately measurable. The crash static on 4.82 megacycles was so intermittent that it required the use of the fluxmeter to obtain a satisfactory measurement.

The average of all those measurements showing no effect of steering is 8.0 decibels compared with the theoretical figure of 10 log $6=7.8$ decibels, for random addition. The random assumption employed in the analysis is thus justified on the average.

Summarizing Discussion

The aim of the signal-to-noise study described in this section has been not so much to evaluate the intrinsic merit of the experimental MUSA system as to compare its behavior with a simple theory. The element of research has been to find out how well the transatlantic waves fit into the background of the simple theory. To this end somewhat artificial devices, thermal noise and rectified carrier, were substituted for static and speech signals.

The study included an analysis of diversity action in which the effect upon the signal-to-noise ratio of (1) delay equalization, (2) detector characteristics, and (3) automatic gain control action was displayed prominently. Although those effects, taken together, are important, they are individually small and could be separately evaluated only by locally controlled test methods.

We propose now to review the results of the tests and studies. The slight decrease in improvement which would have occurred had the speed of the automatic gain control been reduced, and the increase in improvement which would have resulted had noise *power* been averaged do not affect the fundamental considerations and will be neglected here.

One wave bundle received with one branch (Table V) yielded an

[32] K. G. Jansky "Electrical disturbances apparently of extraterrestrial origin," Proc. I.R.E., vol. 21, pp. 1387–1398; October, (1935).

improvement of 7 decibels which is about one decibel less than 10 log $N=7.8$ decibels calculated by simple theory (Fig. 34, Case I). Comments relating to this have been given.

One wave bundle received with two branches steered on each side of the center of the bundle yielded eight decibels improvement (Table V). Of this, one decibel is due to primary diversity action and three decibels are due to the secondary diversity gain. This three-decibel gain was assumed in the simple theory although it was not then designated as secondary diversity gain. It accrues by virtue of voltage addition of the signals and power addition of the noise. Both of these conditions are satisfied in Table V. There remain four decibels which represent the signal-to-noise improvement in each branch, referred to one antenna. This indicates a loss of three decibels as compared with a single branch steered at the center of the bundle, which gives seven decibels; this is reasonable when it is remembered that the branches were steered apart by a phase difference of about 60 degrees ($\phi_A-\phi_B=60°$). A loss of three decibels is about what one would estimate upon inspecting the directional patters for $\phi=60$ and 120, say, on Fig. 20. The procedure in which two branches are steered at one bundle as in the above is frequently employed and is an important factor in the operation of a MUSA.

The case of two wave bundles tabulated in Table V also yields an improvement of 7.5 to 8 decibels. Of this, one decibel and three decibels are due to primary and secondary diversity action, respectively, as in the case of one bundle. This leaves 3.5 to 4 decibels for the signal-to-noise improvement in each branch referred to a unit antenna. But the unit antenna has the advantage of two bundles, whereas the MUSA branch excludes one of them, a three-decibel difference. In comparison with a unit antenna receiving only one bundle, the improvement to be ascribed to one branch thus is increased to 6.5 or 7 decibels. This result compares favorably with the seven decibels yielded by one branch steered at one bundle. It is in this case of two bundles that square-law detectors are most important. Their advantage, amounting to an estimated one decibel, has already been included in Table V, it will be remembered.

The measurements which have permitted the above analysis of the MUSA signal-to-noise improvement were of course supplemented by aural observations made over the course of a year and a half. The listening tests corroborate the analytical results as well as can be expected of such observations. Not infrequently they showed somewhat less than the full eight-decibel improvement. The indications are, however, that a larger MUSA with three (or possibly four) branches would have yielded more nearly its full gain of 10 log N decibels. For, a MUSA receiving system does not perform its functions properly unless it is sharp enough to separate the waves sufficiently to permit effective delay equalization; also, to obtain the full gain, enough branches must be provided to utilize all of the important wave bundles. The Holmdel experimental MUSA is really a conservative approach to the field of steerable directivity. There is, of course, an upper limit to the size of a MUSA, beyond which (1) technical difficulties in phasing, etc., will occur, (2) the cost of the improvement may be less if introduced at the transmitter, and (3) the directional sharpness becomes too great to permit practical operation with waves of the stability encountered in transatlantic transmission. At present, a system about three times the length of the experimental MUSA comprising eighteen antennas and equipped with three branches seems practical. It should yield an improvement of 10 log $18=12.5$ decibels more consistently than the present MUSA yields eight decibels.

It may be worth while here to point out that as the number of antennas in a MUSA system is increased there is no tendency for static to become subordinate to thermal noise (set noise) or vice versa when static, like thermal noise, adds on a power basis. Only to the extent that transmission-line loss increases with the number of antennas will the ratio of thermal noise to static increase.

A type of transmission sometimes occurs for which the experimental MUSA gives only small signal-to-noise improvement. We refer to the highly scattered propagation associated with flutter fading, discussed at the close of Section IV. In such cases signal-to-noise improvement is not highly significant, however, since at least in the worst cases, the distortion renders the circuit worthless. Thus, increasing the transmitting power is likewise ineffective. On the other hand the experimental MUSA can accomplish something by rejecting some of the scattered waves which appear to be responsible for the flutter fading. This is accomplished without a corresponding *loss* of signal-to-noise ratio since, of course, noise is rejected, too. Fortunately, flutter fading does not seem to be associated prominently with greatly depressed field intensity so the failure to secure signal-to-noise improvement with flutter fading does not appreciably penalize the MUSA as a means of extending operation through periods of depressed field conditions.

VI. Recapitulation

The MUSA receiving system described in this paper is the culmination of some four years effort to determine the extent to which receiving antenna directivity may be carried to increase the reliability of short-wave transatlantic telephone circuits.[33] Fundamental experimental studies of wave propagation were made with particular emphasis upon how the waves arrive. Based upon the results of these studies a system was evolved in which a new technique of phasings was required. The result is a steerable antenna whose signal-to-noise advantage is seven to eight decibels compared with the largest fixed antenna that can be employed effectively. By analyzing this improvement and comparing the various contributing factors with theory, it is possible to estimate that a system three times larger than the experimental one will yield an additional four to five decibels, and will perform better consistently. In addition to the signal-to-noise improvement a substantial improvement in quality is obtained by reducing the distortion associated with selective fading. It is both interesting and important to note that whereas so often one advantage is gained only at the expense of another, in the MUSA system the best quality improvement and the greatest signal-to-noise advantage are obtained together, without compromising.

The system developed is expensive and might be thought to illustrate the law of diminishing returns. As a part of a point-to-point radiotelephone system, however, it has certain compensating features not mentioned thus far. One of these is the broad frequency band feature.

With essentially aperiodic unit antennas the MUSA possesses a broad frequency range; i.e., the directional pattern, despite its sharpness, is substantially the same over a band of a hundred or more kilocycles providing the terminal equipment is made sufficiently broad. (See Appendix I.) The broad-band feature is important for its possibilities in multiplexed operation of telephone circuits; i.e., it makes possible, insofar as the antenna system is concerned, the adaptation of some of the carrier telephone methods to radio circuits. It is to be expected that, excepting certain critical cases, fairly large percentage frequency bands will follow virtually the same paths. This assumption was verified by a few experiments in which pulses were received simultaneously from GBS (Rugby, 12,150 kilocycles) and GBU (Rugby, 12,290 kilocycles) 140 kilocycles apart. These tests showed that, although the pulse fading was, of course, not synchronous, the angles involved were alike.

Another compensating feature of the MUSA receiving system is that, with suitable terminal equipment, reception may be carried on from several points at once provided they lie within the horizontal

[33] Potter and Peterson, "The reliability of short-wave radio telephone circuits," *Bell Sys. Tech. Jour.*, vol. 15, pp. 181–196; April, (1936).

angular range of the unit antenna. Some sacrifice in vertical angular selectivity occurs but this is confined to low angles where it is least important.

Certain features of the system make for economies in plant cost. The fact that a great many components are identical permits manufacturing economies. Also, spare units need be provided only for a few vital functions, since the failure of one of the many similar parts does not disrupt service.

The development of steerable directivity has thus far been concerned with receiving antennas. In receiving, one has the obvious advantage of having, in the monitoring branch, a criterion to dictate the steering adjustments. The lack of such a direct criterion for adjusting transmitting directivity does not, however, rule out the possibility, at some future time, of a MUSA transmitting system. That horizontal steering of transmitting directivity may be decidedly important is strongly suggested by observations made on transmissions from Daventry in which significant effects upon flutter fading have been found to be associated with the orientation of the directional transmitting antennas.

Acknowledgment

The experiments described in this paper necessarily involved the co-ordinated effort of many individuals, in both the British Post Office and the Bell System, and their help has been appreciated. Mr. E. Bruce had charge of the design of the rhombic antennas and transmission lines, and Messrs. L. R. Lowry and W. M. Sharpless had important parts in the various phases of the work.

The authors are particularly indebted to Mr. R. K. Potter who contributed much through his keen interest throughout the entire work.

Appendix I

Broad-Band Characteristic of the MUSA

The frequency characteristic of the MUSA may be calculated from (3). Frequency and angle appear only in the form $2\pi a\ (\upsilon - \cos\delta)$ where a is inversely proportional to frequency. By writing the equation

$$\frac{2\pi Df}{c}\left[\upsilon - \cos\delta\right] = \frac{2\pi D(f + \Delta f)}{c}\left[\upsilon - \cos(\delta + \Delta\delta)\right]$$

we express the angular shift, from δ to $(\delta+\Delta\delta)$, of a given point on the directional pattern as the frequency is varied from f to $(f+\Delta f)$. This equation may be rewritten as

$$1 + \frac{\Delta f}{f} = \frac{\upsilon - \cos \delta}{\upsilon - \cos (\delta + \Delta\delta)}.$$

As an example consider $\Delta f = 200$ kilocycles, $f = 10$ megacycles, $\delta = 30$ degrees, and $\upsilon = 1.05$. Then $\Delta\delta = -0.4$ degree. For lower values of δ, $\Delta\delta$ becomes still smaller.

The frequency characteristic expressed in terms of percentage band and angular shift given by the above equation is independent of the size of the MUSA. It relates to the over-all length of the system, however, by the fact that for greater lengths a given angular shift has more effect.

The broad band of the MUSA reflects the fact that, with the terminal at the "leeward" end as assumed heretofore, the delay of the space paths is nearly the same as that of the transmission-line paths so that if the antenna outputs are phased to add at one frequency they will nearly add at other frequencies. If the terminal is located at the center of the MUSA to economize on transmission line, the frequency range is greatly reduced. The broad band may be regained, however, by delays introduced in the receiving equipment. With a center location, the antennas in the forward and rearward sections of the MUSA must have their phases shifted oppositely, and, unless certain other compensating networks are provided, the two phase shifts must be coupled in different phase relations for different wave lengths.

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Volume 25, Number 7 *July, 1937*

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CONDENSER TESTER • • • The Model 101 Production Condenser Tester is described. It measures capacitance and insulation resistance and tests for voltage breakdown, short circuits, and open circuits. (2 pages, $8\frac{1}{2}\times11$ inches. lithographed.)—*Associated Research, Inc., 16 N. May Street, Chicago, Ill.*

DETACHABLE INSTRUMENTS • • • Catalog Section 43–600 describes a new scheme for utilizing one set of ammeters, voltmeters, etc. in any number of separate equipments. Instruments plug into a permanently mounted receptable. (12 pages, $8\frac{1}{2}\times11$ inches, printed.)—*Westinghouse Technical Press Service, East Pittsburgh, Pa.*

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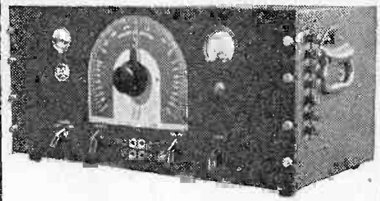

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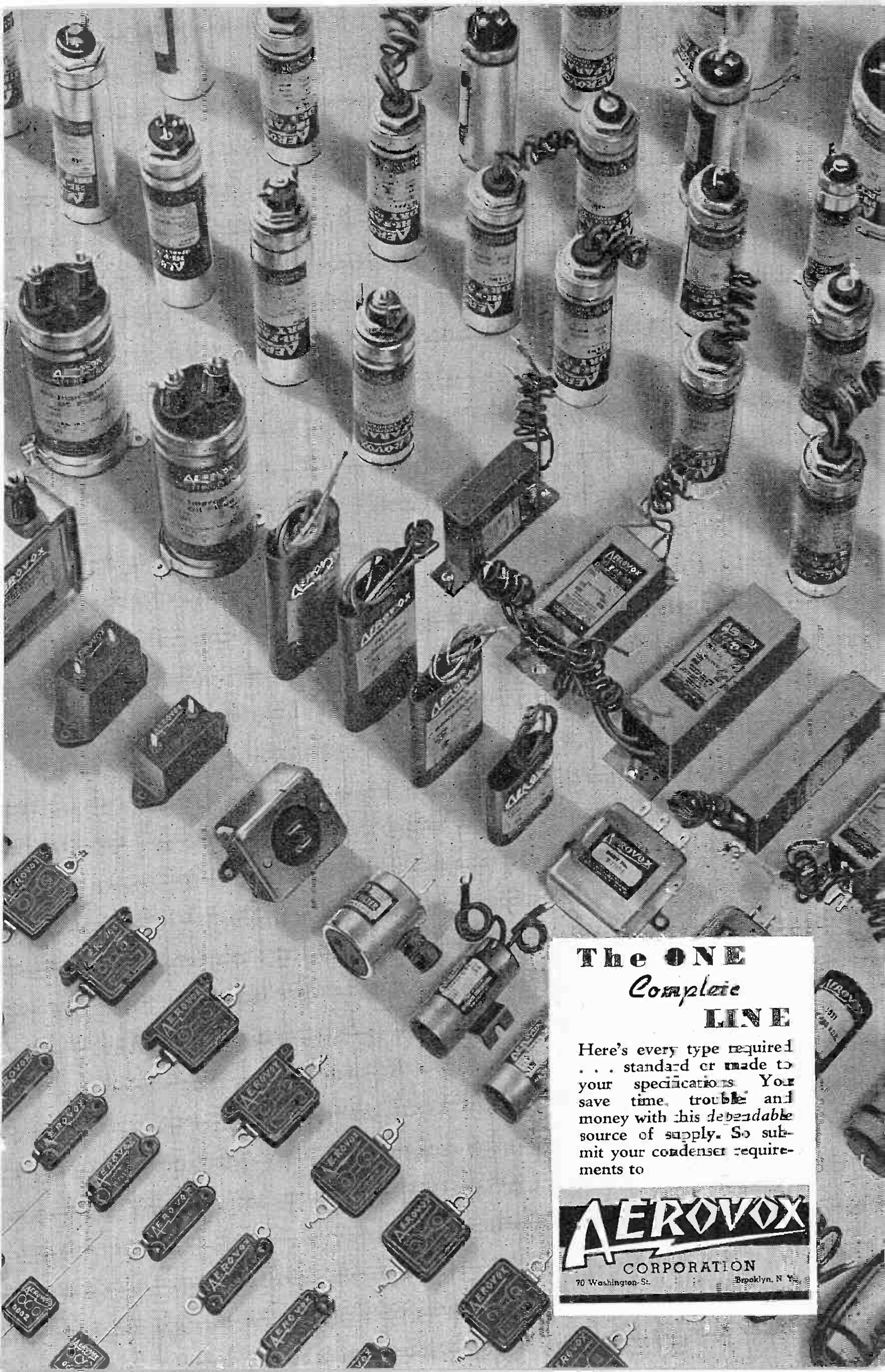
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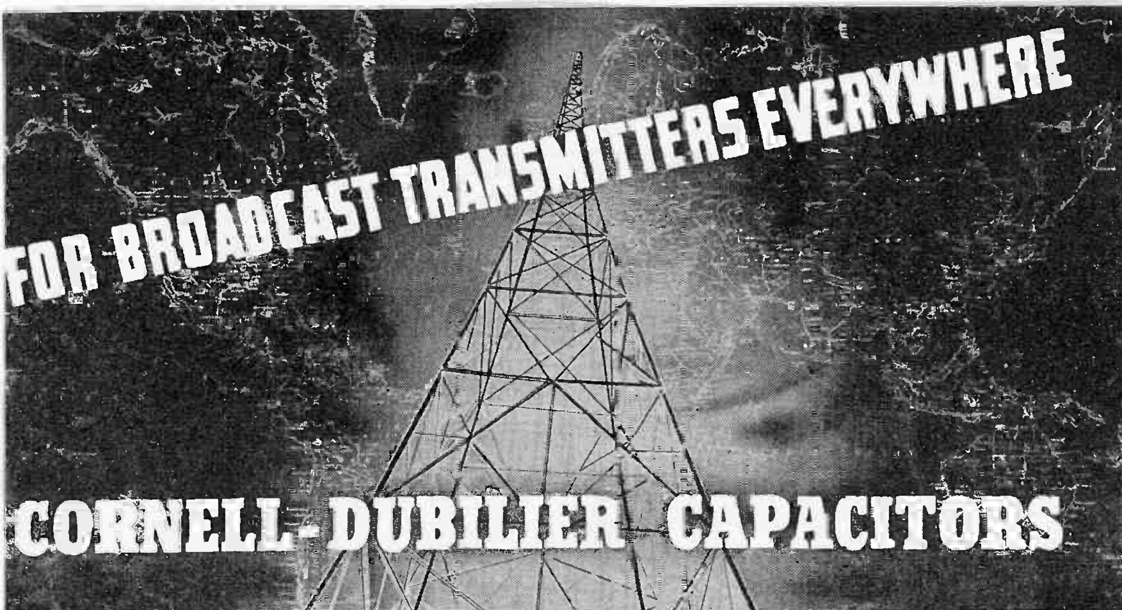

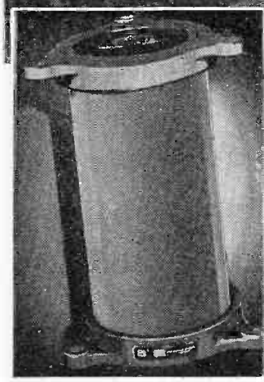

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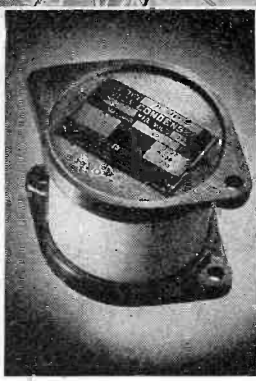

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