BRUCE

VOLUME 23 MAY, 1935 NUMBER 5

PROCEEDINGS
of
The Institute of Radio Engineers

Tenth Annual Convention
Detroit, Michigan
July 1, 2, and 3, 1935

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Institute of Radio Engineers Forthcoming Meetings

TENTH ANNUAL CONVENTION
DETROIT, MICHIGAN
July 1, 2, and 3, 1935

DETROIT SECTION
May 17, 1935

LOS ANGELES SECTION
May 21, 1935

NEW YORK MEETING
October 2, 1935

PHILADELPHIA SECTION
June 6, 1935

PITTSBURGH SECTION
May 21, 1935

SAN FRANCISCO SECTION
May 18, 1935

TORONTO SECTION
May 15, 1935

PROCEEDINGS OF

The Institute of Radio Engineers

Volume 23 May, 1935 Number 5

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Technical Papers

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.

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Institute of Radio Engineers, Inc.

Harold P. Westman, Secretary

Signed ....

Publisher

Subscribed to and sworn before me on this ....30.... day of ...April... 1935.

Bernard Arbital, Notary Public
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GEOGRAPHICAL LOCATION OF MEMBERS ELECTED APRIL 3, 1935

Transferred to the Fellow Grade

New York	Rochester, Stromber-Carlson Tel. Mfg., Co., 100 Carlson Rd.	Graham, V. M.

Transferred to the Member Grade

Maryland	Baltimore, 3310 Windsor Ave.	Plummer, W. E.
New York	New York City, 2344 University Ave.	Taylor, S. G.
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	Pittsburgh, P.O. Drawer 2038	Noble, H. V.

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California	San Francisco, 57 Post St.	Metcalf, H. E.
New York	New York City, 90 West St.	Smith, M. T.
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California	Culver City, 3847 Goldwyn Ter.	Kimball, H. R.
	Inverness, Box 167	Schoenfeld, E.
	La Canada, Route 1, Box 748 P.	Wachner, D. L.
	Long Beach, 115 E. 12th St.	Tapp, J. E.
	Los Angeles, 753 S. Bonnie Brae St.	Everett, F. A. M.
	Los Angeles, 1324 Calumet Ave.	Smith, C. D.
District of Columbia	Washington, 3500-14th St. N.W.	Jensen, J. O.
	Washington, 1332 Irving St. N.W.	Judson, L. H.
Illinois	Chicago, Radio Station WJJD, 201 N. Wells St.	Coleman, H. E.
	Chicago, 4349 W. 14th St.	Mages, M.
	Chicago, 6555 N. Campbell St.	Mitchell, D. H.
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	Owensboro, 121 W. 23rd St.	Hammond, C. R.
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	Ware, 16 Walnut St.	Fitzgerald, J. A.
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	Detroit, 15880 Steel Ave.	Dudeck, P. H.
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	Hackettstown, 143 Main St.	Cortright, R. D.
New York	Brooklyn, 180 Gates Ave.	Phillips, J. J.
	Buffalo, 33 Condon Ave.	Horn, M. V.
	East Aurora, 55 Park Pl.	Andrews, R. W.
	New York City, 463 West St.	Corbin, J. E.
	New York City, 200 Broadway	Schatt, M.
	Schenectady, 13 State St.	Goodhue, W. W.
	Schenectady, General Engineering Lab., General Electric Co.	Muchow, A. J.
Ohio	Cincinnati, WKRC, Inc., Hotel Alms	Dieringer, F. A.
Pennsylvania	Philadelphia, Philadelphia Storage Battery Co., Ontario and C Sts.	Smith, D. B.
	Rutledge, P.O. Box 222	Clapp, R. G.
Texas	Beaumont, Seismo. Dept., c/o Sun Oil Co.	Grenader, P.
	Lubbock, 2413-14th St.	Hewett, R. C.
Wisconsin	Madison, 229 Van Deusen St.	Creutz, J.
	Milwaukee, 785 N. Cass St.	Naughton, G. J.
Australia	Camperdown, Victoria	Emeny, T. F.
Brazil	Rio de Janeiro, Rua da Carioca 45–3°	Labre, J., Jr.
Canada	Bowmanville, Ont., P.O. Box 297	Crowe, F. C.
Channel Islands	St. Peter-In-The-Wood, Guernsey, "Longfrie"	James, E. A.
China	Hongkong, 1 Hollywood Rd.	Chan, A.
	Hongkong, 231 Prince Edward Rd.	Derby, P. W.
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Mexico	Nuevo Laredo, Tam., Matamoros 1308	Cuesta, N., Jr

Geographical Location of Members Elected

Elected to the Student Grade

California	Berkeley, 2418 Ashby Ave	Morrison, K. G.
	Palo Alto, Box 1301, Stanford University	Oliver, B. M.
Indiana	Terre Haute, 229 N. 5th St.	Reedy, P. H.
Michigan	Detroit, 12093 Engleside	Abfalter, H. F.
Minnesota	Minneapolis, 531 Walnut St S.E.	Baranovsky, C.
New Jersey	Camden, 1135 Haddon Ave	Schaevitz, H.
	Collingswood, 830 Stokes Ave.	Moon, D. M.
	Moorestown, 308 E. 3rd St.	Barbier, W. H.
	Union City, 512-37th St.	Braun, H. C.
New York	Troy, 197 Hoosick St.	Christaldi, P. S.
	Troy, 197 Hoosick St.	Ferry, R. N.
Pennsylvania	Emsworth, 151 Center Ave.	McConnell, R. H.
	Philadelphia, 7703 Hasbrook Ave.	Senn, G. F.
Tennessee	Lebanon, Tarver Ave.	Smith, G. G.

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 May 31, 1935. These applications will be considered by the Board of Directors at its meeting on June 5, 1935.

For Transfer to the Fellow Grade

Massachusetts	Cambridge, General Radio Company, 30 State St.	Shaw, H. S.

For Election to the Fellow Grade

New York	Schenectady, General Electric Company	Procter, J. A.

For Transfer to the Member Grade

Indiana	Indianapolis, 122 W. New York St.	Garstang, W. W.
New York	Hartsdale, Hartsdale Towers	Smith, S. B.
	New York City, 2 Horatio St.	Anderson, E. C.

For Election to the Member Grade

Massachusetts	Winter Hill, 149 Sycamore St.	Scott, H. H.
New York	Brooklyn, 18 Maple St.	Morton, A. R.

For Election to the Associate Grade

California	San Francisco, 224 Harriet St.	Baldwin, E. F.
Illinois	St. Charles, Operadio Manufacturing Company	McCraigh, J. F.
Iowa	Ames, 2611½ Knapp St.	Stewart, W. E.
Massachusetts	Newton, Raytheon Production Corp., 55 Chapel St.	Lowery, W. E.
	Springfield, 44 Colonial Ave.	Potter, E. H.
Michigan	Detroit, Detrola Radio Corp., 3630 W. Fort St.	Lichtman, S. W.
	Grand Rapids, 257 Lagrave Ave.	Sanford, L. C.
New Jersey	Bloomfield, Westinghouse Lamp Company	Moran, W. G.
	Camden, 3057 Carman St.	Briggs, A. S.
	Camden, 210 Cooper St.	Morgan, J. M.
	Camden, 1264 Langham Ave.	Teaf, J. H.
	Edgewater Park, Summer Ave.	Hyland, W. A.
	Glen Ridge, 42 Stephen St.	Potter, C. R.
New York	Brooklyn, 207 Park Pl.	Likel, H. C.
	Brooklyn, 102 Berkley Pl.	Phillips, R. K.
	Brooklyn, 1875 Stuart St.	Testan, P., Jr.
	LeRoy, Lapp Insulator Company, Inc.	Lapp, R. S.
	New York City, 218 W. 10th St.	Kinney, G. F.
	New York City, 807 Riverside Dr.	Wolff, S.
Ohio	Cincinnati, 2953 Colerain Ave.	Cooke, C. G.
Pennsylvania	Ardmore	Williamson, J. F.
	Bethlehem, 225 E. Broad St.	Heine, L. J.
	Carnegie, 90 Pilgrim Rd., Rosslyn Farms	Stark, R. E.
	Philadelphia, 522 W. Chew St.	Kelley, E.
	Pittsburgh, 215 Jacksonia St. N.S.	Rittman, F. L.
South Dakota	Pierre, P.O. Box 224	Gull, R. A.
Virginia	Norfolk, V.B.3.B., N.A.S.	Hargis, D. A.
Washington	Tacoma, 1325-6th Ave.	Picken, J. C., Jr.
Australia	Kensington, Sydney, 25 Winburn Ave.	Scott, A. W.
	Melbourne N. 3, University of Melbourne	Webster, H. C.
Austria	Graz, Universitat, Physikalisches Institut	Szekely, A.
Canada	Montreal, P.Q., c/o Northern Electric Company, 1261 Shearer St.	Sillitoe, S.
	Timmins, Ont., Box 592	Rowland, L. J.
England	Bexhill-on-Sea, Sussex, 19 Sea Rd.	Blackburne, A. F. N.
	Blackpool, Lancs., 7 Gordon Ter., Poulton-le-Fylde	Tweedale, A.
	Canterbury, Kent, 18 St. Georges St.	Bradford, R. W.
	Droitwich Spa, Worcs., 66 Tagwell Lane	Dew, W. E.
	London S.W. 1, c/o Grindlay and Company, Ltd., 54 Parliament St.	Min, M. K.
	Newport, I.O.W., The Bungalow, Shide Path, Shide	Carey, R. D.
	Purley, Surrey, Purley Radio, Ltd., 18 Tudor Ct.	Langford, S. C.
	Whitley Bay, Northumberland, Kendal House, 19 Mason Ave.	Sharp, A. V.
France	Brest, Finistere, 71 rue Jean Jaure	Haubert, A.
India	Bangalore, Dept. of Physics, Central College	Narasimhaiya, R. L.
	Baroda, Kothi Pole	Shah, C. C.
	Delhi, Famous Pictures, Chandin Chowk	Kañitkar, G. C.
	Nagpur, Budhawak Darwaja Circle No. 7	Badkes, D. J.

Scotland	Glasgow, 14 Belhaven Ter.	Jefferson, S.
South Africa	Durban, 60 Field St.	Battersby, P. R. A.
Spain	Madrid, Po Prado 40	Escritano, F. C.
Sweden	Lidingo, Nr. Stockholm, Aga-Baltic Radio A/B	Granqvist, C. E.
Territory of Hawaii	Honolulu, University of Hawaii	Miyake, I.

For Election to the Student Grade

California	Pasadena, 1301 E. California St.	Muller, C. R.
	Pasadena, 303 S. Chester Ave.	Pierce, J.
Idaho	Moscow, Delta Tau Delta	Byrne, M. E.
Kansas	Manhattan, 1031 Bluemont Ave.	Evans, R.
Michigan	Houghton, 96 Hubbell Ave.	Chudyk, A.
	Houghton, 109 Isle Royale St.	McArdle, B.
	Lincoln Park, 1288 Washington Ave.	Lawrence, S. C.
New Jersey	Jersey City, 2600 Boulevard	Boyajean, J. A., Jr.
	Pitman, 411 W. Holly Ave.	Hughes, E. T.
Oregon	Corvallis, 1565½ Monroe St.	Sasser, L.
Pennsylvania	Allentown, 1860 S. Wood St.	Bradley, W. E.
	Lansdowne, 234 Windemere Ave.	Tellier, J. C.
	Philadelphia, 6850 Chester Ave.	Herbster, M. O.
	Philadelphia, 3424 Walnut St.	Mode, D. E.
	Philadelphia, 5403 Willows Ave.	Stewart, F. F., Jr.
	Philadelphia, 6002 Oxford St.	Warshaw, J.
	Philadelphia, 5821 Ellsworth St.	Weaver, C. H.

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With deep regret we record the death of

Michael Idvorsky Pupin

President of the Institute, 1917

Michael Idvorsky Pupin was born in Idvor, Bonat, on October 4, 1858. He was a Serb by race and emigrated to this country in 1874. He studied at Cooper Union, Columbia College, University of Cambridge, and the University of Berlin. He started as an instructor in mathematical physics in Columbia and in 1903 was made Professor of Electromechanics.

Some of his outstanding developments were the application of electrical resonance to multiplex telegraphy and wireless telegraphy, the use of fluorescent screens in X-ray photography, and the inductive loading of telephone lines for long-distance transmission.

He was the recipient of many awards and in 1924 the Institute conferred upon him its Medal of Honor. He held eighteen honorary doctorates from American and European universities together with decorations from a number of foreign governments. He became a Fellow of the Institute in 1915.

His autobiography "From Immigrant to Inventor" received the Pulitzer Prize and has been translated into several foreign languages. Dr. Pupin died on March 12, 1935, in New York City.

Meeting of the Board of Directors

The regular monthly meeting of the Board of Directors was held on April 3 in the Institute office and those present were Stuart Ballantine, president; Melville Eastham, treasurer; O. H. Caldwell, Alfred N. Goldsmith, Virgil M. Graham, R. A. Heising, L. M. Hull, F. A. Kolster, George Lewis, E. L. Nelson, Haraden Pratt, H. M. Turner, L. E. Whittemore, William Wilson, and H. P. Westman, secretary.

Virgil M. Graham was transferred to the grade of Fellow. W. C. Ellsworth, H. V. Noble, W. E. Plummer, and S. G. Taylor were transferred to Member grade and H. Dobell, T. J. Guilfoyle, H. E. Metcalf, and M. T. Smith were admitted to that grade. Forty-five applicants for Associate grade and fourteen for Student grade were approved.

A proposal that the recently extablished R.M.A. Committee on Interference be converted into a Sectional Committee operating under the American Standards Association procedure was approved. F. X. Rettenmeyer was named the Institute's representative on the existing committee and will continue on the Sectional Committee if one is formed.

Approval was granted for the establishment as an American standard of a recently completed Underwriters' Laboratories' Standard on Power-Operated Radio Receiving Appliances.

Some material was submitted by A. F. Van Dyck, the Institute's representative on the Sectional Committee on Preferred Numbers, on the work of that committee. It was recommended that a suitable report be prepared for publication in the PROCEEDINGS.

William Wilson was appointed chairman of the Papers Committee for the 1935 Convention and George Lewis and Haraden Pratt appointed members of the committee.

At the end of this report will be found a statement regarding Institute awards which was approved by the Board of Directors and clarifies previous instructions issued to the Awards Committee.

The Emergency Employment Service reported seventeen new registrations making a total of 727. Of these, 535 are Institute members. Seventeen jobs were handled during March and three were definitely filled.

The progress report from the Committee on Licensing of Engineers was reviewed and tabled for discussion at the May meeting of the Board.

Institute Awards

Each year the Institute recognizes outstanding achievements in the radio communication field by the bestowal of two awards: one recognizes, in general, an extensive service over a period of years while the other is usually conferred for a more recent contribution.

Medal of Honor

The Institute Medal of Honor is given in recognition of distinguished service in radio communication. It is awarded to one who has been responsible for an important advance in the science or art of radio communication. This advancement may be a single development or it may be a series of developments which in the aggregate have resulted in substantial improvements in radio communication.

The achievement may be a patented or unpatented invention. It may also be a theoretical analysis of a hitherto unexplained phenomenon of distinct importance to the radio art, though the application thereof need not be immediate. Preference will be given analyses which are directly applicable to the art.

Further, the advance may be a new system of traffic regulation or control, a new system of administration of a radio company or the radio communication service for military, transportation, or other organizations; a legislative program beneficial to the radio art or any portion of the operating or regulating features of the art.

The achievement for which this award is granted must preferably be completely and adequately described in a scientific or engineering publication of recognized standing and should have actually been applied to radio communication problems. A development may be of recent origin or otherwise and a series of developments may extend over a long period of years. Preference will be given to widely used and generally useful inventions.

The recipient of this award shall be named by the Board of Directors which will normally receive recommendations from the Awards Committee.

Morris Liebmann Memorial Prize

The Morris Liebmann Memorial Prize, to perpetuate the memory of the late Colonel Morris N. Liebmann, is made possible through the generosity of E. J. Simon, a Fellow of the Institute. The award consists of the income from a gift of $10,000, and is not a stated amount as it is the interest from the securities in which the principle is invested.

The recipient shall be a member of the Institute who shall have made public during the recent past an important contribution to radio communication. The contribution shall be completely and adequately described in a scientific or engineering publication of recognized standing.

How remote this publication may be is left to the judgment of the committee and will depend upon the rapidity with which the advancement is applied in practice, such application indicating its importance. Where several contributions are being considered, that which is widely used or is generally useful shall be given preference.

The recipient of this award is named by the Awards Committee, appointed annually by the Board of Directors.

Schedule of Radio Emissions of Standard Frequency

The National Bureau of Standards announces changes in its schedule of standard frequency emissions from its station WWV, Beltsville, Md., near Washington, D. C. The changes will substantially increase the service available to transmitting stations for adjusting their transmitters to exact frequency, and to the public for calibrating frequency standards and transmitting and receiving apparatus.

The emissions will be on two days a week instead of one day as formerly, and will be on the three frequencies, 5000, 10,000, and 15,000 kilocycles per second, instead of the single frequency, 5000. The changes are the result of experimental emissions made by the Bureau on 10,000 and 15,000 kilocycles, with the aid of a large number of organizations and persons who observed the received signals at various places. These tests showed that service could be rendered at all distances in the daytime by the use of the three frequencies. With the use of 5000 kilocycles alone it was necessary to have emissions at night in order to give service at distances greater than a few hundred miles from Washington. With the use of the three frequencies no night emissions will be necessary.

Of the emissions now scheduled, those on 5000 kilocycles are particularly useful at distances within a few hundred miles from Washington, those on 10,000 kilocycles are useful for the rest of the United States, and those on 15,000 kilocycles are useful in the United States and other parts of the world as well.

Beginning February 1, 1935, and continuing each Tuesday and Friday thereafter (except legal holidays) until further notice, three frequencies will be transmitted as follows: noon to 1 P.M., Eastern Standard Time, 15,000 kilocycles; 1:15 to 2:15 P.M., 10,000 kilocycles; 2:30 to 3:30 P.M., 5000 kilocycles.

The emissions consist mainly of continuous unkeyed carrier frequency, giving a continuous whistle in the phones when received with an oscillating receiving set. For the first five minutes the general call (CQ de WWV) and the announcement of the frequency are transmitted. The frequency and the call letters of the station (WWV) are given every ten minutes thereafter.

The accuracy of the frequencies transmitted is at all times better than one part in five million. From any of them, using the method of harmonics, any frequency may be checked. Information on how to receive and utilize the signals is given in a pamphlet obtainable on request addressed to the National Bureau of Standards, Washington, D. C.

The Bureau desires to receive reports on reception of these emissions, especially because radio transmission phenomena change with the seasons of the year. The data desired are approximate field intensity, fading characteristics, which of the three frequencies is received best, and the suitability of the signals for frequency measurements. It is suggested that in reporting on intensities, the following designations can be used where field intensity measurement apparatus is not used: (1) hardly perceptible, unreadable; (2) weak, readable now and then; (3) fairly good, readable with difficulty; (4) good, readable; (5) very good, perfectly readable. Statements are desired as to the intensity of atmospherics and as to whether fading is present or not, and if so, its characteristics, such as time between peaks of signal intensity. Correspondence should be addressed to the National Bureau of Standards, Washington, D. C.

Committee Work

Admissions Committee

The Admissions Committee met in the Institute office on April 3 and those present were Austin Bailey, chairman; I. S. Coggeshall, W. F. Cotter, R. A. Heising, L. C. F. Horle, F. A. Kolster, and Donald McNicol. Seven applications were considered and approved. One was for admission to Fellow, another for transfer to Fellow, two for admission to Member, and three for transfer to Member.

Broadcast Committee

A meeting of the Broadcast Committee was held in the Institute office on April 2 and attended by E. L. Nelson, chairman; Wilson Aull (representing J. V. L. Hogan), W. R. G. Baker, H. A. Chinn (representing E. K. Cohan), G. D. Gillette, R. N. Harmon, J. C. McNary, H. A. Wheeler, and H. P. Westman, secretary. The committee first discussed two conferences which are being called by the Federal Communications Commission and then examined proposed recommendations for standards for high fidelity broadcast transmitters. It is anticipated that a report will be prepared on this subject.

Membership Committee

The Membership Committee met on April 3 in the Institute office and those present were I. S. Coggeshall, chairman; W. F. Cotter, F. W. Cunningham, W. G. Ellis, H. C. Humphrey, and C. E. Scholz. The committee reviewed an analysis of membership information on various matters as disclosed through a questionnaire circulated at the March New York meeting and portions of the report were referred to the New York Program Committee.

Papers Committee

The Papers Committee met in the Institute office on April 3 and those present were William Wilson, chairman; H. A. Affel, Edmond Bruce, H. A. Chinn, J. K. Clapp, P. O. Farnham, E. B. Ferrell, L. F. Jones, F. B. Llewellyn, R. M. Morris, A. F. Murray, H. O. Peterson, R. K. Potter, B. E. Shackelford, H. M. Turner, H. A. Wheeler, W. C. White, Irving Wolff, H. S. Rhodes, assistant editor; and H. P. Westman, secretary. As the operation of this committee is almost exclusively by correspondence, considerable time was devoted to a review of its structure, scope of activities, and position in relation to other Institute bodies. Types of papers published in the past were analyzed and the desirability of including in the PROCEEDINGS a larger proportion of papers of a practical nature recognized. The technical problems and procedures to be followed in reviewing papers and reporting on them were discussed in detail. The necessity of reducing papers to a minimum length to permit the inclusion of a greater number of papers was considered.

STANDARDS

Technical Committee on Electronics—IRE Subcommittee on Large High Vacuum Tubes

The Subcommittee on Large High Vacuum Tubes of the Institute Technical Committee on Electronics met at Bell Telephone Laboratories on March 7 and those present were M. J. Kelly, chairman; R. D. Hall, R. W. Larson, E. E. Spitzer, and C. M. Wheeler.

This was the first meeting of the committee and its functions and relations to other groups were discussed. The material which the committee should consider and report on was outlined and various members of the committee assigned portions of the work so that proposed material would be available for action at the next meeting of the committee.

Technical Committee on Radio Receivers—ASA

A meeting of the Technical Committee on Radio Receivers operating under the Sectional Committee on Radio of the American Stand ards Association was held in the Institute office on April 4 and attended by G. L. Beers, chairman; J. W. Fulmer, F. A. Polkinghorn, Sarkes Tarzian (representing J. L. Schwank), E. W. Wilby (representing D. E. Foster), and H. P. Westman, secretary.

The committee considered an extensive report submitted by the International Electrotechnical Commission. The American viewpoints on these proposals will be brought to the U. S. National Committee and conveyed to the American representative at the conference to consider this material scheduled at The Hague on June 18, 1935.

The committee reviewed some other material which will be recommended to the Sectional Committee on Radio for approval as an American Standard.

Institute Meetings

Atlanta Section

The annual meeting of the Atlanta Section was held on January 24 at Georgia School of Technology with Henry L. Reid, chairman, presiding.

A paper on "Design and Operation of Filter Circuits" was presented by I. H. Gerks of the Georgia School of Technology. Professor Gerks presented designs for high-pass, low-pass, and band-pass filters. All formulas used were derived and explained. The use of filters in carrier circuits was described. After the adjournment of the meeting, those present visited the radio laboratories at Georgia School of Technology where various filters which had been set up were demonstrated.

In the election of officers, I. H. Gerks was named chairman; C. F. Daugherty, vice chairman; and P. C. Bangs, secretary-treasurer. The meeting was attended by nineteen members and guests.

Boston Section

The Boston Section met on February 15 at Massachusetts Institute of Technology with E. L. Chaffee, chairman, presiding. Seventy-five members and guests were present and fifteen attended the informal dinner which preceded the meeting.

R. D. Fay of the Electrical Engineering Division of Massachusetts Institute of Technology presented a paper entitled "An Exact Method of Representing by Electrical Circuit Elements Conversion Devices Comprising Coupled Electrical and Mechanical Systems." Professor Fay pointed out that in representing mechanical systems by electrical networks, the usual method is to consider mass, compliance, and friction as equivalent, respectively, to inductance, capacitance, and resistance. In the representation of mechanical systems which are coupled electromagnetically to electrical systems, this arbitrary choice of equivalents is no longer possible if the complete device is to be represented.

By finding the reaction of the mechanical systems on the electrical, an electrical network may be found in which each mechanical circuit element is represented by an electrical circuit element. On account of an inherent reciprocal relationship, mechanical series circuits appear as parallel electrical circuits in which capacitance and inductance represent mass and compliance, respectively.

The equivalent circuit derived from a moving-coil type loud speaker and the air reaction theorem is unexpectedly simple and thereon shows clearly how frequency response and efficiency depend on various design factors. The paper was discussed by Drs. Chaffee and Mimno and following this, the sound laboratories of Massachusetts Institute of Technology were inspected.

Buffalo-Niagara Section

The March meeting of the Buffalo-Niagara Section was held jointly with the Buffalo Engineering Society on the 13th at the Hotel Statler. Two hundred fifty were present and the meeting was presided over by Messrs. Larkin and Kingsley representing the Buffalo Engineering Society and the Institute, respectively.

A paper on "The Engineer's New Tool: The Electron" was presented by O. H. Caldwell, Editor of *Electronics*. The subject was presented in a popular and elementary manner and treated chiefly the various phases of commercial application of electronic devices. Some of the things discussed and described were television, facsimile transmission, wirephoto transmission, electrocardiograph, fever machines, the high-frequency knife, photo-electric sorters, light controls, elevator levelers, and door openers.

Chicago Section

The Chicago Section met on March 22 at the R.C.A. Institute's auditorium. Ninety were present and in the absence of the chairman, H. C. Vance, vice chairman, presided.

L. M. Young, Supervisor of Synchronization for the Columbia Broadcasting System, presented a paper on "Present Practice in Synchronous Operation of Broadcast Stations." In it, he presented an historical outline of synchronization, setting forth the technical phases of it as developed both abroad and in the United States. The paper specifically covered the comparatively recently developed synchronization system used between stations WBBM and KFAB. It covered not only the equipment used in the radio-frequency portions of the system but the audio-frequency delay systems used at the studios. A complete analysis of the results achieved in actual operation was given and covered a long period of observations and measurements made throughout that portion of the country served by both stations.

Cincinnati Section

A. F. Knoblaugh, chairman, presided at the March 12 meeting of the Cincinnati Section which was held at the University of Cincinnati and was attended by forty-six members and guests.

James I. Cornell, chief engineer of the Magnavox Company presented a paper on "Audio-Frequency Transformer Design." In it he derived the equations resulting from the consideration of the equivalent circuit of a transformer giving both the rigorous forms and the simplified forms applicable to the high- and low-frequency ends, respectively. He then showed design curves developed from these equations explaining how these in conjunction with known iron characteristics and a few simple design formulas can be used to produce a transformer of the desired frequency characteristics when operated under specified circuit conditions. The paper was discussed by Messrs. Freeman, Kilgour, Knoblaugh, and Rockwell.

A special committee on radio publicity reported that definite arrangements will be completed by the next meeting for a series of radio talks.

Cleveland Section

The Cleveland Section met on February 28 at Case School of Applied Science. Karl Banfer, chairman, presided and forty-six were present. Nine attended the informal dinner which preceded the meeting.

A paper on "Practical Design Problems of Loud Speakers" was presented by J. G. Tiedje of the Rola Company. In it he reviewed the magnetic theory and gave design desideratum of the dynamic speaker. He showed how electrical and mechanical analogies are used to design and match voice coil and cone. A new double voice coil speaker was described and its theory of operation explained. This type of speaker was developed to eliminate diminution of mass and to decrease resonant peaks in the cone. Its operation was explained by means of electrical analogies. A high fidelity amplifier reproduced phonograph recordings in a demonstration of a loud speaker. Special records were used to illustrate the effects of various types of distortion as produced by the insertion of filters in the recording circuits at the time of recording. It was pointed out that present systems do not give true fidelity but a higher degree of fidelity than formerly available.

Connecticut Valley Section

J. A. Hutcheson, chairman, presided over the March 21 meeting of the Connecticut Valley Section held at the Hotel Garde in Hartford. Seventeen were present at the meeting.

James J. Lamb, Technical Editor of *QST*, presented a paper on "Practical Aspects of Single Side Band Radio Communication." Contending that the single side band transmission is the ultimate in radio communication, particularly for broadcasting, the speaker illustrated his point by describing existing systems of that type now in operation abroad. He outlined means of applying this method to reception alone, utilizing existing forms of transmission, to provide most of the advantages of the system which are freedom from selective or audio-frequency fading, reduction of amplitude distortion and noise, and minimizing interference effects where two transmitters operate synchronously. Each advantage is especially useful in broadcasting and particularly for high-frequency broadcasting. The speaker expressed his belief that single side band receivers were the next step following high fidelity developments and that the advantages as demonstrated in a laboratory set-up would be apparent even to the casual listener, and such receivers would immediately be recognized as being superior to existing types. Physical concepts and a block analysis of the method were illustrated.

Detroit Section

The Detroit Section met on March 15 in the Detroit News Conference Room. A. B. Buchanan, chairman, presided and the attendance was fifty four. Twenty-two were present at the informal dinner which preceded the meeting.

A paper on "Directional Antennas" was presented by R. M. Whitmer, Instructor in the Physics Department of the University of Michigan. In it he outlined the history of directional antennas from the use of the first reflector in 1899 to the present time and summarized briefly their first commercial applications. He then discussed the requirements of directional antennas for transmitting use where gain and directivity are desired and for reception where they may be needed to reduce static rather than to give antenna gain. In receiving use, gain is usually need above ten megacycles while below this, frequency discrimination is needed. An explanation of the theoretical operation of a single reflector system was given and developed to describe the more complex endfire and broadside arrays. The paper was concluded with a discussion of the transatlantic telephone service and an explanation of the rhombic antenna.

A discussion of preparations for the 1935 Convention to be held in Detroit, was presented by H. L. Byerlay, chairman of the Convention Committee, and H. P. Westman, national secretary.

New York Meeting

Three papers were presented at the regular April meeting of the Institute held on the 3rd in the Engineering Societies Building in New York City. The meeting was presided over by President Ballantine and the attendance was 400.

The first two papers appeared in the April Proceedings and were on "Experiments with Directivity Steering for Fading Reduction" by E. Bruce and A. C. Beck and "General Considerations of Tower Antennas for Broadcast Use" by H. E. Gihring and G. H. Brown.

The third paper on "The Broadcast Antenna" by A. B. Chamberlain and W. B. Lodge of the Columbia Broadcasting System was presented by Mr. Chamberlain. He pointed out that during the past several years, the trend in broadcast transmitting antennas has been towards the vertical radiator. The paper was devoted chiefly to a review of actual field results obtained with tower radiators and presented data on efficiency, base voltage, base loss, practical design considerations, and cost. It was concluded that the two-tower conventional antenna as used in the past is definitely outmoded by the single vertical radiator or combinations of vertical radiators to provide directional radiation characteristics.

Philadelphia Section

A meeting of the Philadelphia Section was held at the University of Pennsylvania on March 7 with E. D. Cook, chairman, presiding. One hundred and fifty were present and twenty-one attended the dinner which preceded the meeting.

A paper on the "Differential Analyzer" was presented by Irven Travis of the Moore School of Electrical Engineering. The machine solves differential equations up to the tenth order and having as many as four variable coefficients. The historical development of mechanical devices for solving differential devices was scanned, after which the principle of operation of the differential analyzer was outlined. The relaxation oscillation equation which van der Pol solved by the isocline method was taken as an example to illustrate the principles.

After a short discussion of the principles involved in the analyzer, the meeting was adjourned to the Moore School of Electrical Engineering where the new ten-integrator differential analyzer recently completed was demonstrated in operation. The machine cost $55,000 and required fourteen months for construction. In the example used, characteristic multivibrator wave forms were obtained on the output table.

The April meeting of the Philadelphia Section was held jointly with the Franklin Institute in the auditorium of that organization. H. McClenahan, Secretary of the Franklin Institute presided and introduced Phillips Thomas, Director of Research for the Westinghouse Electric and Manufacturing Company, who presented a paper on "Research and the End Zones."

In this paper, Dr. Thomas described in a popular way recent advances in research and their practical applications, showing especially advances into the end zones of macroscopic and microscopic entities. Numerous demonstrations of special apparatus were given. A model of part of the equipment used at the Century of Progress Exposition to have the light from the star Arcturus set the Exposition's lighting system into operation was demonstrated. The light from this star which had started forty years before was picked up in five different parts of the country and used to operate photo-electric relays. The small amount of energy from this star is about equivalent to that of a candle located half a mile away. Another impressive demonstration was shooting a rubber ball past a gas-filled tube which flashed 7000 amperes per microsecond. The speed of the ball was great enough to make a U dent in a rubber band employed to set off the flash. The ends of the rubber band above and below the ball remained effectively straight. The ball and band appeared stationary when lighted by the flash. A demonstration showing the effect of wind on sleet-covered wires employed a small model and illustrated how the wires are caused to vibrate vertically making them break. A xylophone was operated from a distance by means of a hand flashlight playing on photo-electric tubes.

Dr. McClenahan in his introduction, presented a short description of the work that Dr. Thomas is doing at Princeton University.

Pittsburgh Section

C. K. Krause, chairman, presided at the March 19 meeting of the Pittsburgh Section which was held at the Hotel Fort Pitt. The attendance was thirty five.

The first paper was on "Elementary Principles of the Vacuum Tube Voltmeter" and was presented by C. Williamson, Professor of Physics at the Carnegie Institute of Technology. The author started with simple meters for measuring peak voltages and currents, and continued to circuits using differential galvanometers and double tube meters having very high amplifications. He stated that meters capable of measuring 10^{-13} amperes could readily be made but voltages lower than one microvolt presented difficult problems. The paper was discussed by Messrs. Krause, Stephens, and Wyckoff.

The second paper of the evening on "Practical Applications of the Vacuum Tube Voltmeter" was in the form of a symposium presented by S. F. Lybarger of E. A. Myers and Sons, L. E. Swelund of Westinghouse Research Laboratory, and R. E. Stephens of the University of Pittsburgh.

Mr. Lybarger described and exhibited two voltmeters used in production work, one employing a supercontrol type of tube as an amplifier and a diode as a rectifier giving a straight line relation between diode current and input voltage. Mr. Swedlund exhibited a simple two-range portable meter which was very useful for general laboratory work. Mr. Stephens showed a meter using a low grid current tube capable of measuring very small currents. A general discussion followed the symposium which was participated in by Messrs. Krause, Noble, Place, Williamson, and Wyckoff.

Rochester Section

On March 14 the Rochester Section met at the Sagamore Hotel. The attendance was 102 and ten were present at the dinner which preceded the meeting. Arthur Schoen, presided.

A paper on "Radio Technique in Measuring Cosmic Rays" was presented by L. A. DuBridge, Chairman and Professor of the Physics Department of the University of Rochester. In it, Dr. DuBridge traced the history of the study of cosmic rays, outlining the reasons underlying the initial research work and the following study of this mysterious phenomenon. The main methods of detecting and measuring the rays were discussed and the resulting data given in graphical form. Vacuum tube amplifying circuits have been used in counting systems to amplify the effects produced by cosmic rays to a value to permit their operating recording devices or loud speaker. It was stated that scientists do not believe cosmic rays cause static familiar to radio broadcast listeners except on very rare occasions. In the discussion of the paper which was participated in by Messrs. King, Klumb, and Wallace, it was concluded that the rays probably consist of positively charged particles called positrons approximately equal in number to electrically charged particles or electrons. They have tremendous energies having been measured to values over 10^{10} electron volts and velocities approaching very closely that of light. Their penetrating power is greater at high altitudes and at the earth's magnetic poles, with no variation due to time of day, season of the year, or weather conditions. They have been measured penetrating the equivalent of a sixty-foot thickness of lead.

R. H. Manson presided at the April 4 meeting of the Rochester Section held at the Sagamore Hotel and attended by seventy-eight.

A paper on "Recent Advances in the Science of Acoustics" was presented by S. K. Wolf, Manager of the Acoustic Consulting Department of Electrical Research Products. In it, he showed how acoustical problems may be treated by elementary electrical analogy and the use of electrical equipment such as microphones, amplifiers, and loud speakers in the propagation of sound indoors. Various practical sound problems were presented and analyzed, illustrating the effects of "live" and "pleasant" rooms, as well as "dead" rooms. They showed data on the effect of the placement of a loud speaker in a room, how its location can improve or damage reception depending on the direction in which it is pointed, the reverberation characteristic of the room and the position of the listener.

San Francisco Section

A. H. Brolly, chairman, presided at the March 20 meeting of the San Francisco Section held at the Bellevue Hotel and attended by sixty-three. Fourteen were present at the dinner which preceded the meeting.

Two papers were presented by engineers of the Remler Company. The first on "High Fidelity Amplifier Design" was by Victor Welge who outlined the various problems encountered in the design of high fidelity amplifiers giving high gains. The various types of tubes used for these amplifiers were discussed. The second paper on "Applications of High Fidelity Amplifiers and Reproducers" was presented by R. B. Walder who continued the discussion of the problem and demonstrated various types of loud speakers and other sound equipment.

Seattle Section

The Seattle Section met on March 1 at the University of Washington. The attendance was eighty and E. D. Scott, vice chairman, presided.

G. L. Hoard of the Electrical Engineering Department of the University of Washington presented a paper on "Some Industrial Applications of Mercury-Vapor Tubes." Professor Hoard reviewed briefly the characteristics and limitations of various rectifiers and their applications in commercial fields. He then described recent developments in transmission of power by means of constant-current, direct-current transmission lines with associated rectifier and inverter circuits. The paper was accompanied by a practical demonstration of the circuits and principles involved and was concluded with a description of variable speed commutatorless motors. Messrs. Bouson, Eastman, Hackett, Libby, Renfro and others participated in the discussion.

Another meeting of the section was held on March 29. It also was at the University of Washington and R. C. Fisher, chairman, presided. Forty-four members and guests were present.

The subject of the meeting was "High Radio-Frequency Currents in Medical Treatments and Sterilization of Food Products." C. A. Shadel, Seattle, a physician, introduced the subject with a brief description of methods of treating patients by artificially produced fevers. He was followed by C. E. Jelliff who described the equipment, circuits, and frequencies employed for medical treatments. He described his experiments with high-frequency electromagnetic fields for sterilization of packaged food products.

Toronto Section

The March 8 meeting of the Toronto Section was held jointly with the Wireless Association of Ontario at the University of Toronto. The attendance at the meeting was eighty-seven and the chairman of the Wireless Association presided.

A paper on "Capacitors for Use in Radio Equipment" was presented by P. Robinson of Sprague Specialties Company. In his paper Dr. Robinson paid particular attention to electrolytic condensers including regulating and oil types. He first covered the elementary principles of operation of electrolytic condensers and then dealt in detail with the various design requirements for different applications and discussed the advantages of limitations of these types.

A second meeting of the Toronto Section was held in March on the 18th at the University of Toronto. It was presided over by F. J. Fox, vice chairman and attended by fifty-six.

"A Visit to the British Broadcasting Corporation" was the subject of a paper by R. Price of the Radio Inspection Department of the Department of Marine. It was based upon a recent trip made by the speaker to England.

The development of broadcasting in Great Britain from its inception in 1922 was outlined. The British Broadcasting Company was chartered in 1923 and installed eight one-kilowatt broadcast stations and later eleven relay stations of 120 watts each. In 1926 the charter expired and the British Broadcasting Corporation was chartered. It is not a government department but is responsible to the Postmaster General. In 1927 it devised the twin-wave regional plan now in use. The area served by the corporation was divided into eight regions each of which was to have two fifty-kilowatt stations. One was for entertainment of local interest and one for programs of national interest. This plan with but a few slight alterations has been carried out. The second portion of the paper was a description of the layout and operations of a twin-wave regional station. These stations were designed by the British Broadcasting Corporation's engineering department. The growth of the corporation from its early studios in Marconi House to its present location at Broadcasting House was outlined. The structural and architectural features of Broadcasting House were described in detail and the meeting was closed with a description of programs produced by the corporation.

Washington Section

"The Broadcast Antenna" was the subject of a paper by A. B. Chamberlain and W. B. Lodge of the Columbia Broadcasting System presented at the March 11 meeting of the Washington Section. This was held at the Potomac Electric Power Company auditorium and presided over by E. K. Jett, chairman. One hundred and forty-five members and guests were present and thirty-eight attended the dinner which preceded the meeting.

The paper covered the history of the development of broadcast antennas and showed many illustrations of types of antennas in use throughout the country. Propagation patterns to be expected from the common types of antennas were shown.

Personal Mention

Keith Beisel formerly with Metro-Goldwyn-Mayer Studios is now an engineer in geophysics for the Gulf Research and Development Corporation at Pittsburgh, Pa.

Previously with Lake Research Laboratories, T. A. Cohen is now chief engineer of Wheelco Vacuum Products Company, Chicago.

N. D. Cole formerly with International Devices Company is now aircraft transmitting engineer for the R.C.A. Manufacturing Company, Camden, N.J.

R. H. Cole has left KMOX to join the Field Engineering Department of the National Broadcasting Company with headquarters in Chicago.

Previously with General Household Utilities Company, K. H. Emerson has joined the Auto Radio Engineering Department of Philco Radio and Television Corporation, Philadelphia.

J. E. Fox is no longer with Audiola Radio, having taken charge of the Test Equipment Laboratory of Electrical Research Laboratories, Chicago.

Previously with the Radio Corporation of America, David Grimes has joined the radio engineering staff of Philco Radio and Television Corporation, Philadelphia.

S. K. Groseclose, Lieutenant, U.S.N., has been transferred from Cavite to the radio station at Annapolis, Md.

Formerly with Westinghouse Electric and Manufacturing Company, J. L. Hurff has joined the staff of the Hazeltine Corporation in New York City.

C. H. Jackson is now a radio engineer for the U.S. Department of Commerce at Detroit, Mich., having formerly operated Jackson Laboratories.

M. J. Jelen has left Zenith Radio Corporation to join the staff of Stewart Warner Corporation in Chicago.

E. A. Laport is now transmission engineer for Wired Radio of Ampere, N.J., having formerly carried on a consulting practice.

Formerly with DeForest Radio Tube Company, W. G. McConnell is now design engineer for Radio Receptor Company of New York City.

F. J. Moles has left the General Electric Company to join the staff of Jam Handy Picture Service, Detroit, Mich.

G. E. Sterling has been made inspector in charge of the Fourth Radio District of the Federal Communications Commission with headquarters at Baltimore, Md.

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TECHNICAL PAPERS

RADIO DEVELOPMENTS DURING 1934*

Part I—A Review of Radio Communication in the Fixed Services for the Year 1934

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The field of radio communication in the fixed services, including as it does, a fair share of the total point-to-point telecommunication in the world, is one of major importance. This paper is intended to present a very brief review, largely from an engineering viewpoint, of the more important developments in this field during the year 1934. Detailed information on developments is not included. Such information can be found in other published papers including many which have been presented before this Institute.

During 1934, the following important new international radiotelegraph circuits were placed in service: between Shanghai and London; between Tokyo and Rome; between Honolulu and Papette, Tahiti, via RCA Communications; between New York and Syria via RCA Communications; between England and Australia for public facsimile service; between Aden and Ethiopia; and between West Africa and the Canary Islands.

An additional circuit between San Francisco and Tokyo via Mackay Radio and Telegraph Company and a new circuit between New York and Santiago, Chile, were opened via Mackay Radio and Telegraph Company.

Within United States territory new domestic radiotelegraph circuits were opened by RCA Communications between the following points: New York and Boston; New York and Washington; New York and Chicago; and New York and New Orleans.

Mackay Radio and Telegraph Company opened a new domestic radiotelegraph circuit between New York and Washington, extending new circuits opened late in December, 1933, between New York and New Orleans; New York and Chicago; New York and Seattle; and San Francisco and Chicago.

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New radiotelephone services opened in 1934 from the United States via the Bell System were as follows: a direct circuit between San Francisco and Java, Java previously having been served from the United States on an interconnected basis through London; and a direct circuit between Miami and Baranquilla, Colombia, forming the second circuit to that country, the first having been established to Bogotá in 1934.

Existing services to Europe from both the United States and South America have been augmented by extensions to Algiers, Tunisia, the city of Beyrouth, Syria, and the city of Saigon, Indo-China. Existing services to India and Palestine have been augmented to include the remainder of the important cities in those countries. Some radiotelephone extensions have been made in Egypt.

On December 8 of this year, the Bell System will open a new direct high-frequency radiotelephone circuit connecting San Francisco with Tokyo, which service will directly reach about 380,000 telephones distributed throughout Japan's most important cities. RCA Communications opened a radiotelephone service between Manila and Tokyo and added two new points to the Philippine interisland public radio telephone network.

International Telephone and Telegraph Corporation during December opened new direct radiotelephone circuits between Buenos Aires and Lima, Peru; Buenos Aires and Bogotá, Colombia; between Bogotá and Lima; and between Buenos Aires and Vatican City. These additional facilities in South America will greatly increase the reliability of service between Bogotá, Lima, and European points which are reached via Buenos Aires to the several European radio terminals located at London, Berlin, Paris, Madrid and Vatican City.

Other international radiotelephone services opened were between Tokyo and Manchukuo; Tokyo and Formosa; Tokyo and Java; Moscow and Tiflis; Bogotá and Caracas; and Bogotá and Baranquilla.

Intended primarily for experimental purposes, but being operated in the regular commercial service, is an ultra-high-frequency radio link established by the Bell System between Green Harbor and Provincetown, Mass., which points are on opposite sides of Massachusetts Bay. The radio equipment is unattended and the circuit terminals appear on the switchboards at Boston and Provincetown in such a manner that the radio link may be used interchangeably with wire toll circuits. This experiment is looking forward to providing telephone service where natural barriers make it difficult or expensive to construct ordinary telephone lines.

International Telephone and Telegraph Corporation, through its

Spanish Telephone Company, is installing a similar ultra-high-frequency radiotelephone system between Barcelona and Mallorca in the Balearic Islands. Tests have indicated that the reliability of such a system will be considerably greater than that of the existing service on longer waves established several years ago between Madrid and Mallorca.

A seventeen-centimeter wavelength circuit across the English Channel for teleprinter operation was placed in service in January, manufactured and installed by companies in the International Telephone and Telegraph group.

In England, an ultra-high-frequency radiotelephone link has been in commercial service across the Bristol Channel, and investigations are under way for similar circuits between the mainland and some of the Channel Islands.

Very effective use has been made of two-way radiotelephone ultra-high-frequency installations operating at low power, for communications between all points involved in the construction of the San Francisco-Oakland Bay Bridge, such as the individual piers in the bay. A similar system is being found valuable in the construction of the new aqueduct for carrying water over the mountains from the Colorado River to the City of Los Angeles.

With regard to these new services, entirely new radio stations were completed in 1934 by RCA Communications at Boston, Washington, Chicago, and New Orleans, with others at Seattle, Los Angeles, and Detroit, on which construction has commenced.

New stations completed by Mackay Radio and Telegraph Company are at New Orleans, Washington, Seattle, and Chicago, with construction under way for new stations at Atlanta and Kansas City. This company is also constructing a new large central transmitting station for international and domestic communication on an 1100-acre tract near Brentwood, Long Island, for the purpose of replacing overcrowded facilities at its station near Sayville, Long Island.

Press Wireless, Inc., opened during the year a new station near San Francisco for Hawaiian and transpacific service, in which locality a new receiving station has been planned. This company is constructing a new station at Washington and reconstructing its station at Chicago.

In addition to the services described, an outstanding example of long-distance radio communication during the year is that with the Byrd Expedition near the South Pole. Radiotelegraph service is direct via Mackay Radio through either its New York or San Francisco stations. Radiotelephone service used for supplying material to American broadcast stations is usually relayed via the Transradio station at Buenos Aires to RCA Communications at Riverhead, Long Island. The transmitting power at the antarctic station is about one kilowatt. A three-unit diversity receiving system is used at Buenos Aires. Occasionally when transmission conditions are favorable, the relay at Buenos Aires is dispensed with and the signals received direct at Riverhead, Long Island.

The domestic radiotelegraph circuits operated in the United States by RCA Communications and Mackay Radio and Telegraph Company offer a class of service for which the same charge is made for a minimum of fifteen words as is made by the wire telegraph companies for ten words.

Press Wireless, Inc., has recently inaugurated a newscast service which consists of simultaneous telegraph transmissions on two or three high frequencies occurring two or three times a day for periods of from one-half to one hour's duration each. At present, this service is supplied by Radio Press Bureaus on a paid multiple address message basis and is received by broadcast stations at from 85 to 92 points widely distributed in the United States and Canada, and employed as material for news programs. This service is now operated from New York and may also be established later for transmission from San Francisco.

Globe Wireless, Inc., inaugurated a new deferred radiotelegraph service between San Francisco and Honolulu and Manila, featuring the pick-up and delivery of telegrams at the terminals by mail.

Technical advances during the year have been, in general, largely along the lines of improving existing plant and adapting previously made developments to commercial operation, rather than in the introduction of radically different methods of communication or of operation.

The tendency toward higher powered short-wave transmitters for transoceanic communication has continued, and a number of large transmitters were installed during the year. The larger short-wave telegraph transmitters, now in operation, have actual radio-frequency outputs of the order of fifty kilowatts with eighty kilowatts developed and still higher power under investigation. The larger short-wave radiotelephone transmitters have carrier outputs of about twenty kilowatts capable of 100 per cent modulation.

The need for increased power is being particularly felt on the New York-European circuits to improve the reliability of communication during periods of magnetic disturbance. This area is one of those most vulnerable to such disturbances which is of interest since it is also the seat of the greatest radio communication activity. Special power amplifier tubes capable of providing fifty-kilowatt high-frequency power output per tube are under development. The trend seems to be towards steel-tank type mercury-pool polyphase rectifiers rated at several hundred kilowatts having voltage outputs from 14,000 to 20,000 volts, to supply the anode power for operating the large power amplifier tubes. Mackay Radio and Telegraph Company installed such a rectifier at Palo Alto, California, in July, and RCA Communications have an installation under way at Rocky Point, Long Island, these equipments being of American manufacture. Some important European stations utilize similar rectifiers of European manufacture.

Together with the general trend toward higher power, there has been a very consistent increase in transmitter frequency stability throughout the stations of the world. As a result, high-frequency transmitters generally are now operating with considerably closer tolerances than those recommended by the Madrid Convention. In this country, the recently developed zero temperature coefficient crystal cut is providing a simplification of transmitter frequency control by greatly reducing frequency variations due to crystal temperature changes.

Class B high level audio modulation developed several years ago, has been increasingly applied to radiotelephone transmitters and developments have been made in methods of screen-grid and pentode-grid modulation. The "Compandor" and similar devices have found extended use on several radiotelephone circuits to adjust automatically the transmitter input level in response to variations in speech intensity. Average transmitter modulation is thus increased and the received signal-to-noise ratio improved.

There seem to have been no striking developments in receiving methods. The use of diversity reception continues and the closer spacing of transmitter frequency assignments made possible through improved frequency stability has urged forward the design of more selective receivers. Crystal type filters in superheterodyne receivers have attracted interest. RCA Communications reports the adoption of a triple detection superheterodyne receiver utilizing two intermediate frequencies, making it possible to adjust its response to the band width required for the type of service involved.

A definite trend has been noted towards the automatic operation of transmitters and in some cases receivers, particularly at small unattended stations. This trend is most pronounced in the case of ultra-high-frequency communication apparatus.

Printer operation of radiotelegraph circuits is receiving attention. During past years, both Mackay Radio and RCA Communications have operated successful circuits of this type, the former between Los Angeles and San Francisco, California, and the latter between San Francisco and Honolulu. RCA Communications this year placed in service a two-channel multiplex printer system on its New York-London circuit. Each channel operates normally at a speed of fifty words per minute. That company has developed and used a three-channel multiplex printer system normally rated at a speed of sixty words per minute per channel.

Mention is made of the newly developed facsimile transmitting and receiving system named the "constant frequency variable dot" system, which was recently described before this Institute, and which is now in operation on transoceanic and other long circuits, resulting in a marked improvement of the picture transmission services available to the public.

Much attention has been given to ultra-high-frequency equipment and wave propagation phenomena, primarily for the development of short distance communications in the fixed services. Such systems are capable of transmitting wide communication bands, and are particularly suited for short-distance work where the direct wave only is employed and signal strength variations are minimized as reflections from the ionosphere do not play a part. Special measuring equipments have been developed and transmission studies as short as seventy centimeters and lower are under way.

Special systems employing stable master oscillators and power amplifiers with harmonic generators to multiply the frequency to the desired value have been successfully developed, RCA Communications in particular reporting a power output of 115 watts at a wavelength of seventy centimeters having been thus obtained.

The present tendency in the design of high gain directive high-frequency antennas is to avoid too great a directivity in the vertical plane. Power gains of the order of nineteen decibels above a single half-wave radiator are considered reasonable. Where applicable, aperiodic types of directive high-frequency antennas are in much favor, having the distinct advantage of being useful on any one of a number of different frequencies as well as being unidirectional. Such antennas are desirable where traffic requirements do not justify expensive antenna investments but where more than one frequency must be employed.

Concentric tubular transmission lines for high-frequency antennas continue to be employed. Low loss lines of this type sufficiently flexible to be wound on reels and suitable for burying directly in the ground like power cable have been developed in Germany.

A great deal of interest has been directed towards the study of the transmission medium, the structure of the ionosphere, and its influence on wave propagation. A considerable mass of observed data and derived conclusions has been published, including much speculation as to the mechanics of wave travel. Communication organizations are studying these factors and seeking to correlate them with the results secured in their commercial operations. There is promise that the reliability of radio communication circuits will be improved when these studies have been advanced to a more conclusive stage.

In this connection, the cycle ascribed to sun-spot activity, which is believed to account for the gradual downward shift of the workable frequency spectrum observed for the past few years, is being closely watched, indications being that a reversal in this cycle has occurred.

During the year, the third meeting of the C.C.I.R., or International Radio Consultative Committee, was held in Lisbon. These meetings have been a great aid to international radio communications not only by providing a forum where technical questions of consequence to operating organizations could be discussed among experts, but by promulgating opinions serving as technical operating standards or practices of minimum requirements capable of being met by any one reasonably well versed in the art. The Lisbon meeting, like its predecessors, has promulgated such opinions for future guidance, besides reviewing opinions issued at former meetings and making modifications and substitutions where necessary, to harmonize with new knowledge and advanced experience.

Acknowledgment

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RADIO DEVELOPMENTS DURING 1934*

Part II—A Review of Radio Communications in the Mobile Services

By

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Summary—*In this paper a brief review is given of recent engineering progress in various classes of mobile communication. The principal applications of radio in the mobile services are in the marine, aviation, and police fields. Improved circuits, new tubes, more advanced mechanical design, and better knowledge of the characteristics of short waves have all contributed to a greater extension of mobile radio services.*

Many changes have taken place recently in mobile systems and equipment, largely because of new engineering developments or new and broader applications. In this paper a résumé is given of progress in marine, aviation, police and similar fields where radio is usually the only means of rapid communication.

One of the earliest commercial applications of radio was in the maritime field. Safety of life at sea was and still remains one of the important objectives. In addition message traffic relating to the ship's business or for use of passengers soon reached considerable proportions. The shipboard radio installation at first was rather crude judged by later standards. Vacuum tubes were unknown. The radio transmitter was a spark set, using some form of spark gap in combination with coils and condensers to produce high-frequency oscillations. The radio receiver used a coherer at first, then a little later rectifying crystals provided greater sensitivity. Even with such equipment ranges several hundred miles were possible and safety at sea was greatly enhanced.

When vacuum tubes became available for transmission and reception the range and utility of shipboard stations were broadened considerably. Modulation methods were also devised so that telephony as well as telegraphy could be used.

By about 1925 all of the larger ocean-going liners were equipped with intermediate- and long-wave apparatus, which enabled communication to be maintained with one or more shore points while en route. Smaller vessels, freighters, tankers, etc., were fitted with less expensive

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and lower powered equipment and on long voyages were dependent on relaying or very favorable transmission conditions if ranges of more than 1500 or 2000 miles were to be covered.

The next major step to advance marine communication was short-wave development. Transmitters which provide a range of eighteen to fifty-four meters as well as longer waves were installed on many large vessels. Vessels on round-the-world voyages have been able to maintain contact with the United States every day by working with powerful shore stations on the east or west coasts of this country.

As in other fields, marine radio has been required to meet depression demands for inexpensive equipment. Legal requirements affecting safety of life at sea, international radio regulations and transmission efficiency could not be curtailed. The engineering problem was quite unlike that involved in the design, say, of a midget broadcast receiver to meet a certain price class. However, new marine equipment is now available for small or medium class vessels which provides intermediate- and short-wave service at a moderate expense. Using such equipment, the small passenger or cargo vessel is assured of ranges of 300 to 500 miles with intermediate-frequency operation and a range of about 500 to 3000 miles on the high-frequency channels.

One aspect of marine radio which has been followed actively abroad is the auto alarm receiver. This device actuates a bell or other alarm upon receipt of a signal consisting of three or more consecutive dashes, each dash being four seconds long with a one-second space between dashes. The apparatus must function in the presence of code signals on the same frequency and during moderate static. Ships which do not maintain a continuous operator watch are therefore able, with the auto alarm, to cover the 500-kilocycle distress wave. Several hundred auto alarms are in service on foreign flag vessels. When the United States ratifies the Safety of Life at Sea Convention or enacts similar legislation we may expect to see American designs of auto alarms installed on ships of this country.

Facsimile radio has recently received considerable public attention. Weather map transmission to ships at sea has been under active development during the last few years. A simple carbon paper type recorder is used and the weather map is reproduced in about twenty minutes. The United States Weather Bureau prepares the map daily from data transmitted from a selected number of ships which report weather conditions in their respective areas.

Ship-to-shore telephony is now available on several of the larger passenger liners. Small vessel telephone equipment designed particularly for fishing trawlers, tugs, etc., has been advanced considerably, especially in European waters. Rather simple and inexpensive equipment is used abroad and well over 300 vessels are now fitted with low power telephone sets. In the United States, apparatus for this class of service is more elaborate, provides more accurate frequency control, and being more expensive has not yet reached the same degree of commercial application as in Europe.

The radio direction finder has been an important aid to navigation in the marine field for several years. Improved equipment is now available. Sensitivity and selectivity of the direction finder receiver has been increased. Simple controls to permit sharp null points and sense of direction are used. The use of the null or minimum signal characteristic of a loop and the extension of other services near the radio beacon channels impose severe requirements on the selectivity of a radio direction finder. Frequently when a loop is adjusted for a null or bearing point on a marine beacon it is in a position of maximum response to an interfering signal. New designs of direction finders provide a discrimination factor of one hundred or forty decibels to interfering signals removed by four kilocycles.

In the field of aviation radio in the United States, the service may be divided into two general classes; namely, the Federal radio aids to navigation, and the air lines private communication systems. Federal facilities provide broadcasting of frequent weather reports and also radio range and marker signals to keep planes on their courses. Radio range equipment using the equisignal system has been continouusly improved. In the equisignal system a course or range is laid down between airports by using the intersecting patterns that result when transmission takes place when two loops (or their equivalent) are placed at right angles.

The first radio range installations used the aural or interlocking A–N signals with headphone reception. This arrangement is still in general use. In addition the visual or vibrating reed system has been developed. The visual unit uses two or more tuned reeds, is more free from interference than the aural method, and can be mounted on the instrument panel for easy inspection by the pilot.

Experience with the radio range using crossed loops at the transmitter has shown that errors due to night effect are quite pronounced at even moderate distances. This is due largely to radiation from horizontal parts of the loops. Recent developments have shown that this night effect may be greatly reduced by transmitting with an improved Adcock antenna system. In this system four spaced vertical tower antennas are used, diagonal pairs of antennas being fed by a shielded transmission line.

Radio aids for blind landing, while not yet in extensive use commercially, have been actively developed. An ultra-short-wave landing beam with auxiliary signals to indicate to the pilot when to begin his glide, has been successfully demonstrated. Recently the Army Air Corps blind landing system has been adopted as standard by the Bureau of Air Commerce.

In the Army Air Corps blind landing system, use is made of two small automobile truck transmitting stations. In addition, each truck is equipped with a small secondary transmitter which, operating in conjunction with a second instrument located near the radio compass indicator on the airplane instrument board, causes a light to flash as the airplane passes over each ground station. Thus the pilot, having arrived at a predetermined point by means of the radio loop compass, is informed of his arrival by the visual marker's light flash just described.

In actual operation the two trucks are driven to selected points on the road network surrounding the landing area, and assume positions along a line projected across the field in an into-the-wind direction. Whereas the relative distances of these positions from the field border may be varied to suit conditions of terrain, wind, etc., a convenient combination for most conditions with a Ford trimotor is 1500 feet, and two miles from the field border for the inner and outer stations, respectively. The pilot flying in by instrument from some distant point may, when within thirty or forty miles, tune in on the inner station and fly directly to it by means of his radio loop compass. His momentary arrival over the inner station is indicated by the light flash of the visual marker instrument. He immediately tunes in the different frequency of the outer station and flies to it by the same means. One or more interstation trips serve to establish accurately the desired into-the-wind course, which is then clocked on the directional gyro. In the preparation for the final approach, the pilot lets down to approximately eight hundred feet as indicated by his sensitive altimeter, and heads toward the field, passing over the outer station at this altitude. Immediately on passing this station, the engines are throttled and the airplane by instrument is held in a power glide of such angle as to enable it to pass over the inner station at an indicated altitude of about one hundred fifty feet. Once the final marker light flash has been received, the pilot is through with radio loop compass and marker, and through with altimeter. Reverting to his directional gyro for course, he relies on his flight instruments to maintain the glide angle before mentioned.

The private communication systems of the air transport companies use short-wave telephone sets in the airplanes and at the ground stations or combination telegraph and telephone sets where greater ranges are necessary, such as long flights over water. Recent developments in the airplane equipment include more rugged and lighter apparatus, receivers remotely tuned by a small motor and improved selectivity for weather and radio range signals. The greatly increased speed of modern transport planes has resulted in a tendency to eliminate the usual fixed transmitting antenna, which introduces considerable wind resistance, and to replace it with the older form of trailing wire antenna. Unlike the original trailing wire antenna, no end weight is used and the antenna is not reeled in and out but is allowed to drag along the ground during take-off and landing.

Police radio communication is now quite well known to the general public since many broadcast receivers have been designed to receive the police frequencies. Nearly all radio systems now in use for police service operate in the 1600- to 2500-kilocycle band. Interference between stations due to a limited number of channels and due to the long interfering sky wave range has resulted in new activity to apply the ultra-high frequencies in the thirty- to forty-megacycle range. These ultra-high frequencies have the advantage of relatively short range, together with the possibility of permitting two-way communication by installing compact transmitters and antennas on the patrol cars Some difficulty is encountered with the ultra-short waves due to increased shielding from building or other large structures in cities, and it is possible that these conditions may be overcome by the use of directive antennas at the headquarter's transmitting stations. We may visualize several directive arrays with automatic switching so that police alarms for cars in a particular sector may be reinforced to cover that area more effectively.

There are now over four thousand patrol cars equipped with radio receivers, in a total of about one hundred and twenty-five municipalities, so that it is evident that this form of mobile communication is one that has grown rapidly in a few years. If further development with the ultra-short waves shows that two-way communication is not economical or causes excessive interference, we may expect to see advances in record communication. Small tape printers which will furnish a continuous record of received messages in each patrol car have been developed and might provide greater secrecy and would enable continuous-wave transmission to be used in lieu of telephone modulation.

Radio communication has not as yet been applied commercially to the field of railroad transportation in this country. About eight years ago fairly extensive tests were made of front-to-rear communication on long freight trains. A hundred-car freight train is nearly a mile long. Switching cars in and out of the train, reporting hot boxes or other mechanical difficulties to the engineer, would all be facilitated if rapid two-way communication were possible between the locomotive and the caboose. In the early tests fifty-watt transmitters working around one hundred meters were used. More recently less expensive ultra-high-frequency equipment of a few watts power has been developed and tried on the railroads with success. However, unless it can be shown that definite savings in train operating costs result, applications probably will be limited.

A number of other applications of mobile radio have been developed in recent years. Short-wave transmitters and receivers installed on trucks are used by the Government for emergency service in connection with flood control. Forest rangers employ radio in communicating with one another over areas where wire-line construction would be difficult. Prospecting parties engaged in geophysical work use low power transmitters operating in the 1600- to 1700-kilocycle band. The increased activity in developing portable ultra-high-frequency transmitter-receiver units will undoubtedly result in many other short distance applications, such as on large farms, construction camps, and in motor boats.

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RADIO DEVELOPMENTS DURING 1934*

PART III—BROADCAST TRANSMISSION DEVELOPMENTS AND PROGRESS DURING 1934

BY

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AND

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THE RADIO broadcast engineer, working behind the scenes so to speak, played a highly important part during the past year in disseminating material of great cultural, economic, and informative value to the people of the world. Seated at his control console, he has guided the voices of statesmen, philosophers, singers, and reporters of great news events to the millions of loud speakers. Ranging the field of research, he has made possible the transmission of fine music with ever-increasing fidelity of tone and harmony.

Among the specific developments which have made the engineer's part in broadcast transmission so notable in 1934, have been the increased use of short-wave facilities to extend the scope of the international exchange of program material, continued improvement in fidelity of reproduction, development of the world's highest powered broadcast transmitter at WLW, Cincinnati, installation of antenna systems of greater efficiency, and collection of extensive field survey data. Of singular interest this year has been the more extensive use of low powered short-wave transmitters such as were employed by the Columbia Broadcasting System in its transmission of the first Arctic-to-Antarctic broadcast, by the National Broadcasting Company in its programs from the schooner, *Seth Parker*, and by both networks in the broadcasting of such sport events as America's Cup Yacht races.

Program Material

The extensive "behind-the-scenes" activity of the engineers not only made such unusual broadcasts possible, but also brought to the American radio audience for the first time programs from Norway, Russia, Egypt, The Holy Land, Rhodesia, and India. Among the

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notable broadcasts of the year which were brought to radio listeners on long- and short-wave channels were: the New York Philharmonic Orchestra; the Wedding of the Duke of Kent in London; the Stratosphere Flight; the important Steeplechases and Horse Races from England; the Wagnerian Music Festivals from Bayreuth, Germany; the Eucharistic Congress in Buenos Aires; the Celebration in Tokyo of the birth of an heir to the throne; the Easter Services from Windsor Castle, England; Shakespeare's Birthday Party from Stratford, England; Arrival of President Roosevelt in Hawaii; Bastille Day Celebration from Paris, France; the Paladium Theatre Command Performance from London; Livingstone's Memorial Services from Africa; Von Hindenburg Memorial Services from Berlin, Germany; Dolfuss' Funeral from Vienna, Austria; Armistice Day Programs from New York, London, Prague, Rome, Ottawa, Rio de Janeiro, and Tokyo; World Series baseball games; the popular football games; and the weekly program from the world's most remote broadcast studio—the Byrd Expedition's base in Little America. Talks were broadcast by prominent world figures, including President Roosevelt, King George of England, the President of France, His Holiness, the Pope, Chancellor Hitler, Chancellor Dolfuss, Premier MacDonald, the Prince of Wales, Prince George of England, Senator Marconi, Sir Oliver Lodge, the Archbishop of Canterbury, President Von Hindenburg, Premier Mussolini, and Eamon de Valera.

This is only a partial list of the many events of world-wide interest that have been brought to the broadcast listener through the ingenuity of the radio engineer, but it serves to indicate the extensiveness of the international network. There can be no question but that the worldwide distribution of programs of this nature creates a better understanding between the peoples of a nation and their fellow men throughout the world.

Numerous events which took place in the United States, and which were of international interest, were transmitted to many foreign countries for rebroadcasting by local administrations. There is today a smooth-working and established system of exchanging programs with many broadcast administrations throughout the world.

Wherever a pioneer explores, we are reasonably certain radio will send back to the civilized world a story of his experiences, whether it be in the polar regions, in the stratosphere, or in the depths of the sea. All this is made possible by the radio engineer facing each new problem squarely and finding a solution for each one.

Some of the most worth-while developments which took place during the year were not spectacular nor were they given much publicity.

Some of these developments, however, made possible the handling of important broadcasts. Few people, except those directly engaged in such work, can appreciate the valuable accomplishments by engineers in arranging and setting up equipment for picking up important events like the Metropolitan Opera from the stage, the so-called "stunt" programs, the devising and installing of equipment on airships, steamships, championship golf courses, boat races, etc. The engineer is ever conscious of whatever defects may exist and is striving to improve the pick-ups. He has made possible the greater enjoyment of the symphony orchestras, the operas, and programs in general.

Broadcast Station Equipment

The progress made during the past year in utilizing higher powers and, particularly, the construction of the 500,000-watt station of WLW required a great deal of pioneering by the engineers. It was a big step to take—from 50,000 watts to 500,000 watts. It required the solving of engineering problems in all phases of transmitter design. One outstanding achievement in this connection is the sectionalizing feature which permits the shutting down of a portion of the transmitter for repairs or tube replacement without interruption to the program.

In general, the performance characteristics of the better broadcast stations have been, for quite some time, entirely satisfactory. During the past year, however, a number of new broadcast transmitters of various sizes, having exceptionally good characteristics, have been placed in operation throughout the country.

In addition to the development of a new series of broadcast transmitters there has been made available considerable speech input equipment which is completely alternating-current operated, as far as the power supply is concerned. This equipment, which obviates the need for batteries, charging generators, etc., has proved itself entirely satisfactory in all respects, and its more general application in the future is anticipated.

High quality microphones and amplifiers especially intended for remote, or field pick-up service have been developed and are being used at all the large broadcast centers. This equipment is readily portable, extremely rugged in construction, and provides sufficient amplification to permit the use of low level, high quality microphones for remote pick-ups.

A number of new, easily operated, accurate measuring instruments have been developed in order to facilitate the operation of the broadcast plant at its optimum efficiency, and to maintain the high fidelity of transmission which this equipment is capable of producing. This apparatus permits the broadcast engineer readily to determine the exact performance of his equipment at all times and to maintain it at its best operating condition.

Broadcast Antennas

Among the important developments of the year is the increase in the amount of research and experimental work being conducted on the broadcast antenna and the sometimes neglected ground system. Stations have come to realize that the efficiency of a radiating system is an essential function of good station operation.

The marked inefficiency of some of the older types of antenna systems is now generally recognized and considerable progress is being made in the replacement of these structures with more efficient radiators. These developments have resulted in higher signal intensity at the listener's home, increased service area, and a reduction in the "mushing" zone wherein fading and distortion is caused by the interference of sky wave and ground wave. All these improvements have been obtained with little, if any, increase in operating or maintenance cost.

A great deal of work was done in devising equipment and means of measuring the performance of antennas. In some cases airplanes were used to obtain measurements of waves radiated in the vertical planes. Extensive experiments with models were made to check theory.

During the past year a number of directional antenna systems have been installed at broadcast stations throughout the country. There are several reasons why it is necessary to employ such systems. They may be used for the purpose of obtaining specific interference reduction while still rendering a maximum public service or the geographical location of the station may be such as to permit a more effective coverage of the populated area by the use of a directional antenna system.

The nature of each installation depends upon the prevailing conditions and the requirements to be fulfilled. In one instance the radiation pattern was modified merely to the extent that the radiation in certain directions is reduced to one half while in all other directions it is normal. At another station, which is located between the two areas it is desired to service, a figure-8 pattern is being employed. At still another station it is necessary to suppress the radiation in one particular direction. In this case, while the radiation in practically all directions is equal to that of a 10,000-watt station, the signal intensity in the direction of the desired suppression is equivalent to that of less than a four-watt transmitter.

Field Surveys

In connection with increasing radiation efficiency of antennas, this last year has seen many field strength measurements made. Station managers have become increasingly aware of the value of such measurements, not as a means of determining the practical audience of programs, but to plot the areas of potential service to listeners. These measurements, when sufficiently extended, provide an electrical picture of where the station can be heard, irrespective of the habits of the actual listeners.

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PART IV—A REVIEW OF RADIO BROADCAST RECEPTION DURING 1934

BY

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THE YEAR 1934, so far as broadcast reception is concerned, has lived up to a number of the well-established traditions of the industry, and has marked a continuation of several of the pronounced trends of the past few years. Happily for the manufacturers, however, and probably for the public as well, it has managed to reverse at least one trend which could not have led to anything short of disaster if it had continued.

It is probably safe to say that the engineers who have been retained in the industry's first-line trenches have never worked harder than during the past year. It is therefore all the more important to examine the results of their efforts, and to record their accomplishments. It is apparent, if it were not inevitable, that they have been addressing themselves to increasingly difficult problems, and that, at least in the main, the advances they have made lie buried beneath a maze of technical complication which their own executives, not to mention the public, do not and cannot fully appreciate. What the executives do understand and appreciate is that, while other industries continue to lag, the business of making and selling broadcast receivers is enjoying a healthy increase.

Each year since 1923 at least twenty per cent of the firms in the industry have discontinued. 1934 has been no exception to this rule. At least fifty-seven manufactures of broadcast receivers which were active during 1933 failed to appear in 1934. This has been partly offset, as has also been the rule, by the appearance of a number of new firms, the actual number starting in 1934 being 36. The total number of receiver manufacturers as of December first was 110 as against 131 in 1933. In that year, nine firms did 74 per cent of the dollars business, leaving 122 firms to share the remaining 26 per cent. The situation at the close of 1934 will not be widely different. Apparently there is no greater optimist in the world than a radio manufacturer.

In the first eleven months of 1934, a total of 1510 different models

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have been offered to the trade, an average of almost fifteen models per manufacturer, and over five per day for every business day in the year. These figures are to be set beside the figures of 1933 which show 1557 models offered by 131 manufacturers, and then compared with the earlier years back to 1923, none of which show such large totals. The most profitable year the industry has known, 1929, had only 627 models. One can imagine the bewilderment of the intending radio purchaser if faced with the entire array of these 1500-odd models, occupying, as they would, an entire floor in a large department store

There are several reasons, of course, for this offering of thirty new models every week. But it seems safe to conclude that the underlying cause is our failure to determine, even after fourteen years of broadcasting, just what a broadcast receiver should be. We are still changing the device in its basic specifications, and if with this has come refinement in electrical and mechanical design, these have been the necessary results of the changes we have made, rather than the principal accomplishment of our plans and policies. Some day we shall look back upon these years and see clearly our present lack of decision on the fundamental aspects of our products. It is the engineers who must make these decisions and who will soon come to see the necessity for them.

Trends of the past few years which are continuing in 1934, and which may ultimately lead to the solution of some of the problems on which experimentation still proceeds, must be recorded. Console models, for example, were 62 per cent of all offerings in 1932. In 1933 they had fallen to 55 per cent and in 1934 the figure will be about 36 per cent. There is an unmistakable trend in the direction of the table model, in spite of its inferior acoustic properties. This can only be the result of public response to this type, since there has been ample time for an unfavorable reaction, if there was to be one. The increasing popularity of table models has its relation to the high fidelity program, which will be discussed later.

It is to be noted that the table models as a group include both the so-called midget types, which made their first important demand for popularity in 1930, and the so-called chest types, which were unimportant before 1932. The smaller and cheaper forms of the chest type have pretty well disappeared, while the size and beauty of the midget types have increased. Thus the majority of table models are these better and larger midgets, and they represent a very considerable advance, not only in appearance but in technical detail, over similar models of earlier years.

Other types which are appearing in increasing numbers are phonograph combinations, and battery models. The phonograph combinations are increasingly of the automatic type. At least 25 per cent of the manufacturers have included phonograph combinations in their 1934 lines. This figure compares with 14 per cent in 1932 and 19 per cent in 1933. With the new efforts now being made to sell records, we may look for a further increase in phonograph combinations in 1935.

The number of universal AC–DC models is slightly higher in 1934 than it was in 1933. The increase, however, is small, and seems to indicate that this type is receding in the direction which its technical limitations would make desirable.

The statistics regarding vacuum tubes are interesting and encouraging. Only four new receiving tubes, and three new ballast tubes, were introduced during 1934. In 1933, which represents a peak in this particular class of experimentation, forty-one new receiving types were produced, and in the receivers of that year fifty-three different types of tubes were employed. The extent to which last year's program of uncontrolled expansion still haunts the industry is reflected by the fact that radio service men are today calling for 216 different tubes. The engineers are to be congratulated upon the degree of coördination and coöperation between tube and set designers which has resulted in this marked reduction in the introduction of unnecessary tube types in 1934. This is only one example of the ways in which the engineers can and must concern themselves with industry policies, to the mutual advantage of all.

The trend toward a reduction in the number of tube types, with the possible future standardization on perhaps one tenth of the number now being produced by the tube manufacturers, deserves the serious support of every engineer. The utilization of any one of the types now available must include a consideration as to whether that type is one which ultimately can be discontinued. The 1934 models do not show much regard for this aspect of the problem. There is an obvious tendency to use a different tube in every socket, and to increase the number in the largest receivers. The receivers of 1932 had from four to fifteen tubes. In 1933 the spread was from two to seventeen tubes. In 1934 there are one-tube models and there are twenty five-tube models. As against this, however, the average number of tubes per set is decreasing. The average 1933 receiver had eight tubes, while the average 1934 receiver will have only six tubes. This is probably because for each new model having an increased number of tubes, several models with only a very few tubes make their appearance.

The let-up in the race to produce new tube types has given the tube engineers time to produce important improvements in design and construction of the established types, and in production and testing technique. Notable progress has been made, for example, in the elimination of microphonic action. The dome-shaped bulb, introduced in 1931, has been utilized more effectively to provide rigid top support for the elements. Resilient mica pads or spring wire clips fastened to the top mica spacer press against the dome walls. The support of the heater filament has also received attention, and new filament materials have been developed. Side hooks or damping wires are used in some types to arrest vibration. Improved automatic welders have been developed which greatly increase the reliability of the welds by almost completely eliminating the personal factor of the operator. These changes have resulted, not only in greatly reduced microphonic trouble, but also in the now almost universal practice of shipping the tubes in the sockets.

It is probably true that the tube manufacturers employ a larger number of engineers per unit of product than any other branch of the industry. More and more the performance of the broadcast receiver is being built into the tubes. It is no longer left as something to be coaxed out of the tubes by clever circuit design. The elimination of interelectrode capacity in 1929 marked the beginning of an effort to remove all those difficulties which arise in the tube. This effort has continued throughout 1934 and the coöperation between tube and receiver engineers has been increasingly intelligent and fruitful.

The price of broadcast receivers has increased remarkably and most encouragingly, and this increase appears to have stimulated, rather than retarded sales. From the best figures available, it seems certain that 1934 sales, measured in units, will be at least 15 per cent in excess of the 1933 total. Measured in dollars, the increase will be considerably greater, if Christmas sales come up to the expectations of the retail trade.

Average advertised prices, which of course do not take into account the actual number of each model sold, may be taken as the best measure of price changes available at this time. These figures show that the average price of all types of home receivers rose from $48.28 in 1933 to $59.60 in 1934, an increase of over 22 per cent. The average of the lowest prices has increased only very slightly, the major portion of the advance having taken place in the medium and better grade models. The average of the highest prices in all lines, for example, is $110.40 as against $76.52 in 1933, an increase of almost 45 per cent.

Models that cover only the broadcast range have actually decreased in average price, and are selling approximately 10 per cent below the 1933 figures. The great gain has been in the multiple-band receivers. The gain has also been particularly in the table models of the midget type, although the chest types also show a healthy upward movement. Average prices for console models, on the other hand, have increased only a little over 6 per cent. Automobile receivers, not included in the figures just given, have increased in average price only a little over 4 per cent.

The public response to the multiple-band types leaves no doubt that the engineer has achieved a very great increase in the performance capabilities of the instrument, and in the services and satisfactions to be derived from it, at only a very moderate increase in cost and price. The improvement is worth many times what it costs.

It is obviously impossible to discuss, except in the broadest outline, the technical features which distinguish 1500 different models, even if we note that the same chassis is used, on the average, in three models, and that there has been a marked tendency, this year, to use the same chassis in a table model and in a console. In many cases where this has been done, a larger speaker is employed in the console to provide better fidelity and to help justify the higher price, without, however, any change in the chassis itself.

In broad outline, then, the most notable technical advance in the receivers of 1934 has been in the expansion of the frequency range. This is no new feature, since extended range receivers have been produced every year since 1926. But 1934 marks the first attempt to exploit world broadcasts as the main sales argument, and it has met with very gratifying success. It has its political and social implications, which are of great importance, and the public response to the all-wave types bespeaks an increasing world curiosity and consciousness which the radio engineer has fostered and fed, and which statesmen, the world over, must reckon with.

In 1932 only 47 per cent of the manufacturers offered models covering more than the American band. In 1933, 75 per cent of them had such models, and in 1934 only the smallest firms were still holding back, 91 per cent of the lines including extended-band receivers. Seventy-five per cent of the 1934 models are multiple-band types.

The expansion of the frequency range has brought with it a host of new and difficult problems for the engineer. Not all of these have been finally solved in 1934, but such marked advances have been made that the year must be recorded as marking the conquest of the range from 500 kilocycles to 20 megacycles, with notable examples down to 140 kilocycles and up to 36 megacycles. The American broadcast frequency range has a ratio of less than 3 to 1. In the all-wave models, this ratio increases to 40 to 1, and in some models that ratio is as high as 250 to 1. Thus the frequency range has been expanded from 14 to

85 times, and the difficulty of the technical problems which the engineer has had to solve are probably roughly in proportion to these figures.

The first problem to be solved was that of coil design. It is one thing to choose values for a fixed inductance and a variable capacity which will tune over a 3-to-1 frequency range, and to develop an efficient inductance for this purpose. It is quite another problem, however, to redesign the inductance so that with appropriate switching it may be tuned over a 40-to-1 range with the same variable condenser. Yet in many of the all-wave models, this is the arrangement used.

The second problem was the design of suitable switch gear. Here the requirements were far more difficult than in any earlier radio switching mechanism. It was necessary, in an all-wave model, to accomplish at least twelve circuit changes with a single knob, and yet keep the capacities introduced by the switch itself, as well as its contact resistance, at very low values. This result was accomplished by building the switch in units, one of which could be located near each coil, the several units being operated by a common shaft with a suitable knob.

The varying ideas of the many designers, represented in the 1500 models, made it necessary for the switch manufacturers to produce designs that were capable of almost limitless combinations in the circuit changes they could produce. This they have succeeded in doing, in ways that are not only electrically satisfactory but remarkably small and inexpensive as well. The problem was at least as much a matter of mechanical as of electrical design, and the ingenuity displayed speaks well for the mechanical skill of the industry's engineers.

The indicator has been a problem in itself. When there were only the ninety-six channels of the American band to be shown, the expedient of frequency numbers, with a calibration of only reasonable accuracy, was sufficient. With the number of channels greatly increased, and the requirements for accurate frequency readings much more severe, it was essential that new types be produced. The answer, so far as the great majority of models is concerned, was the airplane dial. This was not new in 1934, because it had been used extensively in European receivers before that, and it has also appeared on a relatively small number of earlier American models.

The indicator and the drive gear were almost entirely a mechanical problem, as were the switch gear and the compact arrangement of a multiplicity of coils and trimmer condensers. The various mechanical necessities associated with the coverage of several frequency bands have caused a very high degree of skill in mechanism to be put into the 1934 designs. Moreover, perhaps as the result of the increased complexity of the apparatus itself, the excellence of the mechanical design throughout the receiver has increased noticeably in 1934. It has been said, probably with considerable justice, that radio was still mechanically crude. Much of the basis for this criticism has been swept away in the 1934 designs, and the year probably marks the greatest advance in perfection of mechanical detail that has so far been made.

1934 has seen the all-wave program well launched. If the gains that have been made are to be consolidated, if public interest in international broadcasts is to be maintained, if the sale of all-wave apparatus is to continue to increase, then still further improvements and refinements must be made in 1935. Additionally, the number and quality of the short-wave programs must increase. Our neighbors across the sea are already taking advantage of listening American ears. They must go forward with this work. The engineer, who has created this new service, must carry on, until reception in the added bands is just as perfect, from a technical standpoint, as on the domestic frequencies.

Another and perhaps even more ambitious advance has been launched during 1934, although only a relatively small number of manufacturers have as yet offered models which include it. This is the "high fidelity" program which has received so much attention in the Institute, in the Radio Manufacturers Association, and in the radio press. The progress which has been made in the laboratories, but which has not as yet found its way into the product, cannot be here discussed for obvious reasons. It seems safe to say, however, that increased audio-frequency response with negligible distortion will be among the chief features to be stressed in the 1935 sales campaigns.

The high fidelity models already released provide some insight into the problems involved. It is apparent, for example, that flat response even to 10,000 cycles, cannot be tolerated under all receiving conditions. This will be true at least until much has been accomplished in the broadcast stations to improve the quality of the program as radiated. The requirement in the receiver, therefore, is that there shall be either manual or automatic control of band width, and preferably also of sensitivity, in addition to the usual level control and the quite common tone control. The result, in some of the models already released, is a marked increase in the number of control knobs, with labels to identify them. It seems safe to expect that this practice will again become common, but if present offerings are an indication, it can be done in such a way as to enhance, rather than detract from, the appearance of the instrument.

Since high selectivity and high fidelity are not compatible, so long as frequency assignments to broadcast stations are made on the present 10-kilocycle basis, expedients have been developed during 1934 to vary the admitted band width. Most of these are based on the principle of introducing absorption circuits to broaden the response in the high fidelity position. Interesting networks of this type have been developed and are now in production.

Much progress must be recorded in the development of loud speakers having a reasonably uniform extended range. These new speakers are of both single and double unit types. Several excellent demonstrations of the performance of these improved speakers have been given during the year, before the Institute and other bodies, and the results are already available. Acoustic treatment of the cabinet to develop the full capabilities of the new speakers is also a noteworthy step in the high fidelity advance.

It must be remembered that the effort to secure high fidelity reproduction did not begin in 1934. It has been going on for years, almost since broadcasting began. The importance of the present campaign lies not in any single technical advance, but rather in a coördinated and coöperative engineering program, in whose benefits all will share. The ideal performance is at last receiving systematic study, and all the factors which affect it, many of which are outside the receiver itself, are being examined. The progress toward the ideal can therefore be organized into a logical plan.

This paper would not be complete if it failed to lay final emphasis upon the profound social significance of the advance into the realm of international broadcasts. The engineers, by making the all-wave receiver a commercial possibility, have made much more than a mere contribution to the prosperity of their industry. It is always an easy matter for the historian to look back upon the scientific advances of former years, and see what their effect has been. It is important for us, however, as we review the progress of 1934, to realize that with the increasing use of all-wave receivers there will come an increasing international understanding and good-will, that cannot fail to bear fruit in amity and peace.

The radio engineer first provided a new means of communication that spanned the gap to previously isolated points. He made his great contribution to the safety of life at sea. Then came his entrance into the field of entertainment, with a new cultural influence that has made its lasting mark upon the ritual of the American home. He created, in the space of a few years, a new legion of music lovers, and he brought the satisfactions of music to thousands more who long had loved it, but to whom it was otherwise inaccessible. In the realms of domestic politics, he brought our great men to our firesides, so that we could learn to understand their personalities and policies. From these excellent beginnings, the radio engineer has turned his space waves to account in the work of the police and the detection of crime, in communication with aircraft and safety in aviation, and in many other needful and beneficient services. His is a glorious tradition.

But in his gift of international broadcasts, by which the soul of all the world is laid bare, and nations can no longer make a successful secret of their plans and ambitions, the radio engineer may well find his deepest satisfactions.

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RADIO DEVELOPMENTS DURING 1934*

Part V—Progress in Fields Allied to Radio During 1934

By
Keith Henney
(Managing Editor, *Electronics*)

In the allied fields of sound motion pictures, public address systems, recording and reproduction of sound on disk and film for use in theaters, in broadcasting or in the home, and in the growing industry built around the use of vacuum tubes and circuits for purposes other than communication, progress has been steady but not startling. The large research groups continue to search out and develop new methods, new apparatus, and new uses for the existing technique.

Noiseless recording, characterised by the fact that when there is no sound on the stage, or in the studio, there is no sound from the loud speakers in the motion picture house, has undergone some change and considerable improvement. The elimination of background noises of the type that used to assail the ears of theater patrons during the supposedly breathlessly silent periods of the drama increased by the same ratio the volume range of sound that could be reproduced. Therefore the heavier sound portions of the recording could be reproduced with a volume more nearly that actually present in the recording studio.

During the year new microphones of the velocity, moving coil, and crystal type made their appearance. These were of benefit not only to broadcasting and the motion picture art, but to the recording of music for later reproduction in the home. To some extent they have been employed in public address and announcer systems as well.

Electrically-cut phonograph records are being sold in increasing numbers. Combination radio-phonographs are now found in the lines of most radio manufacturers and actually seem to be taking hold with the public. The vertically-cut records of wide volume and tone range and long playing time are still unavailable to the public. It is hoped that the beauty of these acetate records will ultimately be made available to the home and the school.

Continued development in pick-up units has aided the home and the broadcast studios that use electrical transcriptions.

To a very limited extent music is being sent into hotels and restaurants by wire. In some parts of the country well-organized

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services of this type exist, but nowhere to the extent that it has been practiced abroad. So far as the home is concerned, there has been little endeavor to sell program services via wire lines.

Loud speakers continue to develop but too slowly to keep up with progress in the remainder of the art. Wide-range speakers have been demonstrated during the year, notably the Olsen speaker of RCA Victor. For wide tone range it is still current practice to use two or more speakers. One is the conventional dynamic speaker covering up to perhaps 2500 cycles per second and the other speaker is a small unit handling the higher frequencies. This is commonly known as "tweeter."

The acoustic labyrinth of Olney of Stromberg Carlson is an interesting advance of the year. More efficient loading of the loud speaker is effected so that the over-all system is more efficient. In addition the response to lower frequencies is enhanced, even though the cabinet is comparatively small.

One momentous and stirring undertaking has come to fruition during the past year. This is the making of the "talking book" for the blind. The machine as it is being sold is a combined radio and phonograph playing disk records. The machine is easily portable, operates from direct and alternating current, has a tone quality comparable to the better midget receivers, and is sold for cost, practically, by the American Foundation for the Blind. The tuning dial is engraved in Braille characters so that the sightless can read, accurately, the position of the pointer, more accurately in fact than can the seeing with the average American brand of tuning dial.

For the 114,000 blind in the United States, this process of making available the world's literature must be a godsend. The national government is making the records and loaning them to the blind, and they are transported to and from the user without cost to him.

Miss Helen Keller is soon to speak before the forty-eight state legislatures in a campaign to give to the meritorious these machines free of cost. The present campaign calls for approximately two thousand machines in each state to be purchased by the individual states.

In the realm of public address, several events of international importance occurred during the year, each made audible to vast throngs of people. Hitler is reported to have addressed a half-million listeners at one assembly. The Eucharistic Congress in Buenos Aires was a good example of what sound projection can accomplish. At this assembly there were over one million in attendance and yet all could hear the proceedings.

During the year there were a number of kidnapings. At least one of them, the Goettle case, was aided in its solution by apparatus in common use by radio and sound engineers. Here a microphone and recording machine were installed in a place known to harbor criminals. The police were looking for someone else, but found the kidnappers.

During the year a new type of loud speaker was developed and installed on the Coast Guard ship *Tampa*. It was used at the International Yacht races to handle the ocean-going traffic. The human voice by this device can be projected over distances of several miles. At the mouth of the horn the sound volume is reported to be greater than that of Niagara Falls. Sound pressures of one pound per square inch were reported.

Very recently moving pictures were sent from Australia to England in what was probably the most expensive news reel ever filmed. This was the scene of the Scott-Black plane landing in Australia, winners of the race from London. The film was enlarged sufficiently to be sent via radio-photograph transmission to London where the individual frames were reduced and finally projected in moving picture theaters. The cost of the transmission was reported to be $4950 per foot of film.

During the year the application of vacuum tube technique to problems of industries other than communication continued at an accelerated pace. Phototubes, cathode ray tubes, amplifiers, rectifiers, thyratrons, and grid-glow tubes all are finding their way into industrial plants and laboratories. Counting, sorting by color or weight or size, protection of life, limb, or property from all manner of hazards, control of motors, change of electrical power from one form to another, control of temperature, humidity, or of manufacturing processes all are benefiting as engineers outside the radio field learn that a vacuum tube is a device of greater application than radio alone.

During the year a notable advance in tube manufacture was recorded. This is the all-metal tube. In the past industrial men considered a glass vacuum tube fragile, and of too short life to be considered for use in a factory. These new all-metal tubes should be most valuable in dispelling such ideas. They do not look like vacuum tubes. They look like sections of conduit or stove pipe with pigtail connections hanging out the ends. They look strong and unbreakable, like in fact, a piece of factory equipment. They are being engineered in all sizes and types of tube and to have lives of three years or more on continuous duty.

One of the most important uses of tube outside communication has been in the control of welding processes. In this case the tube-controlled welder has been of considerable serivce in making the tubes themselves. Here a tube is literally used to make a tube.

The use of vacuum tube technique to aid the medical profession has been extended. The electric knife, an oscillator, is capable of salvaging many lives irretrievably lost to the older operating methods. Treatment of various diseases by electrical heating has been extended. Many hospitals now consider an "artificial fever" machine an ordinary piece of equipment.

The talking book has a corollary in the work done to aid the hard-of-hearing. During the year considerable advance has been made in hearing aids using amplifiers. Bone conduction experiments have been markedly successful not only to enable people to hear better but in many cases to be improved permanently in hearing.

All manner of vacuum tubes and circuits are being used by industrial engineers. A number of radio men, finding it difficult to secure employment in their chosen industry, have turned their knowledge of vacuum tubes to good service in other industries. It is felt that radio and communication engineers should not overlook the possibilities of utilizing their knowledge in this expanding field.

No survey of the activities of the year would be complete without a hasty look at the industry as a whole and of the place of the engineer within that industry. Wireless is only about thirty-five years old; Marconi sent his first messages in the years around 1899–1900. In November, 1899, he installed apparatus aboard the *S. S. St. Paul* and actually received news reports aboard when the ship was fifty miles from Needles. This was indeed a remarkable event at the time. Today a great portion of our newspapers are printed from radio dispatches; some of them are actually printed by radio facsimile.

In 1920 there was no KDKA. And yet in 1933 the annual business of the portion of the industry related to broadcasting was of the order of $200,000,000—a growth of extraordinary extent in a space of fifteen years. The attached figures give an idea of the present extent of the radio business.

This industry is based entirely upon engineering. Each advance is the product of engineering brains, and there should be more recognition of the vital part played by the engineers than there actually is. Somehow or other, it has come about in the radio industry that the engineer is not well thought of by the commercial interests. His part is not clearly recognized, and this is reflected in the remuneration he receives.

This situation where the sales personnel is more highly paid than the engineers is not unique to the radio industry, but data on comparative salaries indicate that in no other industry where the engineers have equivalent responsibilities are they so badly treated. In smaller companies the engineers are frequently hired and released immediately they have designed the various models the manufacturer wishes to

TABLE I

INDUSTRIES BASED ON THE VACUUM TUBE

Telephone	
Tolls from long lines plus fees from associated companies	
1915	$ 6,544,462
1933	86,695,109
Radio Receivers and Tubes	
September 1921 KDKA began broadcasting	
1933 radio receiver sales, units	3,806,000
radio receiver sales dollars	130,899,000
1933 radio receiver tubes, units	63,295,000
radio receiver tubes dollars	56,599,000
Sound Motion Pictures	
1926—Al Jolson and the Jazz Singer—first popular "talkie"	
1933 gate receipts	$495,000,000
Number of theaters	12,500

TABLE II

RADIO COMPARED TO OTHER INDUSTRIES

Industries	Value of Product—1931
Radio	$ 193,000,000
Clocks and Watches	45,000,000
Refrigerators	144,000,000
Automobiles	1,567,000,000
Aircraft	40,000,000
Household Washing and Ironing Machines	51,000,000
Cigars and Cigarettes	968,000,000
Optical Goods	28,000,000
Photographic	80,000,000
Electrical Machinery, Except Radio	995,000,000

TABLE III

THE RADIO INDUSTRY OF THE UNITED STATES

	Total Investment	Annual Gross Revenue	Number of Employees	Annual Payroll
Radio manufacturers,[1] distributors, etc.	$ 150,000,000		[2]75,000	$ 80,000,000
Broadcast stations	30,000,000	$75,000,000	9,000	30,000,000
Listeners' sets (18,000,000 homes)	1,800,000,000			[3]210,000,000
Commercial ratio stations	30,000,000	10,000,000	15,000	4,000,000

[1] 165 manufacturers.

[2] Employees at peak of seasonal employment.

[3] Annual operating expense of listeners sets for tube replacements, electricity, batteries, servicing, etc.

AUTOMOBILE RADIO SETS	
Units made, 1933.	724,000
Value at retail (average $39.50).	$28,598,000

RADIO SET COMPONENTS	
Cost per set for selected parts	$6.08
Total annual market	$22,000,000

RADIO RECEIVERS	
Unit Sales, 1933	3,806,000
Midgets	2,226,000
Consoles	856,000
Auto radio	724,000
Total value, retail (less tubes)	$130,899,000

RADIO TUBES	
Tubes, made, 1933	63,295,000
Exported	7,690,000
Sales in U.S.	55,605,000
Total value sales in U.S. at retail	$56,599,000

sell. Then the engineer must find another manufacturer who wishes to buy, for as short a time as possible, the experience, training, and knowledge of this same engineer. It is true that in a few of the larger companies the engineers share in the profits, but this is the exception rather than the rule. It seems certain that since ten of the 135 manufacturers in the radio receiver business do 75 per cent of the business, the chances of an engineer making much more than a living are remote.

This trouble probably originates with the engineer himself; he enjoys his work, he is a young man, still unwilling to take a larger share of responsibility in the company for which he works. To advance higher than the grade of engineer, which rates low in the minds of the company owners, the engineer must think more highly of himself, must be willing to consider problems other than straight engineering. He must get a broader view. Then perhaps the company will feel that the engineer is some one more than a queer fellow who likes his job.

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SOME DATA CONCERNING THE COVERAGE OF THE FIVE-MEGACYCLE STANDARD FREQUENCY TRANSMISSION*

By

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Summary—*Beginning in January, 1931, the Bureau of Standards has transmitted a standard frequency of 5000 kilocycles per second each Tuesday for two hours during the day and two hours at night. These transmissions have for their purpose the furnishing of an accurately known frequency to the public. They are used especially for calibrating the frequency standards of the field offices of the Federal Radio Commission and engineering and testing laboratories. At the request of the Bureau reports were sent in showing how satisfactorily the transmissions were received at many places in the United States. A study of about 2900 reports was made, covering a period of about two years during which a 1-kilowatt transmitting set was used. This transmitter has since been replaced by a more powerful one. The weekly reports indicated that at some time during the weekly transmission periods, satisfactory reception was obtained at all localities reporting, except when prevented by electrical storms or electrical interference.*

I. Introduction

FOR more than ten years the Bureau of Standards has transmitted standard frequency signals. Beginning January 6, 1931, the Bureau has transmitted a standard frequency of 5000 kilocycles per second each Tuesday for two hours during the day and two hours at night. The endeavor has been to furnish this service so that frequency standards located at any place in the United States might be checked conveniently by comparison with these transmissions. One purpose among others was to furnish standard frequency service to the Federal Radio Commission's radio inspectors located in a number of the large cities. In order to find out how well the transmissions were received throughout the country, in 1931 requests were made of several Government departments and others to send reports to the Bureau describing reception of these transmissions. About 2900 reports were received, covering reception of the small 150-watt transmitter used at first and the 1-kilowatt transmitter used until April, 1933. A 30-kilowatt transmitter[1] has been used for the transmissions since April,

* Decimal classification: R555. Original manuscript received by the Institute, March 26, 1934. Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[1] The radio transmitting sets used for the transmissions are described in the paper, by L. Mickey and A. D. Martin, "Development of standard frequency transmitting sets," *Bur. Stan. Jour. Res.*, vol. 12, p. 1; January, (1934). RP630.

1933, but this paper includes data only on the transmissions with the earlier 150-watt and 1-kilowatt transmitters.

The most widespread set of reports were those submitted by the former Airways Division, Bureau of Lighthouses, Department of Commerce, as furnished by the radio operators at the various Airways radio stations. The Airways Division reports cover a period from February, 1931, through March, 1932, except for the months of May and June, 1931. Many reports were received from Army and Navy stations located at various points in the United States. The reports, including some from commercial organizations and from individuals, give considerable data on the reliability of reception and the distance range of reception for the 5000-kilocycle transmissions when a transmitter with a power output of not more than 1 kilowatt was used.

The data which have been assembled cover a period from January, 1931, to December, 1932, during which time the standard frequency station was located at College Park, Maryland, eight miles northeast of the Bureau's main laboratory. While the data do not cover this period as completely as might be wished, yet taken as a whole they give interesting information. During the period covered there were 180 transmissions of two hours each.

The hours of transmission were changed somewhat during this period. The transmissions were made at the following times:

January to June, 1931,	1:30– 3:30 P.M. 8:00–10:00 P.M.
July to October, 1931,	2:00– 4:00 P.M. 10:00–12:00 midnight
October, 1931, to April, 1932,	2:00– 4:00 P.M. 8:00–10:00 P.M.
April, 1932, to October, 1932,	2:00– 4:00 P.M. 10:00–12:00 midnight
October, 1932, to April, 1933,	10:00 A.M.–12:00 noon 8:00–10:00 P.M.

The interpretation of the hundreds of reports received was difficult, in that no two observers described the reception conditions in the same way. Some observers gave comments on weather conditions, for example, and omitted an estimate of the relative intensity of the reception. Such reports were accordingly of no value in determining even the relative intensity of reception for that date at that location. The reports were tabulated after an effort was made to express them in the same terms. In order to do this a method similar to the FRAME quality-of-signal code of the Radio Corporation of America was used, with some changes and additions.

II. Results

1. *Relative Intensity.* Approximately 2900 reports were received from 80 points in the United States. In many cases the reports were not complete or numerous enough to furnish full data for the 23-month period. The reports were assembled and the relative received intensity for day and night reception, on a scale of 1 to 9, were plotted for each locality for all transmissions reported. In this manner it was usually evident whether a day transmission or a night transmission was received with greater intensity. In some cases the two transmissions were received equally well. These data, when plotted on a map of the United States, showed some sections reporting best reception in the day, other sections reporting best reception at night, and other sections reporting no difference in day and night reception. Reports were not received from enough localities, however, to determine these different areas with any exactness.

The data indicate that the following general statements may be made. The strongest daytime reception was observed in an area having a radius of about 500 kilometers (or 300 miles), although reception suitable for frequency measurements was obtained during the day up to a distance of about 800 kilometers (500 miles). Points beyond obtained best reception at night.

The data do not show any changes in the above general statement with respect to season. This may be due in part to the method of averaging the data for the two-hour periods, and to the fact that some of the data submitted cover only a portion of the two-hour period. For example, the transmission may have been observed for fifteen minutes, during which time a strong signal was heard and was reported accordingly; an hour later the signal might have been much weaker, which if taken into account would have given a lower signal intensity number to plot for that transmission. However, all the data submitted were used, in order to have as complete a picture as possible of the peculiarities of these transmissions noticed at various points.

2. *Fading.* The data submitted regarding the fading experienced on the 5000-kilocycle transmissions were averaged in the same manner as the data on relative received intensity. The data were then plotted, on a scale of 1 to 9, for day and night for the various transmissions. These charts were then examined to see which localities showed less fading in the daytime, and which at night. A few localities were found

where the data indicated no marked difference in fading between day and night. These various points, when plotted on a map, showed even less definite area boundaries than those for relative intensity previously mentioned.

Most of the eastern quarter of the United States experienced less fading during the day transmissions than at night. Less fading was experienced at night in the Mississippi River Valley and west thereof (although very scant data were available from farther west because the signals could not be heard during the day). The locations from which the most data were submitted showed no variation in fading with respect to season.

3. *General Discussion.* The other information sometimes given in the reports, regarding musicality of note, atmospheric disturbances, interference, and use for measurement, amplified the reports and in some cases explained why the transmission was not successfully heard.

A number of interesting features were brought out in the study of the data. In the western part of the country the received intensities increase as the two-hour evening period progresses. During part of the year the beginning of the transmissions sent from 8 to 10 P.M., E.S.T., reached the west coast about the sunset hour there, with the result that during the first half hour of the transmission the standard frequency signals could not be identified, but the intensity of the signals increased to a maximum during the remainder of the time. This result would be expected. In the eastern part of the country, in general, the received intensity is approximately constant during the two-hour evening period. In a few cases, however, the intensity decreased in the latter part of the period, the reverse of the condition noted in the western part of the country; this may perhaps be attributed to a combination of circumstances including changes in the ionosphere layers, and differences in the angles of incidence of the waves on these layers.

The data show no evidence of a "skip" distance for the times at which the transmissions took place. This is in agreement with most previously published information on the subject,[2,3] although Ladner and Stone[4] present curves showing a skip distance for 5000 kilocycles of about 500 kilometers (300 miles) for late night. Data were available from six cities at distances between 465 and 528 kilometers from the transmitter. Night transmissions were not heard at Williamsville, N.Y. (480 kilometers), one evening in October, one evening in No-

[2] Chester W. Rice, "Short-wave radio transmission and its practical uses," *QST*, vol. 11, p. 8; July, (1927); vol. 11, p. 36; August, (1927).
[3] "The Radio Engineering Handbook," p. 442, (1933).
[4] "Short-Wave Wireless Communication," p. 48, (1933).

vember, 1931, and one evening in March, 1932. Serious interference was responsible for the latter failure to hear the transmissions from 8 to 10 P.M. Some interference and atmospherics were present on the other two evenings. Observations were made but one day per month there. Reports received for March and July, 1931, from Williamsville, showed that the night transmissions were received with greater intensity than the day transmissions.

Weekly reports from Columbus, Ohio (528 kilometers), indicated that with but few exceptions the day transmissions were received with greater intensity than the evening transmissions. The failure of two evening transmissions to be heard satisfactorily could be attributed to atmospherics. Reports from Albany, N.Y. (490 kilometers), were similar to those from Columbus. A limited number of reports from Buffalo, N.Y. (465 kilometers), showed little difference between night and day transmissions, while reports from Schenectady, N.Y. (495 kilometers), and Cleveland, O. (483 kilometers), showed better night reception than day reception.

There is accordingly little evidence in the data to substantiate a skip distance for 5000 kilocycles.

III. Conclusions

An analysis of the reports shows that the transmissions from the 1-kilowatt transmitter were not receivable at all times throughout the whole of the United States, but that during some portion of the transmission periods reception was possible at each locality except when prevented by unusual atmospherics or electrical interference. The latter condition prevails in some of the large cities and adds to the difficulty of any radio reception. This emphasizes the value of the higher powered transmitter installed by the Bureau of Standards subsequent to the period covered by these tests.

A section of the country within about 500 kilometers (or 300 miles) of the 1-kilowatt transmitting station was found to receive the strongest signal during the day. The greater part of the country received the strongest signal at night. Most of the eastern quarter of the United States experienced less fading during the day than at night.

No clear evidence of a skipped area was found.

IV. Acknowledgment

This opportunity is taken to thank the many observers who sent reports on the reception of the 5000-kilocycle transmissions, thus assisting in making the transmissions more useful. Thanks are particu-

larly due to the following organizations for the large number of reports submitted: the American Telephone and Telegraph Company; the Radio Corporation of America; the former Airways Division, Bureau of Lighthouses, Department of Commerce; the former Radio Division, Department of Commerce; the Navy Department, and the War Department.

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THE ECLIPSE OF AUGUST, 1932, OBSERVED BY RADIO FACSIMILE*

By

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(General Electric Company, Schenectady, New York)

Summary—*In connection with the eclipse of August, 1932, a good deal of interest was shown in the theory of the corpuscular shadow which was expected during the two hours before the optical eclipse. A radio receiving station equipped to take continuous facsimile records of a signal from Schenectady was therefore set up at Conway, New Hampshire. The records showed a marked change in conditions during the period of the expected corpuscular shadow. This paper contains samples of the facsimile records and an interpretation of the phenomena observed.*

A NUMBER of publications have already been made of radio observations during the eclipse of August, 1932. These observations deal mostly with measurements of the height of the reflecting layers and variation of intensity of the ionization of those layers. The evidence collected by the several observers seems to be in agreement showing that the variations coincide with the optical eclipse. No indications were, however, found of a corpuscular eclipse, which in accordance with predictions of astronomers should take place during the two hours preceding the optical eclipse. The records which are herewith submitted show a marked change in radio transmission during those two hours. The arrangement of the tests differed from those of other observers, and we are to all appearances here dealing with a different set of phenomena. There is thus no reason to assume that this evidence is contradictory to the findings of others which deal with the conditions of the reflecting layers.

The wavelength used in our test was 34.6 meters or 8655.5 kilocycles. On the other hand, the observations reported by Kenrick, Mimno, Pickard, and Wang deal with frequencies of 1640, 3042, 4540 kilocycles and a transmission distance of 25 and 100 kilometers. These observations were reported by A. E. Kennelly in a memorandum of the U.R.S.I. on October 19th, 1932. Another set of observations by Kirby, Berkner, Gilliland, and Norton[1] deals with frequencies between 1700 and 6900 kilocycles and describes local measurements in Washington and Sidney, Nova Scotia, to record the height and critical frequency

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[1] *Bur. Stan. Jour. Res.*, December, (1933); Proc. I.R.E., vol. 22, pp. 247–264; February, 1934.

of the layer. In our observations we used a frequency high enough to penetrate these layers so that reflections from the layer should not be expected. Furthermore the distance of transmission from Schenectady to Conway, N. H., was about 300 miles or 500 kilometers. A frequency for these tests had been selected so that the receiving station would be at the edge of or somewhat beyond the skip distance. This condition was chosen in the hope that the direct rays would not reach us and that such signals that we might receive would be due to irregular scatterings and reflections. These phenomena are especially apparent in television under certain unfavorable conditions where the multiple reflections cause several images, both positive and negative, which rapidly appear and disappear, suggesting a "dance of ghosts." We concluded, however, that television would not be the best medium for these observations because what we desired most of all was a permanent record so that the results could be accurately compared with other results at a later date.

In our test of facsimile transmission between San Francisco and Schenectady some years ago, we had found that the ghost images of television can also be observed on the facsimile record. Instead of attempting to transmit writing or pictures, we selected a type of signal with continuous wave radiation interrupted sixty times per second, each interruption being one five-hundredth of a second. A record of this signal gave parallel black lines on a white background if the record was perfect. The signal from Schenectady which we recorded at Conway, N. H., during normal conditions in the afternoon previous to the eclipse proved, as we expected, that we had to deal with multiple reflections. Though the signal was strong, it was of a type with rapid fadings that gives distortion of speech and music. On the record it resembles an irregular mixture of black marks on white background and white marks on black background, alternating with totally black and totally white streaks. This is the kind of signal that is particularly useless for facsimile and television; and was just what we wanted. Just what phenomena we might observe was not clear to us in arranging the experiment and we rather feared that the results would be negative because the corpuscular eclipse according to predictions would be localized over the Atlantic Ocean entirely to the north and east of our line of transmission from Schenectady to Conway, N. H. We were therefore not a little surprised when two hours before the optical eclipse the signal from Schenectady faded out completely. The change was so striking that we wondered if something had gone wrong with our recording apparatus but everything was allowed to run without any change in adjustment and the signal remained practically zero for the following two hours except for a few bursts, and remained so until shortly before the optical eclipse when the intensity rose rapidly as shown on Fig. 1. The strong peak at the very time of the optical

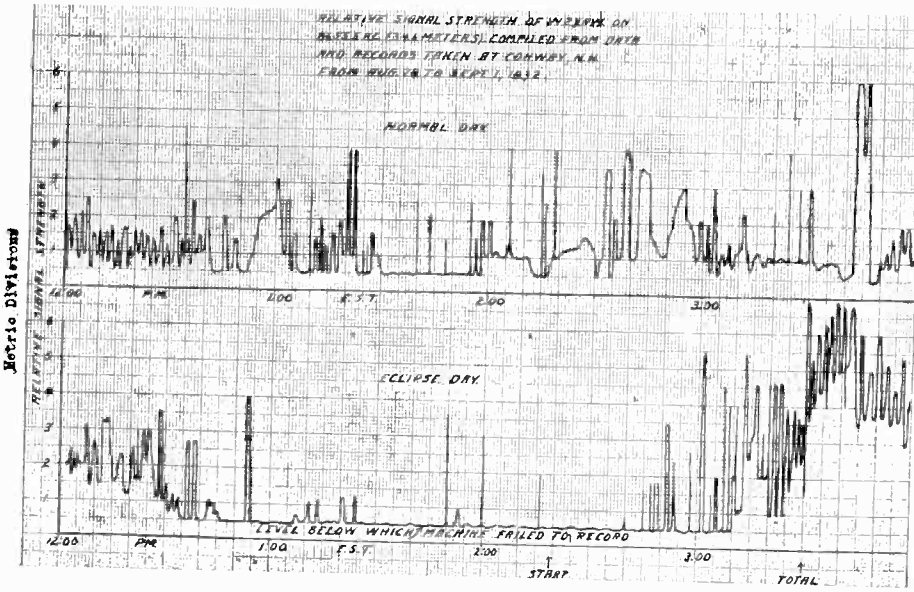

Fig. 1

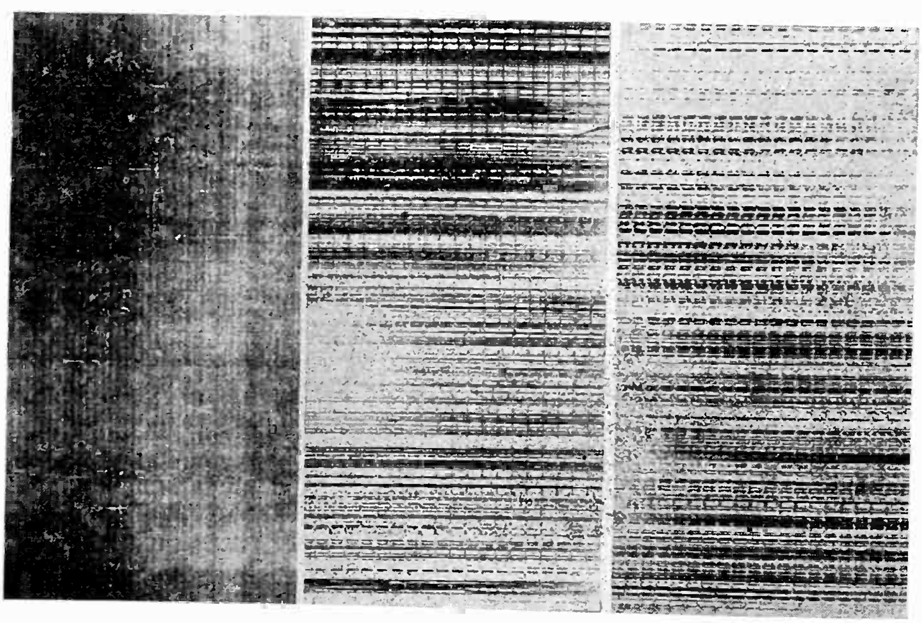

Fig. 2

eclipse may be a coincidence but the contrast between the day of the eclipse and a normal day is very striking. Photographic samples of the continuous carbon record are shown on Fig. 2. The first of these is typical for the period of the corpuscular eclipse. The two others were taken from the afternoon record after the optical eclipse. In order to check the transmission over the Atlantic Ocean where the corpuscular eclipse was expected we kept continuous watch on a German telegraphic station with approximately the same frequency and it was found that during the two hours when the signal from Schenectady disappeared the signal from Germany rose to a much higher intensity.

The observations were made by E. Phillipi and L. J. Hartley. When service was maintained whereby all General Electric office mail and copies of drawings and newspapers were sent to Schenectady by radio facsimile, Mr. Phillipi had been in charge of the transmission of facsimile from San Francisco to Schenectady for a year. Mr. Hartley had spent several years on the development of television for which we had made a variety of tests with different frequencies over different distances.

The arrangement of our apparatus for observations of the eclipse was thus based on our previous experience with television and facsimile rather than on any theory of how such observations should be made, and our expedition was undertaken largely with the hope that we would discover something accidentally. Our experience with television and facsimile, however, gave us a background for interpreting the records which we made.

In our tests between San Francisco and Schenectady we had found that the only condition under which a good facsimile record can be made is one where the signal received is a single refracted ray. Fig. 3 shows a sample of one of the pictures sent across the continent made with the same recorder as the one used during the eclipse. Fig. 4 shows the recorder. The record received in Conway, N. H., appears very different, however, and shows conditions exceedingly bad for facsimile transmission. This does not mean that the signal was not strong enough, in fact there was plenty of strength when the signal appeared, but the record shows a succession of rapid fading periods and a scattering of the markings which should lie on straight lines. One of the samples shows black markings on a white background, whereas the other sample shows a negative record with white markings on a black background. Both of these conditions are typical and alternate more or less in either television or facsimile when the signal contains two or more rays following different paths. The scattering of the markings shows that the signal has traversed a variable distance. This variability appears to correspond to a time interval of about one five-hundredth of a second which would indicate that the distance traversed varies with an amount of about 600 kilometers. From this we would infer that if the vari-

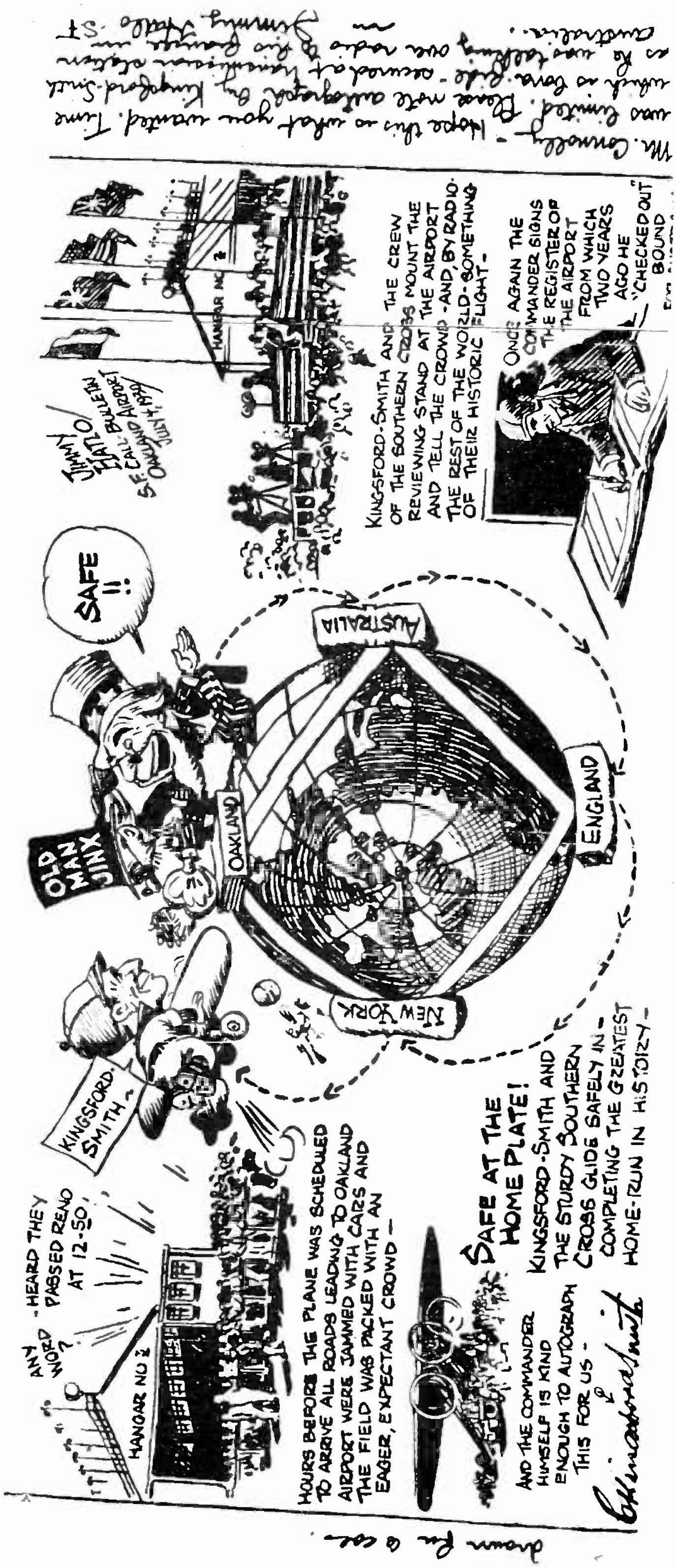
ANY WORD?
- HEARD THEY PASSED RENO AT 12-50.
HANGAR NO 2
HOURS BEFORE THE PLANE WAS SCHEDULED TO ARRIVE ALL ROADS LEADING TO OAKLAND AIRPORT WERE JAMMED WITH CARS AND THE FIELD WAS PACKED WITH AN EAGER, EXPECTANT CROWD -
AND THE COMMANDER HIMSELF IS KIND ENOUGH TO AUTOGRAPH THIS FOR US -
SAFE AT THE HOME PLATE!
KINGSFORD-SMITH AND THE STURDY SOUTHERN CROSS GLIDE SAFELY IN - COMPLETING THE GREATEST HOME-RUN IN HISTORY -
KINGSFORD-SMITH
OLD MAN JINX
SAFE !!
NEW YORK
OAKLAND
AUSTRALIA
ENGLAND
JIMMY HATLO
S.F. CALL BULLETIN
OAKLAND AIRPORT
HANGAR NO 2
KINGSFORD-SMITH AND THE CREW OF THE SOUTHERN CROSS MOUNT THE REVIEWING STAND AT THE AIRPORT AND TELL THE CROWD - AND BY RADIO THE REST OF THE WORLD - SOMETHING OF THEIR HISTORIC FLIGHT -
ONCE AGAIN THE COMMANDER SIGNS THE REGISTER OF THE AIRPORT FROM WHICH TWO YEARS AGO HE "CHECKED OUT" BOUND
Mr. Connelly - Hope this is what you wanted. Time was limited.

Fig. 3

ability in the length of the path is 600 kilometers, the total path would be of the magnitude of at least a couple of thousand kilometers. From examination of these records we thus reach the conclusion that the direct refracted ray reaching the receiving station is inappreciable. This is in accordance with our expectation from the choice of a frequency. Furthermore, we can conclude that the signal which did reach us traveled a distance of about 1000 kilometers and back again. Thus it is probable that it has been reflected at some point 1000 or more kilometers away.

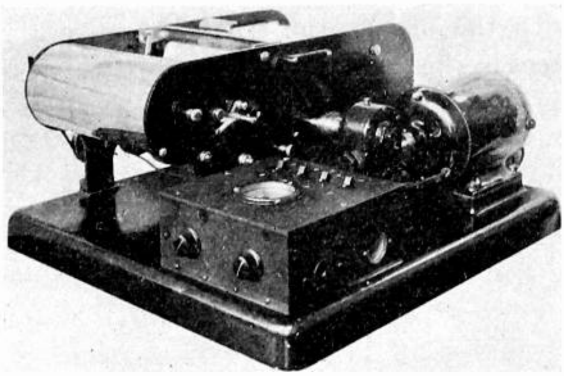

Fig. 4

This is about as far as we can go in direct conclusions from examination of our evidence and the theory of explanation which is given is a conjecture based upon this circumstantial evidence.

In attempting to interpret these results it first occurred to me that certain phenomena observed by A. Hoyt Taylor might be the guide to an explanation. In making oscillograph records of radio echoes around the world, Taylor found a discrepancy in his results which he explained by assuming that the original signal had not traveled directly from the transmitting station to the receiving station but had skipped the receiving station and was received after having been reflected from some point 1000 kilometers away. The character of our records indicates that this is the kind of signal we are dealing with. If we now assume that the reflecting medium has something to do with the corpuscular emanation from the sun, we may assume that during normal daytime conditions there are present reflecting electronic clouds and that the points from which these reflections reached us were located in the path of the corpuscular eclipse. Possibly the reflection may have something to do with the magnetic north pole which may tend to guide or localize the corpuscular emission. If now the electronic cloud disappeared during the corpuscular eclipse we should fail to receive this reflection during that period. This explanation would also be consistent with the observation that the signal from Germany increased in strength and clearness during the corpuscular eclipse. It may be assumed that the electronic clouds to the northeast of us served as an obstruction to the signal from Germany, while they reflected the signal from Schenectady, and that the clearing of the atmosphere would increase the clearness and strength of the German signal.

If it is assumed that the reflection is produced by the localization of the corpuscular emission by the earth's magnetic field this would be consistent with the observation that the aurora borealis creates severe disturbances in the transmission of short waves between Europe and America.

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NOTES ON PROPAGATION AT A WAVELENGTH OF SEVENTY-THREE CENTIMETERS*

By

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Summary—*Quantitative field strength observations have been made on a wavelength of 73 centimeters with improved apparatus. The methods are described. Propagation data have been obtained with the receiver installed in an automobile and an airplane. Further observations were made on the ground at a distance of 113 miles, 8000 feet below the line of sight from the transmitter. The results show the nature of the propagation of 73-centimeter waves over distances up to 175 miles. Below the transmitter's horizon, rapid attenuation occurs with increase in distance from the transmitter, the plane of polarization of the transmitted signal remains unchanged, and various types of fading are observed.*

THE search for new means of communication leads to propagation studies of the higher frequencies, and it is believed that the 411-megacycle (73-centimeter) range is but a stepping stone to yet higher frequencies. New uses of ultra-high frequencies have given further encouragement to these studies. Some quantitative results obtained with recently developed apparatus indicate possibilities of obtaining much more information concerning the propagation of these waves.

Early experiments were made using superheterodyne receivers utilizing oscillating Barkhausen circuits for the first detectors. With a portable receiver of this type, using a superregenerative second detector and a half-wave doublet antenna, 69-centimeter signals were heard in an airplane at distances up to 68 miles and approximately 500 feet below the line of sight from the transmitter at Rocky Point, Long Island. The signal was also heard at a distance of 56 miles and 400 feet below the line of sight on the Empire State Building in New York City. Tests in a car were made using a diamond antenna with a power gain of six over a half-wave doublet. With this equipment, the signal was heard at distances up to 30 miles and 210 feet below the line of sight. No fading was observed during these tests except when the signal was heard at a lower level on the Empire State Building, 650 feet below the line of sight. Here the signal was subject to slow fading, possibly due to reflection from a small blimp which was near the propagation path part of the time. The horizontal V type transmitting antenna was 70

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feet above the ground, 170 feet above sea level, and had a power gain of 100 over a half-wave doublet. The power input was approximately five watts.

More recently, propagation data have been obtained with a superheterodyne receiver which was a large improvement over the old receiver. This receiver used a push-pull radio-frequency amplifying stage, a push-pull detector, both employing tetrode tubes, and a 73-centimeter heterodyne oscillator using a triode vacuum tube. The tubes which made this conventional design possible were experimental models loaned to us by RCA Radiotron Co., Inc.[1] The measured gain was approximately 45 from the 411-megacycle (73-centimeter) signal input voltage to the 4.5-megacycle voltage on the grid of the first intermediate-frequency amplifier tube. The over-all gain was sufficient to make audible the noise originating in the 73-centimeter tuned grid circuit of the first amplifier stage.

This receiver was installed in a car with the small diamond antenna previously referred to, and the signal was heard practically all along the road from the transmitter at Rocky Point to Montauk Point, Long Island, a distance of 58 miles. At Montauk Point, the signal was weak and fading badly and could be heard only at intervals of a few seconds. Increasing the transmitter power to 100 watts, from 30 watts, gave a stronger signal with longer intervals of audibility. The transmitting horizontal V antenna was 70 feet high (170 feet above sea level) and had a power gain of about 80 over a half-wave doublet. Montauk Point is about 2700 feet below the horizon of the transmitting antenna.

At Highlands, New Jersey, a distance of 65 miles, on a hill 220 feet high overlooking the ocean, and 3000 feet below the line of sight, the signal was fairly steady and of moderate strength during the observation lasting three quarters of an hour. The transmitting antenna was 220 feet above sea level.

The receiver was set up at the foot of a 165-foot tower at Arney's Mount, New Jersey, 113 miles from Rocky Point. On the top of the tower was mounted a remote controlled, rotatable half-wave doublet antenna with reflector. A two-wire transmission line down the tower connected the antenna to the receiver. This antenna was 395 feet above sea level, and 8000 feet below the line of sight from the transmitting antenna at Rocky Point. The terrain between Rocky Point and Arney's Mount is relatively flat. The polarization of the transmitted signal was periodically changed from vertical to horizontal for a 48-

[1] Thompson and Rose, "Vacuum tubes of small dimensions for use at extremely high frequencies," Proc. I.R.E., vol. 21, no. 12, pp. 1707–1721; December, (1933).

hour period. The received signal was always vertically or horizontally polarized as transmitted, and the vertically polarized signal was always much the weaker. Some unknown factors stopped all reception of the signal for the last 24 hours; rain during that period may have been the cause.

In this test, the transmitter was used alternately with two identical antennas, 200 feet above sea level, one arranged to transmit vertically, and the other, horizontally polarized waves. The power radiated was the same with each antenna as indicated by a pick-up device in their beams.

On another occasion at Arney's Mount, the signal was heard over a 44-hour period, using horizontal polarization with the transmitting antenna 220 feet above sea level. During both tests the signal was continuously audible for periods of one-half minute or less, and occasionally for longer periods of not more than five or ten minutes. The periods of inaudibility varied from part of a second to several minutes. The fading varied from a fraction of a second to several minutes per cycle. Violent bursts of signal with a temporary change to more rapid fading were observed during the sunrise and sunset periods, especially just before sunrise. However, until more observations are made, we do not conclude that the sunrise and sunset periods are critical to 73-centimeter propagation. It was noticed that the night signals were much stronger than the daytime signals. Incidentally, we have as yet observed no selective fading on these ultra-short waves.

The transmitting antennas used had a power gain of 100 over a half-wave doublet, and a power input of about 30 watts.

Observations were made in an airplane with a standard shielding harness on the electrical system. The diamond receiving antenna used, was terminated with a suitable impedance network to minimize ignition pick-up from the direction of the motor, without affecting signal pick-up from the opposite direction. The ignition shielding and antenna damping gave a total reduction in the ignition interference of approximately 38 decibels.

Observations were made with the Rocky Point transmitter radiating horizontally polarized waves on a V antenna having a power gain of 100 over a half-wave doublet. Careful flying was necessary on the part of the pilot in order to stay on the narrow beam.

While flying away from the transmitting antenna, along its beam, data were taken to give field strength variations with distance at a constant altitude. Fig. 1 shows these data corrected for the error caused by the vertical directivity of the transmitting antenna.

Up to eight miles the data taken were very erratic because the vertical directivity pattern of the transmitting antenna consisted of many ears with zero points in between. The lowest zero point comes at an angle of six degrees, or at a distance of six miles at an altitude of 3400 feet. Consequently, the data were not plotted at distances up to eight miles.

The wavy nature of the curve is the result of the combination of the direct ray and the ray reflected from the ground. Nearly all of the ground reflection took place, in this case, within a few miles in front of the transmitting antenna since its height was only 120 feet above

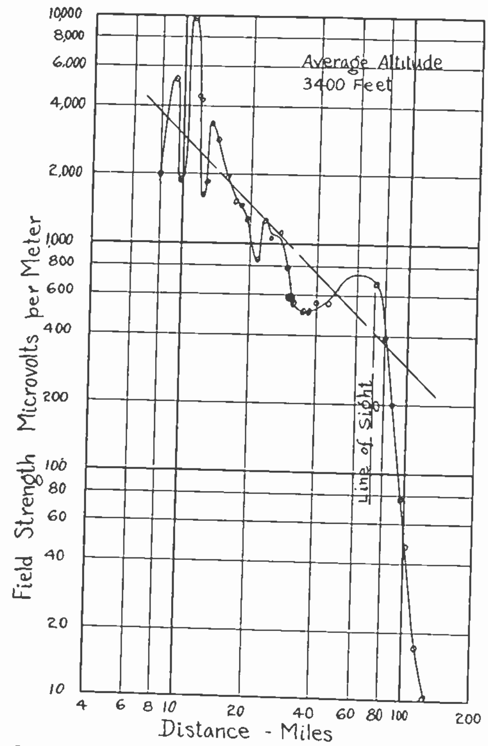

Fig. 1—Data taken in airplane along beam of transmitting antenna. 73-centimeter transmission.

ground. Correlation between the maximum and minimum points observed, and those theoretically predicted was rather difficult because of the uneven and sloping nature of the country directly in front of the transmitting antenna. However, fair agreement was obtained.

Inspection of Fig. 1 shows the rapid attenuation experienced with distance beyond 80 miles at which the airplane was below the line of sight. This attenuation occurs nearly as the inverse ninth power of the distance.

The dashed line in Fig. 1 is drawn in with a 45-degree slope representing the average of the data taken up to 80 miles. The 45-degree slope shows the attenuation to be linear over this distance which agrees with the theoretical calculations. The actual field strength values observed are nearly one fifth of those expected from this particular transmitting system. Frequency modulation at the transmitter caused the signal to sweep in and out of the relatively narrow selective response of the receiver, giving a correspondingly smaller output reading, which accounts for most of the error noted above.

Field strength measurements were not made beyond 125 miles because the signal was too weak to measure with the ignition interference present. However, the tone modulation could be heard through the ignition, and the signal was audible up to 172 miles. Between 140

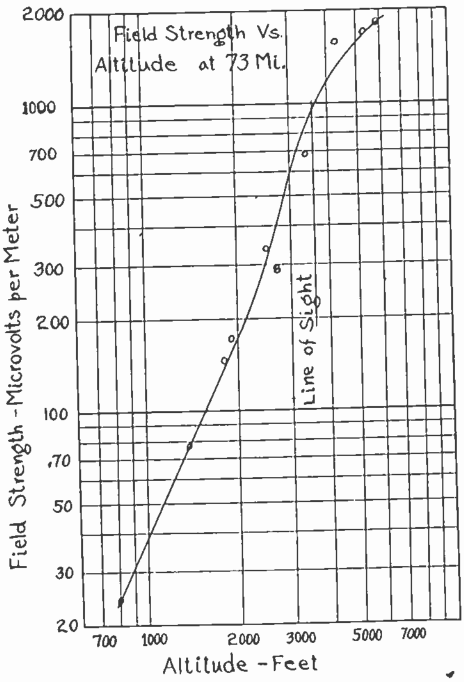

Fig. 2—Data taken in airplane at 73 miles. Field strength vs altitude. 73-centimeter transmission.

and 172 miles fading was observed, which was quite violent at the greater distances.

Fig. 2 shows the results of data taken at a distance of 73 miles at various altitudes. At this distance, the airplane was able to go above the line of sight and it may be observed that the rate of increase of field intensity is dropping off in this zone.

Fig. 3 shows the results of data taken below the line of sight at a distance of 113 miles at various altitudes. Comparison between this curve and the previous one shows the field intensity to increase with altitude at a greater rate at the more distant point.

For field intensity measurements, the receiving system was calibrated in terms of microvolts per meter and a special field generator was built for this purpose. The general principle used was to calculate the field strength set up at various distances by an antenna of known height having uniform current distribution. The voltage across this antenna was measured by a vacuum tube voltmeter, care being taken to measure the true voltage as nearly as possible by the use of low inductance leads and a special triode vacuum tube.[1] The current was readily determined from the antenna capacitance and the known

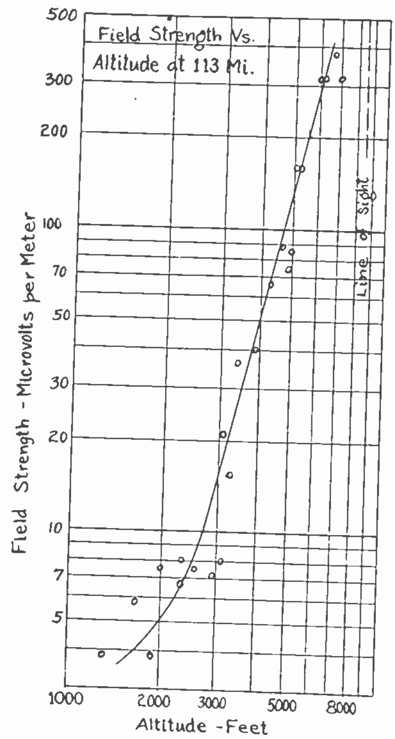

Fig. 3—Data taken in airplane at 113 miles. Field strength vs. altitude. 73-centimeter transmission.

voltage across the antenna. The field intensity resulting from the direct radiation to the receiving antenna was calculated from the known values of current in the antenna, its effective height, distance, and wavelength.

The field generator, Fig. 4, is a portable instrument completely shielded in a metal box which contains the triode oscillator[1] and batteries, and a separately shielded compartment for the vacuum tube voltmeter. The antenna consists of a thin circular plate ten centimeters in diameter spaced one centimeter from the top of the box. This gives an antenna of known effective height. The antenna is supported by a central metal post insulated at its base through which is fed the antenna current from the oscillator.

A suitable location for calibrating the gain of a receiving system in terms of field intensity would be one where the reflection from the ground was negligible, leaving only the direct wave which is known. Such a location is generally impractical and reflection from the ground must be allowed for, as was done in the calibration of our receiving systems. The procedure followed was to mount the field generator several wavelengths above the ground on an insulated support, and to move the receiving system away from it, measuring the maximum and minimum values of the received signal and the respective distances while keeping the receiver output constant.

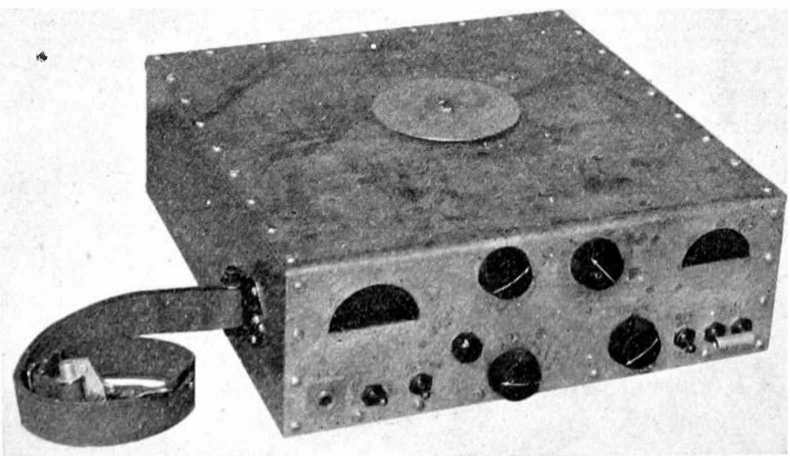

Fig. 4—Field generator showing antenna.

A typical curve obtained by such a procedure is shown in Fig. 5. The dashed line drawn through the average of this curve gives the input to the intermediate-frequency amplifier corresponding to the direct field radiated by the generator. This line indicates a linear attenuation with distance, with no ground reflection, which agrees with the theory. The lower line shows the calculated field radiated by the generator to which the intermediate-frequency input is proportional. This relationship gives a calibration of the intermediate-frequency gain control with field intensity since the relation between the intermediate-frequency input and gain control setting is known.

This is but one of several methods of procedure that may be followed in calibrating a receiving system with a standard field intensity generator. One advantage obtained by the use of such a generator is that the receiving system is calibrated as a whole, including the characteristics of the antenna and transmission line. It was assumed from experience with similar types of receivers that the output of the ultra-high-frequency unit of the receiver was proportional to the input for the range of voltages encountered.

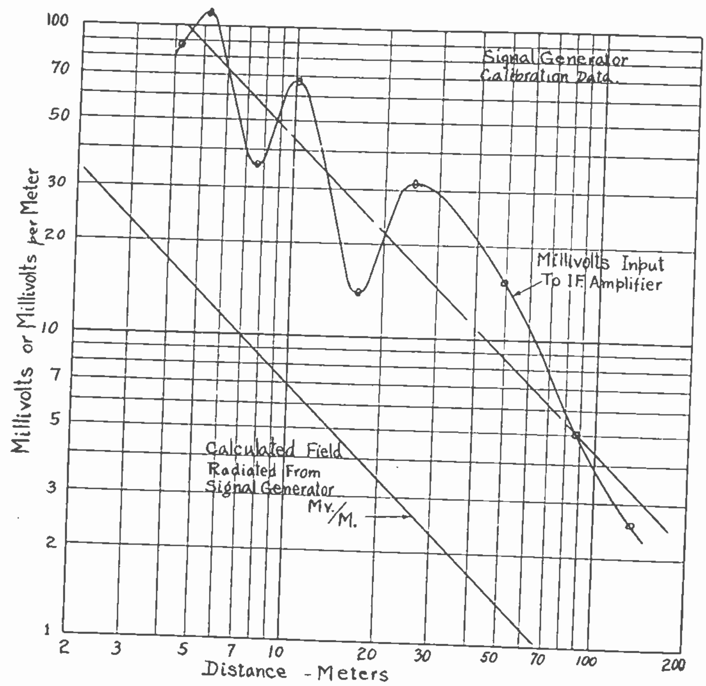

Fig. 5—Sample of data used in calibrating receiver with field generator.

Conclusion

Several significant characteristics of 73-centimeter propagation are apparent.

The attenuation increases very rapidly with distance below the line of sight. Other observations indicate less rapid attenuation of lower frequencies below the line of sight.[2]

No shift of polarization of either vertically or horizontally polarized waves has been observed as far as 8000 feet below the line of sight.

Increased fading occurs with distance below the line of sight.

Observations so far have shown that the horizontally polarized waves are received with greater intensity than the vertically polarized waves at 8000 feet below the line of sight.

Field intensities well below the line of sight are considerably stronger at night than during the daytime.

[2] Trevor and Carter, "Notes on propagation of waves below ten meters in length," Proc. I.R.E., vol. 21, no. 3, pp. 387–426; March, (1933).

Observations indicate that the standard field intensity generator may be expected to give reliable results.

Acknowledgment

We are indebted to RCA Radiotron Co., Inc., for their coöperation with respect to special tubes, and to Messrs. N. E. Lindenblad and O. E. Dow of RCA Communications, Inc., for supplying the transmissions for observation.

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RADIO PROPAGATION OVER SPHERICAL EARTH*

By

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(Bell Telephone Laboratories, Inc., Deal, New Jersey)

Summary—*The paper shows how Watson's solution for the propagation of electromagnetic waves over perfectly conducting spherical earth merges into the Abraham solution for propagation over a perfectly conducting plane for shorter distances.*

The effects of refraction by the lower atmosphere and of the imperfect conductivity of the earth are taken into consideration. The magnitude of the former, which is appreciable, is obtained. The latter is relatively unimportant for ocean water and frequencies of the order of a megacycle and less.

The theoretical solution for radio propagation over perfectly conducting spherical earth with atmospheric refraction is in agreement with available experimental data for propagation over ocean water for frequencies below a few megacycles.

Eckersley's extension of Watson's solution to take into account the effect of the imperfect conductivity of the earth by the phase integral method is found to contain approximations which render its results questionable.

Theory

THE electrical disturbance at the surface of the earth due to a vertical dipole has been calculated by G. N. Watson[1] and others. The results for the case of perfectly conducting spherical earth with transmitter and receiver both situated on the surface may be reduced to the form

$$E = \frac{30(2\pi)^{5/3}HI}{a^{5/6}\lambda^{7/6}\sqrt{\sin\theta}} \sum_{n=1}^{\infty} \frac{e^{-\beta_n(2\pi)^{1/3}\frac{d}{a^{2/3}\lambda^{1/3}}}}{\rho_n}, \tag{1}$$

where ρ_n and β_n are constants whose values have been calculated as follows:

$\rho_1 = 0.8083$

n	ρ_n/ρ_1	$\beta_n\sqrt[3]{2\pi/a^2}$
1	1.000	0.00376
2	3.188	0.01199
3	4.74	0.0178
4	6.047	0.0227
5	7.236	0.0272
6	8.336	0.0313

* Decimal classification: R111. Original manuscript received by the Institute, November 23, 1934. Presented before U.R.S.I. meeting, Washington, D. C., April 26, 1935.

[1] G. N. Watson, "The diffraction of electric waves by the earth," *Proc. Roy. Soc.* (London), A, vol. 95, pp. 83–99; October, 7, (1918).

and,

H is the effective height of the transmitting antenna in kilometers,
I is the transmitting antenna current in amperes,
λ is the wavelength in kilometers,
a is the radius of the earth in kilometers $(=6370)$,
d is the distance between transmitter and receiver in kilometers,
θ is the angle at the center of the earth subtended by radii to transmitter and receiver $(=d/a)$, and
E is the received field strength in volts per kilometer.

ρ_n and β_n were evaluated for $n=1$ by G. N. Watson,[1] for $n=2$ and $n=3$ by H. M. Macdonald,[2] while the remaining values have been calculated by the present author.

For distances for which this solution would be used (i.e., where the effect of the ionized region of the upper atmosphere may be neglected) $\sin\theta$ very nearly[3] equals θ so that the above formula reduces to the following

$$E = \frac{30(2\pi)^{5/3}HI}{a^{1/3}\lambda^{7/6}d^{1/2}} \sum_{n=1}^{\infty} \frac{e^{-\beta_n (2\pi)^{1/3} \frac{d}{a^{2/3}\lambda^{1/3}}}}{\rho_n}. \tag{2}$$

This equation may be reduced to a form more readily comparable with the Abraham[4] solution for the field strength over a conducting plane,

$$E = \frac{120\pi HI}{\lambda d}. \tag{3}$$

Equation (2) then becomes

$$E = \frac{120\pi HI}{\lambda d} f(x), \tag{4}$$

where,

$$f(x) = \frac{\sqrt[3]{\pi^2/2a}}{\rho_1} \sum_{n=1}^{\infty} \frac{\sqrt{x}}{\rho_n/\rho_1} e^{-\beta_n \sqrt[3]{2\pi/a^2} x} \tag{5}$$

and,

$$x = \frac{d}{\sqrt[3]{\lambda}}. \tag{6}$$

The constant before the summation sign is equal to 0.1136 when the earth is the sphere under consideration.

[2] H. M. Macdonald, "The transmission of electric waves around the earth's surface," *Proc. Roy. Soc.* (London), A, vol. 90, pp. 50–61; April 1, (1914).

[3] This approximation introduces an error of less than one tenth of a decibel for distances less than 2250 kilometers.

[4] M. Abraham, "Elektromagnetische Wellen," *Enc. der math. Wissen*, vol. 5, part 2, pp. 483–538.

Equation (4) states that the field strength at a point on the surface of a conducting sphere is less than that on the surface of a conducting plane by a factor which is a function of the quotient of the distance along the surface by the cube root of the wavelength.

This factor is plotted in Fig. 1. For small values of $x = d/\sqrt[3]{\lambda}$ it approaches unity so that the Watson solution for radio propagation over the surface of a perfectly conducting sphere merges into the Abraham solution for propagation over a perfectly conducting plane at short distances. In order to depict this graphically the curves that result from neglecting all terms except the first, first two, first three, etc., have been plotted. It will be noted that as more terms of the

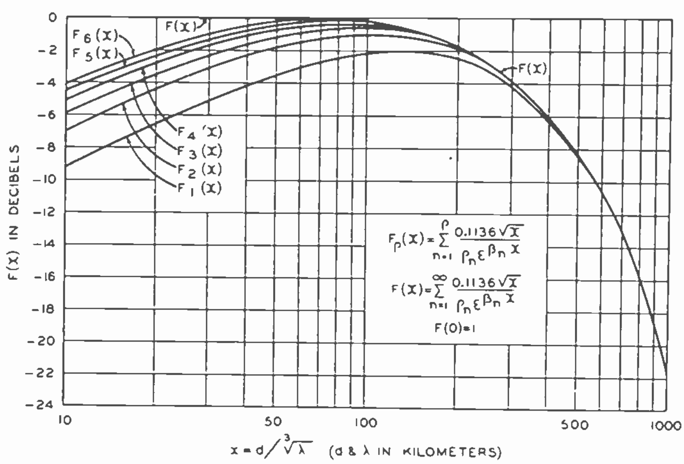

Fig. 1—Successive approximations to Watson's formula for the ratio of the field received over perfectly conducting spherical earth to that over perfectly conducting plane earth.

complete Watson solution are added the resulting curves more nearly approach the Abraham solution for the shorter distances. When x equals 160 the curvature of the earth reduces the field strength one decibel. At this point the error in neglecting all of the terms except the first results in an error of a decibel. For larger values of x the first term approximates the complete series with increasing accuracy, as shown in the curves of Fig. 1. *In other words, no error greater than one decibel is incurred if the Abraham solution is used when* $d/\lambda^{1/3} < 160$ and *only the first term in the Watson solution is employed when* $d/\lambda^{1/3} > 160$.

In obtaining the solution for the propagation of radio waves over the surface of the earth, besides assuming the earth to be a perfect conductor, Watson assumed that the electromagnetic properties of the air were independent of the height above the earth's surface. Data to be presented later indicate that neglecting refraction in the lower atmosphere introduces the greater error for certain frequencies. Fortunately in such cases, it is simpler to extend the solution to take into account atmospheric refraction than the imperfect conductivity of the earth.

It is known[5] that for electromagnetic waves propagated along the surface of the earth, the optical effect of the existing changes in refractivity with height in the lower atmosphere is the same as the effect that would be produced if the earth's radius were increased. If this "effective radius" is substituted for the actual radius in (5) the resulting equation for the ratio of the received field strength to that which would be received over a perfectly conducting plane becomes

$$F(y) = 0.1136\sqrt{y} \sum_{n=1}^{\infty} \frac{1}{\rho_n/\rho_1} \epsilon^{-\beta_n \sqrt[3]{2\pi/a^2}\, y} \tag{7}$$

where,

$$y = x/\sqrt[3]{K^2} = d/\sqrt[3]{\lambda K^2} \tag{8}$$

and K is the ratio of the effective radius of the earth to the actual radius.

From this it can be seen that the effect of refraction is to multiply the distance at which a given reduction in the field due to the earth's curvature occurs by a factor which is equal to the two-thirds power of the ratio of effective to actual radius of the earth. The analysis of the available meteorological data in the aforementioned article[5] indicates that this radius ratio is about 4/3 on the average. This results in an increase of 1.21 times in the distance at which the reductions in fields occur.[6]

The ratio of the field received over perfectly conducting spherical earth with refraction by the lower atmosphere to that which would be received over a perfectly conducting plane is shown in Fig. 2.

Watson[7] has pointed out the relation of the empirical Austin-Cohen formula for long-distance long-wave communication,

$$E = \frac{120\pi HI}{\lambda d} \epsilon^{-0.0015d/\sqrt{\lambda}}, \tag{9}$$

to the above diffraction formulas. He showed that this formula, (9),

[5] J. C. Schelleng, C. R. Burrows, and E. B. Ferrell, "Ultra-short-wave propagation," Proc. I.R.E., vol. 21, pp. 427–463; March, (1933), and *Bell Sys. Tech. Jour.*, vol. 12, pp. 125-161; April, (1933).

[6] The increase in range is not as great as this due to the inverse distance factor.

This advantage would not be realized for waves greater than a certain length. This limit occurs when that part of the atmosphere for which the refractive index no longer decreases at the assumed rate becomes important in the propagation of the waves.

[7] G. N. Watson, "The transmission of electric waves around the earth," *Proc. Roy. Soc.* (London), A, vol. 95, pp. 546–563; July 15, (1919).

could be obtained by considering the earth surrounded by a conducting shell some 100 kilometers above the earth's surface. He also showed that the factor $\lambda^{-1/2}$ instead of $\lambda^{-1/3}$ occurs only when the effect of the upper atmosphere becomes important. Equations (1), (2), (4), and (7)

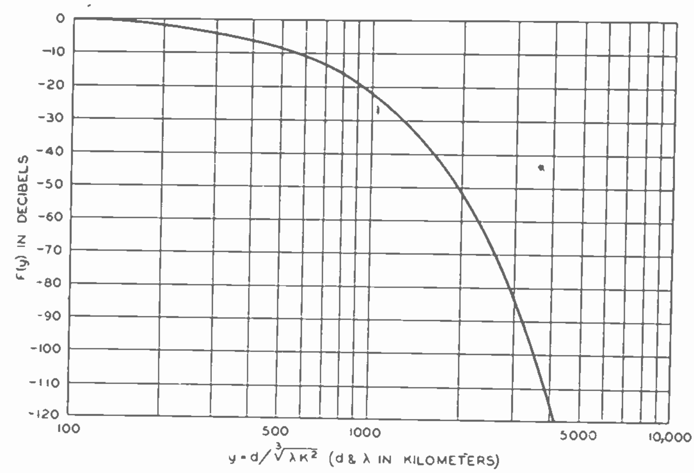

Fig. 2—Ratio of the field received over perfectly conducting spherical earth with refraction by the lower atmosphere to that over perfectly conducting plane earth.

apply only for distances in which the effect of the upper atmosphere may be neglected.

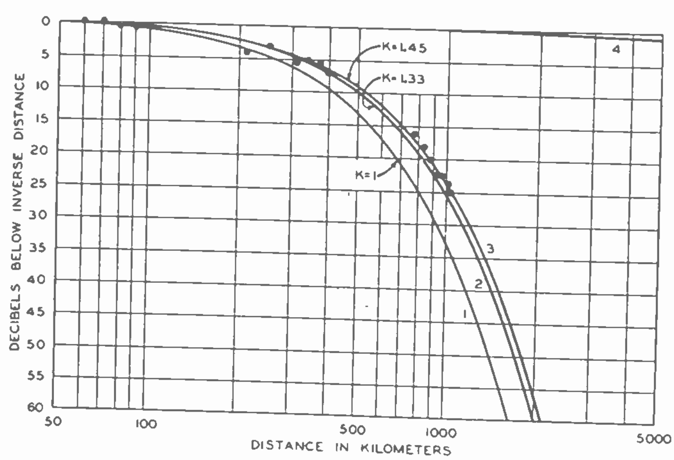

Fig. 3—Comparison between theory and experiment on 0.8 megacycle. Experimental points show received field strength from S.S. *America*, March, 1922, taken from Fig. 16 of "Radio transmission measurements" by R. Bown, C. R. Englund, and H. T. Friis, PROC. I.R.E., vol. 11, pp. 115–152; April, (1923).

Curve 1. Theoretical neglecting refraction.
Curve 2. Theoretical assuming average refraction. From meteorological data.
Curve 3. Theoretical assuming refraction to give best fit with experimental points.
Curve 4. Theoretical for plane earth taking finite conductivity into account.

Experiment

In Figs. 3 and 4 the theoretical curve of Fig. 2 has been superimposed upon experimental data obtained for 0.8- and 4-megacycle transmission, respectively. Theoretical curves are shown for radius ratios of 1, 4/3, and 1.45. The latter gives the best fit with the experimental data. The curve for a ratio of 4/3 estimated from available meteorological data is in fair agreement with the data, but since this is only an estimate of the average value of the ratio it is possible that 1.45 is a better value for the conditions of the experiment. It is doubtful, however, whether the precision of the experiment would justify distinguishing between these two values. It will be noted that the

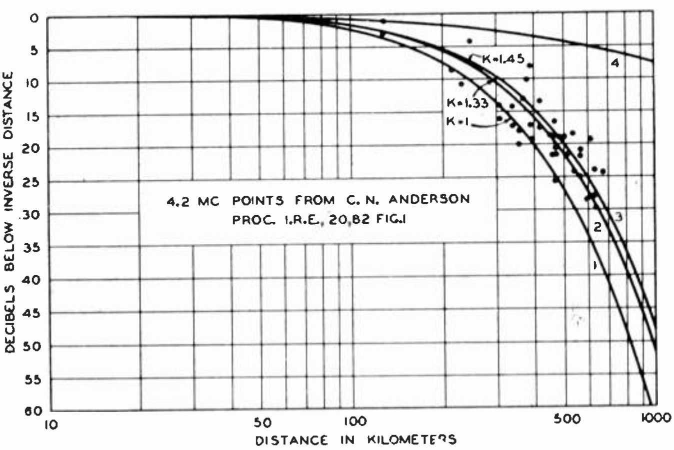

Fig. 4—Comparison between theory and experiment on 4.2 megacycles. Experimental points from Fig. 1 of "North Atlantic ship-shore radiotelephone transmission during 1930 and 1931," by C. N. Anderson, Proc. I.R.E., vol. 21, pp. 81–101; January, (1933).

Curve 1. Theoretical neglecting refraction.
Curve 2. Theoretical assuming average refraction from meteorological data.
Curve 3. Theoretical assuming same refraction as curve 3 of Fig. 3.
Curve 4. Theoretical for plane earth taking finite conductivity into account.

effect of refraction is appreciable and that the agreement between experiment and theory is greatly improved by taking the effect of refraction into account.

As an indication of the effect of the finite conductivity of ocean water, the theoretical curve for propagation over imperfectly conducting plane earth has been added in each case. Curve 4 for imperfectly conducting plane earth is substantially the same as that for a perfectly conducting plane for 0.8 megacycle (Fig. 3), indicating that the effect of the imperfect conductivity is negligible on this frequency. For 4 megacycles, Fig. 4, curve 4, the effect of the imperfect conductivity, while not negligible, is small compared to the effect of the earth's curvature.

If an attempt be made to take into account the imperfect conductivity of the earth by applying Eckersley's extension of Watson's solution, curve 3 for $K=1.45$ of Fig. 4 would be moved almost back to curve 1 for $K=1$. There are, however, several reasons for questioning this extension of Watson's work that will be discussed later.

Data published by Bion and David[8], to show the inadequacy of Sommerfeld's solution for the propagation over sea water in the wavelength range 150 to 700 meters, have been plotted in Fig. 5. While

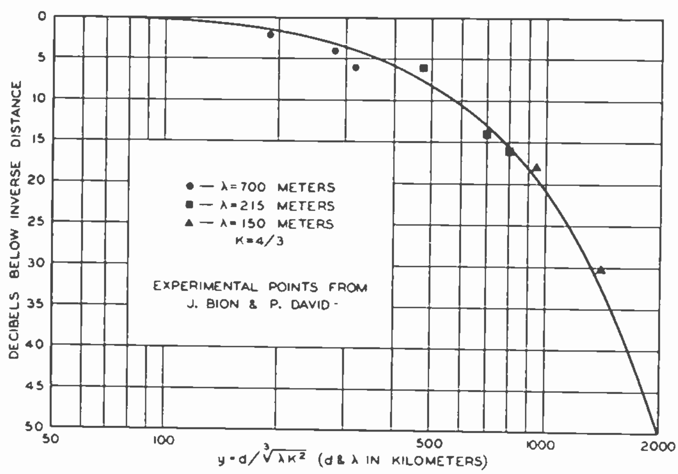

Fig. 5—Comparison between theory and experiment on 2, 1.4, and 0.43 megacycles.

Experimental points from Bion and David; theoretical curve from equation (7).

only eight points are shown they represent data taken at regular intervals on a ship whose distance from the transmitter was continuously increased up to 1050 kilometers so that their precision is far superior to that possible with single measurements. The points have been plotted against the parameter $y=d/\sqrt[3]{\lambda K^2}$ using 4/3 for the value of K. The points lie close to the theoretical curve, substantiating the theoretical curve and indicating that atmospheric refraction was sufficient to increase the effective radius of the earth by the factor 4/3 for radio propagation (in this frequency range) over the Mediterranean Sea in January and February, 1932.

[8] J. Bion and P. David, "Sur l'affaiblissement des ondes moyennes et intermediaires se propageant de jour sur mer," *Comptes Rendus*, vol. 194, pp. 1723–1724; May 17, (1932).

Effect of Imperfect Conductivity

Due to the complications introduced into the problem of the propagation of electromagnetic energy around the surface of the earth by the effect of imperfect conductivity, no rigorous solution has been made to date. The approximate solution due to T. L. Eckersley,[9,10] however, has been used[11] to calculate the field strength of the ground wave at distances beyond those for which the solution for transmission over an imperfectly conducting plane applies. The results of this solution will be compared with the rigorous solutions of special cases, leaving a discussion of some of the approximations made and the uncertainties introduced thereby for the appendix.

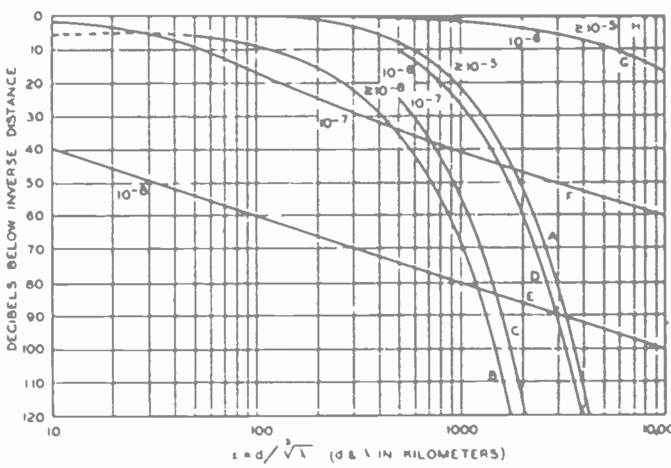

Fig. 6—Comparison of theoretical curves for radio propagation. The numbers on the curves indicate the value of $\sigma^{1/2}\lambda^{5/6}$ for the case represented by the curve in question—(conductivity in electrostatic units and wavelengths in kilometers).

Theoretical curves obtained by various methods for propagation over the surface of the earth are presented in Fig. 6 for comparison. Curve *A* is for perfectly conducting spherical earth based on Watson's solution. Curve *B* is based on Eckersley's solution for a spherical earth whose conductivity is small enough so that its magnitude is unimportant but large enough so that it is essentially a conductor rather than a dielectric.[12] Curves *C* and *D* result from using the coefficients given by Eckersley corresponding to the values of $\sigma^{1/2}\lambda^{5/6}$ indicated on

[9] T. L. Eckersley, "Radio transmission problems treated by phase integral method," *Proc. Roy. Soc.* (London), A, vol. 136, pp. 499–527; June 1, (1932).

[10] T. L. Eckersley, "Direct ray broadcast transmission," Proc. I.R.E., vol. 20, 1555–1579; October, (1932).

[11] See for example, "Report of committee on radio propagation data," Proc. I.R.E., vol. 21, pp. 1419–1438; October, (1933).

[12] For detailed explanation of this curve see the Appendix.

the curves. Curves E,F,G, and H are for imperfectly conducting plane earth based on the solution by Sommerfeld,[13] Weyl,[14] Wise[15] and others and evaluated by Rolf,[16] for the corresponding values of $\sigma^{1/2}\lambda^{5/6}$ indicated on the curves.[17] The part of curve H shown also coincides with the solution for perfectly conducting plane earth as determined by Abraham.[4] This indicates that for conductivities greater than those for which $\sigma^{1/2}\lambda^{5/6}=10^{-5}$ the earth may be regarded as a perfectly conducting sphere.

The fact that the plane earth solution for values of the parameter of the order of 10^{-7} and less (curves E and F) gives lower fields than Eckersley's solution for spherical earth indicates that the approximations made introduce large errors in these regions of the solution. This inconsistency between the Eckersley solution and the rigorous solution for plane earth in itself would indicate that the solution is not valid for values of $\sigma^{1/2}\lambda^{5/6}$ less than 10^{-7}. While no glaring inconsistencies are evident from Fig. 6 for values of the parameter somewhat greater than this it is the writer's opinion that implicit faith should not be placed in the results without experimental verification due to the nature of the approximations made in obtaining the solution.[18] Comparison of curves D and A shows that the Eckersley modification of the Watson solution for values of the parameter of the order of 10^{-6} is small which is consistent with the results for plane earth, curve G. It is in this region that Eckersley presents experimental data to substantiate his solution.

Recently Eckersley* has made the plausible suggestion that his curves should be shifted vertically until they are tangent or nearly

[13] A. Sommerfeld, "Über die Ausbreitung der Wellen der drahtlosen Telegraphie," *Ann. der Phys.*, vol. 4, no. 28, pp. 665–756; March, (1909), and "Ausbreitung der Wellen in der drahtlosen Telegraphie. Einfluss der Bodenbeschaffenheit auf gerichtete und ungerichtete wellenzuge," *Jahr. der drahtlosen Tel.*, vol. 4, p. 157, (1910).

[14] H. Weyl, "Ausbreitung elektromagnetischer Wellen über einem ebenen Leiter," *Ann. der Phys.*, vol. 4, no. 60, pp. 481–500, (1919).

[15] W. Howard Wise, "The grounded condenser antenna radiation formula," Proc. I.R.E., vol. 19, pp. 1684–1689; September, (1931).

[16] B. Rolf, "Graphs to Prof. Sommerfeld's attenuation formula for radio waves," Proc. I.R.E., vol. 18, pp. 391–402; March, (1930).

[17] The usual parameter, $\sigma\lambda^2$, that occurs when the field over imperfectly conducting plane earth is plotted against distance, becomes $\sigma\lambda^{5/3}$ or $(\sigma^{1/2}\sigma^{5/6})^2$ when the field is plotted against $d\lambda^{-1/3}$.

[18] Since the writing of this paper an article by Jean Marique entitled "Note sur quelques measures due rayonnement des stations de navires," *L'Onde Electrique*, vol. 13, pp. 149–156; March, (1934), has come to the attention of the author. Experimental data are presented from which he concludes that Eckersley's results do not apply for distances of the order 400 to 500 kilometers at a wavelength of 600 meters.

* T. L. Eckersley, "Study of curves of propagation of waves," Document A. G. (1934), no. 11, comm. II; International Scientific Radio Union, Vth Assembly.

tangent to the Sommerfeld curve. This results in the curves of Fig. 7. Here the abscissa is chosen so that all of the Sommerfeld-Rolf curves coincide. If the effect of imperfect conductivity were unimportant, the curves for spherical earth would begin to depart from unity at the points A, B, C, etc. The effect of imperfect conductivity is to move these points to A', B', C', etc., on the present Eckersley theory. The horizontal motion was calculated by the approximate phase integral method, while the vertical motion is the result of this recent assumption. It can be seen that for the poorer conductivities the recent assumption causes a greater change in the value of the field strength than that calculated by the phase integral method. While this assump-

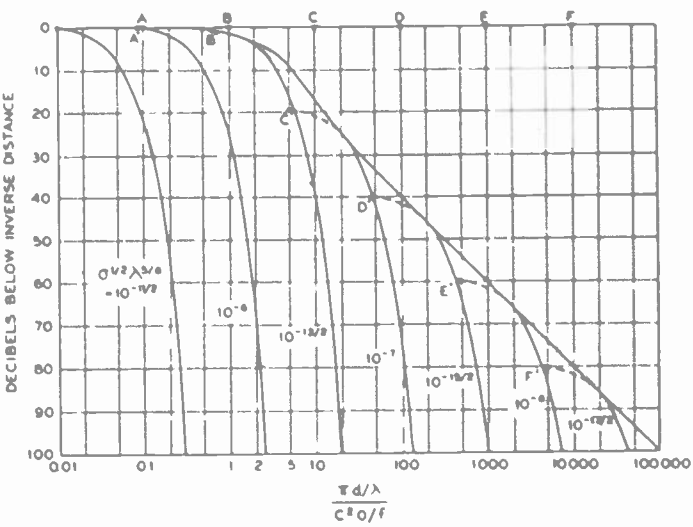

Fig. 7—Revised Eckersley curves for imperfectly conducting spherical earth. (The conductivity in e.m.u. is represented by σ and in e.s.u. by $c^2\sigma$, $c=3\times10^{10}$.)

tion has removed the most obvious inconsistency in the results, the writer believes that they still require experimental verification before reliance should be placed in them.†

Appendix

The rigorous solution for the perfect conductivity case, (1), may be expressed in the form,

$$E = \sum_{n=1}^{\infty} A_n \cos \lambda_n \tag{10}$$

where A_n and λ_n are functions of ρ_n. By his approximate phase integral method Eckersley was able to evaluate λ_n in the above expression.

† The above paragraph and Fig. 7 were added on April 4, 1935.

He found the same relationship between λ_n and ρ_n as Watson. The ρ_n's he obtained, however, differed from those obtained by Watson. The values of ρ_n as determined by Eckersley may be expressed by

$$\rho_n = \frac{[3\pi(n - a_n + \eta)]^{2/3}}{2} \tag{11}$$

where η depends upon the ground constants, being zero for perfect conductivity. a_n is a constant independent of n whose value Eckersley found by comparison with Watson's results to be $\frac{3}{4}$. Herein is one of the inaccuracies introduced by the approximate method, for to obtain the correct values of ρ_n, a_n must be allowed to vary with n. While the necessary variation is small[19] for the case of perfect conductivity, without further proof we have no assurance that it is not much larger for the more general case.

Eckersley's method does not tell us anything about the magnitude of A_n in (10). He tacitly assumed A_n to be independent of the conductivity. An equally logical assumption leading to a different result would be that the functional relationship between A_n and ρ_n be independent of the conductivity. Both are undoubtedly incorrect but the error introduced may not be large for the better conductivities.

In obtaining curve B of Fig. 6 the values of a_n given in footnote 19 were used so that Eckersley's solution would be consistent with Watson's solution for the perfect conductivity case. The values of A_n were calculated on the assumption that the functional relationship between A_n and ρ_n be independent of the conductivity. If the magnitude of A_n were assumed independent of the conductivity, curve B would be raised approximately seven decibels.

[19] $a_1 = 0.7819$, $a_2 = 0.7577$, $a_3 = 0.7544$, $a_4 = 0.7530$, $a_5 = 0.7523$, and $a_6 = 0.7519$. For larger values of n, a_n approaches 0.75 more closely.

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SERIES MODULATION*

By

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Summary—*In this paper it is pointed out that the type of modulating system used in any given case depends to some extent upon the particular type of service involved. The limitations of existing types of control are discussed, and a detailed theoretical and experimental investigation of the so-called series type of modulation is reported. Operating data, in the form of graphs, are presented for those existing tubes which because of their characteristics are adapted for use in connection with this type of control. The advantages and limitations of the series method are outlined, and the desirability of an improved tube for use as a series modulator is stressed.*

INTRODUCTION

THE rapid extension of the field of communication engineering, particularly in connection with those applications which involve the use of high-frequency alternating currents, has tended to emphasize the importance of the means whereby audio and visual generated potentials may be impressed on the carrier current. Further, the increasing diversity of high-frequency communication agencies makes it more or less apparent that a single system of carrier wave modulation is not necessarily adapted to all of the various communication processes which now obtain and which may be developed in the near future. With this situation in mind there was initiated at this laboratory several years ago a research and development program having as an objective the careful study of the then existing systems of modulation, and the design and development of possible improvements along these lines. Among the feasible systems which have received attention is the plan commonly referred to as series modulation. By series modulation is meant a procedure whereby the modulating tube is connected in series with the anode potential supply of one of the tubes constituting the high-frequency chain of circuits. A practical circuit arrangement of this nature was recently disclosed by the author.[1] Before, however, entering into a discussion of the theoretical and practical aspects of this means of modulation it will be in order to examine briefly the limitations which obtain in connection with those systems of modulation which are now in common use.

* Decimal classification: R385. Original manuscript received by the Institute, April 19, 1934.

[1] U. S. Patent No. 1,882,122, October 11, (1932).

Limitations of Older Systems

Until quite recently the "choke" or Heising system of modulation has been the one most commonly used. This method is, however, being rapidly displaced by two other systems. This change in modulation technique has been due to the inherent limitations of the choke method. Since the impedance of a choke is a function of the inductive reactance, and since the reactance is a function of the frequency, it is physically impossible to design a choke which will exhibit the same impedance for all signaling frequencies. The practice is, of course, to attempt to design a choke which shall have an impedance sufficiently high to reduce the lowest audio-current components to a negligible magnitude. The choke system is accordingly sometimes referred to as one in which "constant current" obtains, but it is a matter of common engineering experience that the current through such a choke is not constant, even in the case of a well-designed unit of 30 or more henrys. If the modulation choke is to carry even moderate current magnitudes, such as obtain in low level modulation practice, the unit is both heavy and expensive. The necessity of avoiding magnetic saturation of the iron necessitates a liberal amount of core material and thus contributes to the weight factor. While the weight is not a serious matter in fixed radio stations it does become an important factor in connection with mobile installations.

Not only is there the possibility of frequency distortion at low frequencies, but corresponding distortion may also obtain at the higher signal frequencies due to the unavoidable distributed capacitance of the choke winding.

Though still extensively used in this country the choke modulation system is, as implied above, being displaced by two other methods which to some extent avoid certain of the limitations outlined above.

One of these methods is a revival of one of the oldest plans known to the art. Reference is here made to the grid system of modulation. This general type of modulation was probably first suggested by the late Charles V. Logwood. Logwood's method consisted in impressing the signal voltage directly on the grid of the oscillator. In 1923 the author outlined a practical system of grid modulation[2] using a triode as a grid leak.

A number of years ago van der Bijl suggested a plan whereby radio-frequency carrier voltage and the signal voltage are simultaneously impressed on the grid of a class A amplifier. More recently commercial equipment has been developed which makes use of a circuit layout

[2] "An improved system of modulation in radio telephony," Proc. I.R.E., vol. 11, no. 5, pp. 479–492; October, (1923).

whereby the signal and radio-frequency voltages are simultaneously applied to the grid of a low powered radio-frequency amplifier.

In general, grid-circuit modulation schemes require only a relatively low signal level and absorb but little energy in and of themselves. They, however, have one defect in common; viz., that it is more or less difficult to adjust such circuits so that amplitude distortion is entirely avoided.

A second plan for modulating the carrier wave which is coming into favor at present is commonly referred to as class B modulation. This system is a special form of plate modulation, and makes use of the now popular class B audio amplifier organization. A good exposition of this plan of control is to be found in a recent paper[3] by C. L. Farrar. In the installation described by Professor Farrar the output of the class B audio amplifier is superimposed on the constant anode potential of the output stage of the radio-frequency train of amplifiers, thus bringing about "high level" modulation. In certain commercial broadcast equipment the class B scheme is applied to one of the intermediate radio-frequency amplifiers, rather than to the output stage, thus effecting an economy in tube capacity as well as power consumed by the modulator.

There is, however, one serious limitation to the transformer coupled class B system of modulation as it is commonly employed, and that is that it is extremely difficult to avoid frequency discrimination in the coupling transformer, as in the earlier choke system. Here again also we encounter the matter of weight, when dealing with portable transmitter units. Certain inherent defects in the class B scheme can be materially minimized by the use of a circuit recently suggested by the author,[4] and which will form the subject of a subsequent paper.

Theory of Series Modulation

In connection with all applications involving a carrier wave it is of prime importance that there be no distortion of the signaling frequency. Particularly in the fields of sound and visual broadcasting any appreciable frequency discrimination is inadmissible. Of the systems of control thus far developed series modulation is the only plan which is inherently capable of giving a strictly flat frequency response. An elementary circuit embodying the series principle of control is shown in Fig. 1(a). Tube A and its associated connections represents a radio-frequency organization, while tube M is a triode *acting as a variable "dropping" resistance*. Tube A acts as a fixed resistance. In Fig. 1(b),

[3] "Class 'B' audio power amplifiers," *Radio Eng.*, January, (1932).
[4] U. S. Patent No. 1,896,742, February 7, (1933).

R_M represents the resistance of the modulator, R_A that of the radio-frequency amplifier tube, and E_b the common anode potential. The anode current through the two tubes in series will be determined by the expression

$$I_p = f(R_A, R_M, E_b), \tag{1}$$

where R_A and R_M represent the *grid-controlled direct-current resistance* of the amplifier and modulator tube, respectively.

Because of the various types of service in which tubes function there is no common reference condition by which the grid-controlled resistance of tubes can be compared. The term *static* resistance means nothing unless the corresponding grid bias is specified; it is for this reason that we have chosen to use the term "controlled resistance." As we employ the term in this connection, controlled resistance of the tubes is taken to mean the ohmic resistance which the tubes offer when

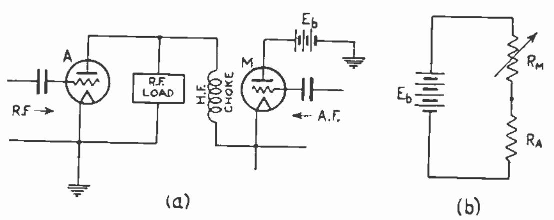

Fig. 1

biased to give the normal unmodulated carrier output. For instance, a 203A tube biased at -42 volts has a controlled resistance, as shown by measurement, of 54,000 ohms and an 830 used in the high-frequency modulated stage (class C) shows an operating effective resistance of about 18,000 ohms.

If we assume that E_b is held constant and that R_A remains substantially so, we are primarily concerned with the variations in R_M. But it is to be remembered that R_M and R_A are *in series*, and we must therefore consider what change in the *total* resistance will be brought about by any fractional change in the value of R_M, due to a given signal input level.

Suppose $R_A = R_M$, and further assume that the characteristics of the modulator tube are such that a given change in grid potential will change the tube's controlled resistance by 50 per cent. On this basis the *total change in resistance* would be 25 per cent. If, however, $R_M = 2R_A$, a 50 per cent change in R_A would bring about a change of 33 per cent in the total resistance. It is therefore evident that it is desirable, in a series system of modulation, to use as a modulator a tube whose controlled resistance is high compared with the controlled resistance of the tube being used as a radio-frequency amplifier.

A rough estimate of the comparative utility of a tube as a series modulator can be formed by computing its controlled resistance when the tube is biased to give normal anode current when operated as a class A unit. In the case of a screen-grid tube the screen-grid bias complicates the problem, but for purposes of appraisal the bias of the screen grid can be held at normal value. For instance, an 860 tube with its screen grid at +500 volts and the control grid at −30 has a controlled (static) resistance of something like 40,000 ohms, while a 203A biased at −30 shows a resistance of 50,000 ohms. It is therefore evident, on the basis of the foregoing comparison, that the 203A is more suitable for use as a series modulator than the 860. The allowable plate dissipation, however, is slightly higher in the case of the screen-grid unit. This and other considerations will be referred to later.

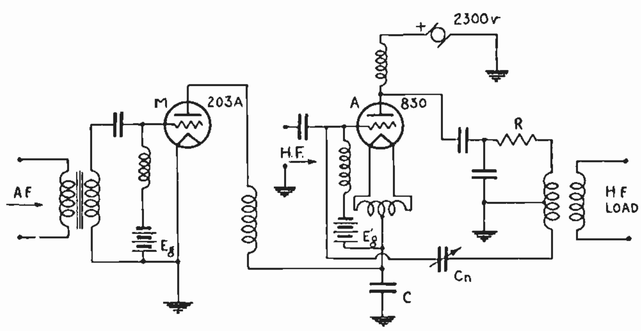

Fig. 2

OPERATION

A typical series modulation set-up is shown in the diagrammatic sketch appearing as Fig. 2. In the circuit illustrated it will be noted that the filament of the modulator M is at earth potential while in the theoretical diagram (Fig. 1) it is the filament of the radio-frequency amplifier which is grounded. It has been found that either plan is practicable, though with the former set-up provision for grid bias can be somewhat more conveniently arranged. The capacitance of the blocking condenser C must be of such a magnitude that it will not by-pass the higher audio frequencies. A capacitance of the order of 0.0002 microfarad or less is desirable. The placing of the modulator tube next to the source of anode potential (Fig. 1) avoids the use of this blocking condenser. With the combination shown in Fig. 2 very satisfactory modulation may be obtained, both as regards depth and fidelity.

Fig. 3 shows the experimentally determined characteristics of the combination diagramed in Fig. 2. The graph gives the relation which obtains between the grid potential of the modulator (203A) and the drop (E_a) across the radio-frequency amplifier tube, the anode current (I_p), and the radio-frequency tank current (I_{osc}).

An anode voltage of 750 is recommended by the manufacturers as a suitable anode potential when the 830 is operated in class C service, with a bias of -180 volts. Referring to curve A it will be evident that with the applied electromotive force (2300) available in the tests referred to, a grid bias of about -38 volts gave an anode potential (E_a) of 750 for the 830 and an unmodulated carrier current of approximately

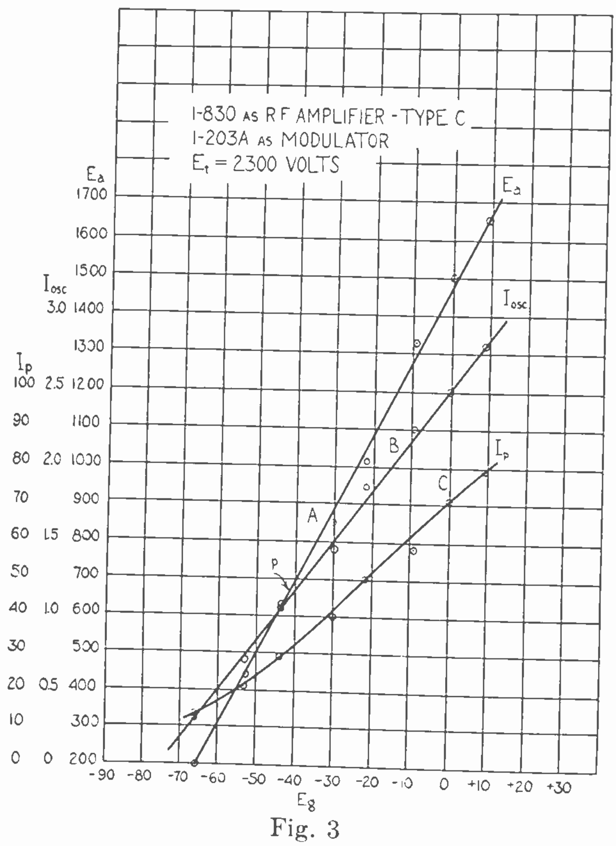

Fig. 3

1.4 amperes. (The radio-frequency tank circuit was so loaded that about 50 per cent of its energy was dissipated in the resistance R.) In actual operation its grid bias was set at -40, thus reducing the carrier anode potential on the 830 to 700. Under the latter operating conditions it was possible to cause the anode potential to have double its carrier value without the grid of the modulator becoming positive. The curves show, however, that it would have been possible to allow the grid to swing at least 10 volts positive without causing distortion. In order to bring about 100 per cent modulation the radio-frequency anode voltage must of course vary between zero and $2E_a$, where E_a is the voltage across the tube *A* when the radio-frequency amplifier is delivering normal unmodulated carrier output. It is seen that in this case a modulator grid swing of 75 volts would bring about complete modulation.

Curve *C* (Fig. 3) indicates that there is some departure from linearity at the lower values of E_a; the radio-frequency tank current (curve *B*), however, shows strict linearity throughout the observed range.

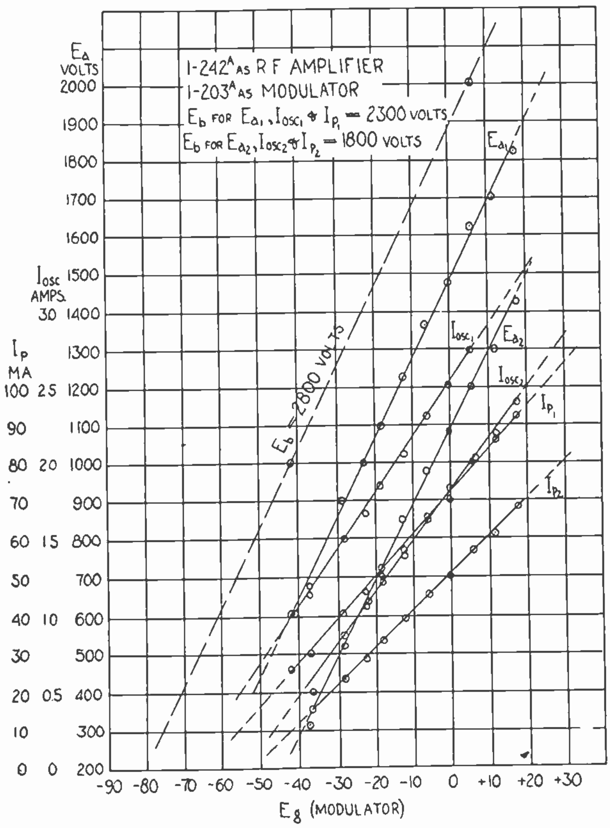

Fig. 4

In Fig. 4 is seen the interrelated variables, above mentioned, as they worked out in the case of the 242A tube used as a radio-frequency amplifier in conjunction with a 203A as a series modulator. It is to be noted that two sets of curves for this set-up are given, one for an applied voltage (E_b) of 2300 and a second where E_b is 1800. The importance of the proper applied over-all voltage for a given tube combination is strikingly shown by these graphs.

Suppose, for the purpose of discussion, that the 242A is to be operated at a normal anode potential (E_a) of 1000 volts and that the available terminal voltage is 2300. In order to modulate completely the output under the conditions named, the anode voltage on the 242A must vary between zero and 2000. Under these conditions the graph (Fig. 4) shows that the grid bias on the modulator (203A) must be −23 volts, resulting in an unmodulated tank carrier current of 1.64 amperes. The graph shows that in order to double the carrier voltage setting, it would be necessary that the modulator grid should swing 25 volts positive. The observed readings were not carried that far, but it is safe to assume that the relations would not be linear on that part of the characteristic, hence distortion would obtain. An examination of the 1800-volt curve indicates that if one were to use that over-all potential the modulator must needs be biased at −4 and that the grid would swing nearly as much positive as negative, a condition which would be worse than the situation just cited.

This undesirable condition can be obviated by applying an over-all potential of 2800 volts, as shown by the dotted graph. The 2800-volt line was drawn by interpolation. When employing an E_b of 2800 volts, a bias on the modulator of −42 would give the desired E_a of 1000 volts. Under these conditions the grid of the modulator need only swing to +6 in order to give 100 per cent modulation. Since the characteristics are seen to be linear in that region, the distortion would be negligible. With this particular tube combination, then, complete modulation could be secured by operating with an over-all voltage of 2800 and a modulator grid swing of approximately 90 volts.

Screen-Grid Tubes as Series Modulators

On first thought it might seem that the screen-grid type of tube might function particularly well as a control unit when employing the series form of modulation. A closer study of this type of tube, however, discloses the fact that the screen-grid tube has certain inherent limitations when used as a series modulator. The operating characteristics of a combination consisting of a 242A as a radio-frequency amplifier and an 860 as a modulator are shown in Fig. 5.

On examining these graphs it will be evident that, when operated under the conditions shown, the characteristics show considerable departure from linearity even at zero grid bias of the modulator; curvature also begins at about −50. A set of curves are also shown for the condition where two 860's are operated in parallel to modulate the 242A, the idea in using two tubes being to augment the total possible plate dissipation. The data as represented by the curves tend to show that a single 860 when used as modulator, would have to be operated with a grid bias between the limits of zero and −50 volts. Under these limitations the direct-current drop (E_a) over the radio-frequency tube when delivering unmodulated carrier does not exceed 725 volts, with the result that the output of the radio-frequency amplifier is somewhat less than that delivered by the system when a 203A functions as modulator. A second 860 in parallel obviously does not increase the output but does divide the modulator plate load.

The screen-grid tube does, however, possess one advantage, as a modulator, over a three-electrode unit; the working resistance of the tube can be controlled by means of the screen-grid potential, as well

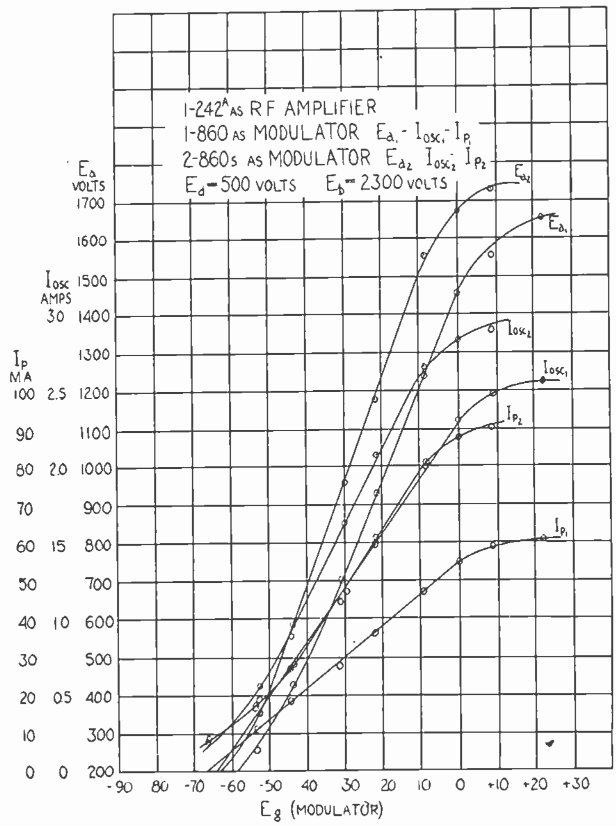

Fig. 5

as by the control grid. The curves set forth in Fig. 6 illustrate this point. It will be noted that for comparatively low and high values of E_d, the characteristic is not linear, particularly in the latter case. A 203A characteristic is shown for comparison purposes.

In the case of the triode, used as a control unit, the depth of modulation for a given signal input is determined by the nonsignaling value of E_g; increasing the negative bias tends to increase the percentage modulation and vice versa. This is due to the fact that an increase in negative bias increases the ratio of R_M to R_A. If the grid bias of the modulator is too low, the average amplitude of the modulated carrier current will be less than the nonsignaling value with the result that the modulation will be "down" rather than "up." In the case of the screen-grid modulator the percentage of modulation can accordingly be controlled by adjusting either or both E_d and E_g. It follows from the foregoing discussion that decreasing E_d will increase the degree of modulation. In practice when using a single 860 as a modulator and a 242A as the radio-frequency amplifier (with the available E_b of 2300) it was found that the optimum screen-grid potential is +450 and that

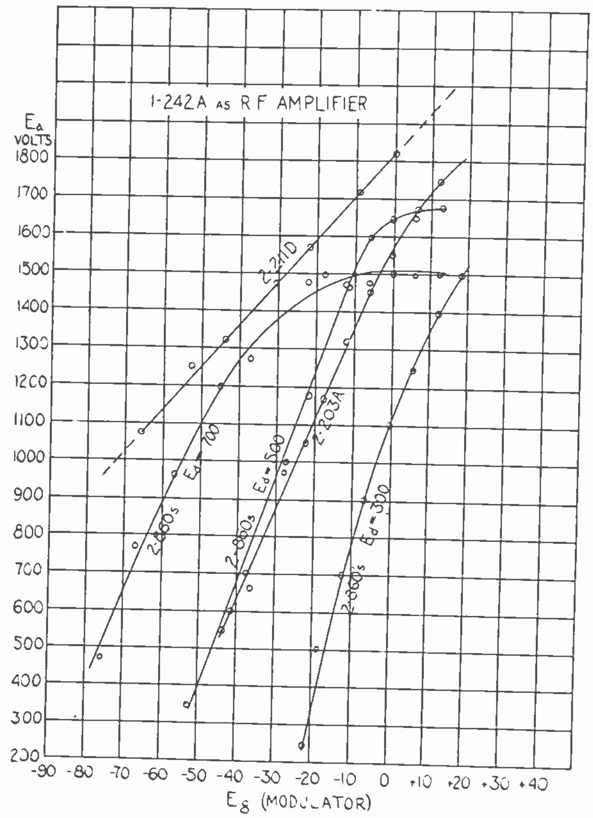

Fig. 6

the control-grid bias is −28. It is obviously important that the screen-grid potential be held absolutely constant. A higher over-all voltage (E_b) would have been more satisfactory.

The modulation characteristic for a pair of 211D tubes used with a 242A as a radio-frequency amplifier is also shown in Fig. 6. Due to the low controlled resistance of the 211D this tube is seen to be comparatively ineffective as a series modulator. An examination of the curves (Fig. 6) discloses the reason for this low modulation efficiency. The grid swing necessary to bring about 100 per cent modulation with the 211D is nearly threefold that required in the case of the 203A. Using a value of 2300 for E_b an experimental comparison of a 203A and a 211D as modulators was made. It was found that for a given signal input the percentage modulation when using the 203A as a modulator was approximately 50 per cent higher than when employing the 211D. The difference would have been even more marked had the over-all voltage been higher. This experimental evidence confirms the theoretical conclusions as to the desirability of a high resistance tube for use as a modulator, advanced in an earlier section of this discussion.

Fidelity of Reproduction

In the operating layout shown in Fig. 2 the only capacitance involved in the audio circuit is that of the blocking condenser C together with any inherent capacitance in the heating circuit. By proper attention to design both of these capacitances may be made of such a low value that their combined effect will not be appreciable below 10,000 cycles. Since this is true, and since inductance is absent, frequency discrimination is practically nil.

Because so far as the modulator tube is concerned we are dealing with what amounts to a pure resistance, and since throughout the comparatively straight portion of the modulating characteristic $(E_g - E_a)$, the controlled resistance of the tube is very nearly a linear function of the grid potential, it follows that there will be comparatively little amplitude distortion. Even though the ordinary static characteristic of a tube shows some curvature, as is the case of the 203A for instance, this undesirable condition will tend to be improved when a comparatively high resistance (in this case the radio-frequency tube) is in series with the modulator. The effect of this resistance in straightening out the characteristic is well known in the art. It is thus evident that, with this system of modulation, a certain amount of possible amplitude distortion is automatically corrected for.

Exacting musical tests have been made of the radio-frequency output of the organization shown in Fig. 2 when using the several tube combinations referred to in the preceding paragraphs, with very satisfactory results. Oscillographic studies have also been made which confirm the auditory observations.

In Fig. 7(a) is to be seen the oscillogram of the output of the speech amplifier employed in securing certain experimental data connected with this study. The source of energy was a sine wave electromotive force of constant frequency and amplitude generated by a special electro-acoustic organization. In the same illustration is shown (b) a record of the same sound tone made by rectifying a portion of the output of the modulated radio-frequency stage. It is to be seen that the modulation is nearly 100 per cent and that there is only a slight amount of distortion. How much of this distortion was due to the rectifying organization and how much to the radio-frequency circuits

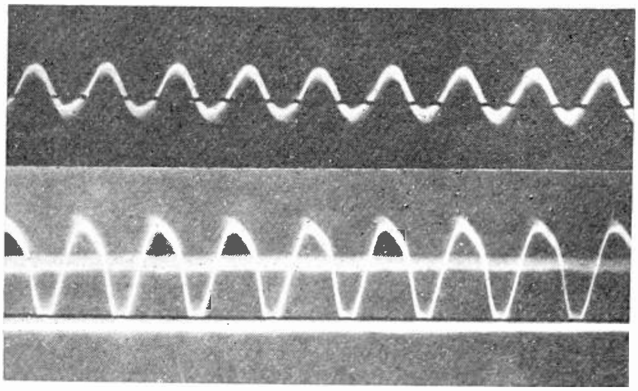

Fig. 7

was not determined. In making this oscillogram a 203A was modulating a 242A, the latter operating at less than rated output.

A series of distortion measurements were also made in the modulated radio-frequency output by means of a General Radio distortion factor meter. The data thus secured are shown graphically in Fig. 8. The

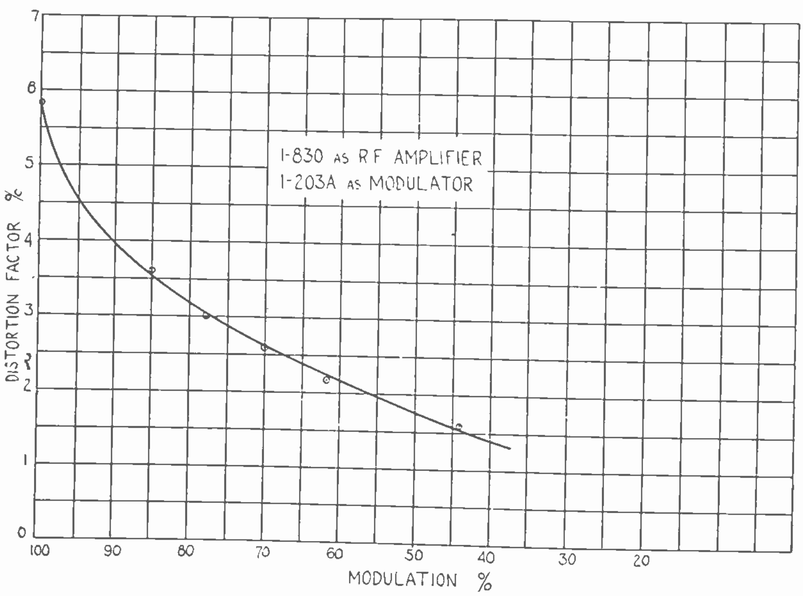

Fig. 8

distortion which may have been due to the last audio stage and to the high-frequency rectifier unit is included in the distortion thus measured. Bearing this in mind, it is evident that it is possible by proper circuit design to produce a modulated carrier which will not exceed the permissible engineering limit of distortion (5 per cent) at 100 per cent modulation.

Efficiency and Power Limitations

In the experiments referred to in the earlier part of this paper the radio-frequency power level output was of the order of 12 watts. This would, of course, be "low level" modulation. With a proper value of E_b and the necessary radio-frequency excitation, the 203A-830 or the 203A-242A combination is capable of delivering at least 25 watts of practically distortionless modulated radio-frequency power. Unfortunately there is not available at the present time a tube suitable for use as a series modulator whose plate dissipation is sufficient to permit series modulation at a higher level, unless it be the 861. What is needed is a triode whose plate dissipation is of the order of 100 watts when operating in class A service and whose grid-controlled resistance (at normal values of E_g and E_p) is of the order of 10,000 ohms. It is to be hoped that such a unit will be available in the near future.

English engineers[5] evidently have developed tubes suitable for series modulators which are capable of handling considerable power, thus making it possible to modulate at a higher level, and thereby reducing the inherent distortion due to succeeding radio-frequency stages. The Marconi engineers have developed the series method of modulation to the point where it is possible to secure a radio-frequency output of some 30 kilowatts modulated to 90 per cent with a distortion factor below 4 per cent.

The over-all efficiency of the series modulator and the radio-frequency amplifier can be readily computed by the relation

$$\text{efficiency} = \frac{I_p^2 R_A/2}{I_p^2 R_A + I_p^2 R_M} = \frac{R_A}{2(R_A + R_M)}.$$

The introduction of the constant 2 is based on the assumption that the radio-frequency amplifier operates at an efficiency of at least 50 per cent. In our tests no particular effort was made to secure high efficiency. When delivering normal carrier output (see Fig. 3) the 830 showed a controlled ohmic resistance of 18,000 and the 203A, 54,000 ohms. Substitution in the above equation, therefore, gives an over-all efficiency of approximately 12.5 per cent. This is, of course, a low efficiency, but since only a few watts are involved, the matter of

[5] A brief account by W. T. Ditcham of the British engineering practice in connection with series modulation is to be found in the March-April, (1933), number of the *Marconi Review*.

efficiency is relatively unimportant. However, by proper attention to the adjustments of the radio-frequency amplifier circuit the efficiency could probably be raised to something like 25 per cent.

Conclusion

Our calculations and experiments lead us to the following conclusions:

(1) Of the tubes now available on the American market, the type 203A is probably the most suitable for use as a modulator at low power levels.

(2) A 203A as a series control unit used in conjunction with one or more 830's makes it possible to modulate completely a carrier at the 25-watt level without frequency discrimination and with a negligible amplitude distortion.

(3) With the tube combination above suggested, the over-all voltage need not exceed 2500. This relatively high supply voltage may, in certain cases, impose a limitation on the use of this type of modulation in portable transmitters, but does not serve to restrict its use in connection with fixed installations.

(4) There is little if any tendency for the transient peak voltages to cause flashovers either within or without the modulator tube.

(5) In arranging operating conditions the modulator grid bias and the over-all voltage should be so adjusted that the normal radio-frequency carrier output occurs when the fixed modulator grid bias falls at the median point of the straight portion of the static characteristic of the modulator tube. It is advisable to adjust E_g and E_b so that the E_a equals twice its unmodulated carrier value when the least negative grid swing reaches zero.

(6) In selecting a tube for use as a series modulator the controlled resistance of the tube, measured when the fixed grid bias has the value above indicated, may be taken as a criterion of suitability. This controlled resistance should be high compared with the corresponding resistance of the tube combination which serves in the radio-frequency system. Since the modulator tube functions as a class A unit, plate dissipation should be provided in adequate amount.

(7) In order to secure 100 per cent modulation at normal signal input the ratio E_b/E_a should be of the order of three to one.

(8) In a triode modulator the percentage modulation is controlled by the value of the fixed grid bias. The greater the negative bias the deeper the modulation. In the case of the screen-grid tube the depth of modulation can, within limits, also be controlled by means of the screen-grid potential.

(9) The weight of the modulating radio-frequency stage is materially less when using series modulation than when the choke or transformer plan is employed.

(10) There is need of a tube specially designed for use as a series modulator.

In conclusion it may be said that work is in progress on the design of two commercial models embodying series modulation; one a compact portable unit and the other a 100-watt layout which will serve as the basic unit in a larger broadcast transmitter.

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AN ANALYSIS OF CLASS B AND CLASS C AMPLIFIERS*

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Summary—*A mathematical analysis of the plate-current flow in class B and class C radio-frequency power amplifiers is presented, due consideration being given to the nonlinearity of the tube characteristics and the discontinuity of plate-current flow. A simple and highly approximate equation for the fundamental harmonic component of amplifier plate current in terms of the applied continuous and alternating grid and plate potentials and the load impedance is obtained. Equations for determining the optimum load impedance and proper grid biasing and exciting potentials for maximum power output are derived. Satisfactory agreement is indicated between predicted and experimental outputs for a 500-watt power tube operated over a wide range of exciting and biasing potentials.*

Introduction

Of the many branches of nonlinear electric circuit theory, perhaps none is of greater theoretical or practical interest than that relating to the operation of class B and class C radio-frequency power amplifiers. Unfortunately, the large number of variables present in these systems renders a precise theoretical treatment of the various circuits employed quite impracticable, with the result that the majority of treatments of these circuits have been confined to analyses of idealized systems in which the mathematically troublesome tube characteristic curvatures have been replaced by simpler linear characteristics. Generally speaking, these simplifications in theory have been quite justified, for the broader fundamental characteristics of these amplifiers are not altered to an appreciable degree by comparatively large changes in tube characteristics. On the other hand, it must be admitted that the simplified forms of analysis are of rather doubtful value for purposes of engineering calculations. For such applications a somewhat more rigorous analytical treatment of nonlinear amplifier circuits is preferable, the accuracy demanded being of approximately the same general order as that with which the values of the several circuit components may be determined.

The present paper attempts, in a general way, to present a method of attack upon several problems common to class B and class C power amplifiers. The analysis presented is not rigorous, being derived from a combination of several rapidly converging series expansions, but is

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capable of sufficient accuracy to meet the majority of engineering requirements. The theory includes the effect of tube characteristic curvature and of the discontinuity of plate-current flow, but omits consideration of grid currents, plate-current saturation, and variation in tube parameters.

THEORY

To facilitate the study of discontinuous plate-current flow it has been found desirable to form a new algebraic function, some of the properties of which are herewith presented.

Consider the function

$$U_x = \frac{1}{2}\left[1 + \frac{x}{\sqrt{x^2}}\right].$$

When x takes on positive values, U_x is equal to unity. When x takes on negative values, U_x is equal to zero. In the case of the conjugate function

$$V_x = \frac{1}{2}\left[1 - \frac{x}{\sqrt{x^2}}\right],$$

when x is greater than zero, V_x is equal to zero, and when x is negative, V_x is equal to unity.

Multiplying U_x by x we obtain the function $U(x)$, which is defined by the relation

$$U(x) = \tfrac{1}{2}[x + \sqrt{x^2}].$$

When x takes on positive values, $U(x)$ is identically equal to x, whereas when x assumes negative values, $U(x)$ is equal to zero. The conjugate function, $V(x)$, is obtained by multiplying V_x by x.

The following tabulation gives several of the most important properties of the U and V functions:

$$\begin{aligned}
U_x + V_x &= 1. && \text{(a)} \qquad & [U(x)]^n &= x^{n-1}U(x) && \text{(d)} \\
U(x) + V(x) &= x. && \text{(b)} \qquad & [U(x)]^n &= (x)^n U_x && \text{(e)} \qquad (1) \\
U(x)V(x) &= 0. && \text{(c)} \qquad & [V(x)]^n &= x^{n-1}V(x) && \text{(f)}
\end{aligned}$$

If x is a single valued, periodic function of time all of the U and V functions defined above may be expressed in the form of Fourier series. It is also possible to express these functions in the form of rapidly converging power series. For example, the power series representation for the function $U(x)$ is derived by expanding $\sqrt{x^2}$ in a Taylor's series about the point b^2, and substituting the resulting series in the defining equation for $U(x)$. The series thus obtained is of the form

$$U(x) = \frac{1}{2}(x + b) + \frac{1}{2b}(x^2 - b^2) - \frac{1}{8b^3}(x^2 - b^2)^2 + \cdots$$

or, collecting terms of like power in x,

$$U(x) = B_0 + B_1 x + B_2 x^2 + B_4 x^4 + \cdots B_m x^m + \cdots \tag{2}$$

the coefficients of all odd powers of x, except the first, being equal to zero, and all coefficients except B_1 being functions of the point of expansion, b. The series is absolutely convergent for such values of x as satisfy the relation $x^2 < 2b^2$.

In a similar manner the series expansion for the function U_x is derived by substituting the expansion for $\sqrt{x^2}$ in the defining relation for U_x, and performing the indicated division to obtain a series of the form

$$U_x = C_0 + C_1 x + C_3 x^3 + C_5 x^5 + \cdots C_m x^m + \cdots \tag{3}$$

the coefficients of all even powers of x being equal to zero, and all coefficients except C_0 being functions of the point of expansion, b.

Turning now to the application of the U functions to the theory of class B and class C amplifiers, it is well known that the equation

$$i_p = K(\mu e_g + e_p)^n$$

quite accurately represents the triode characteristic for all values of the quantity $(ue_g + e_p)$ from zero to such values as approach that required for temperature saturation of the tube. It is evident then that the expression

$$i_p = K[U(\mu e_g + e_p)]^n \tag{4}$$

represents the triode characteristic with an equal degree of accuracy for all values of the quantity $(\mu e_g + e_p)$ from $-\infty$ to such positive values as that required for temperature saturation. The principal restrictive assumption necessary in the application of (4) is that the grid potential never becomes so high compared to the plate potential as to cause the grid current to become an appreciable fraction of the plate current.

Referring now to the schematic of Fig. 1, which may be taken as representative for both class B and class C amplifiers, it is evident that the equation for plate current takes the form

$$i_p = K(U[\mu(E_c + E_g \cos wt) + E_b - Zi_p])^n \tag{5}$$

where E_b is the continuous impressed plate potential, E_c the grid biasing potential, E_g the amplitude of the grid exciting potential, μ the amplification factor of the tube, and Z the value of the load impedance. Upon setting

$$
\left.
\begin{aligned}
\mu E_c + E_b &= E_0 &\quad (a)\\
\mu E_g &= E_1 &\quad (b)\\
E_0 + E_1 \cos wt &= e &\quad (c)\\
e - Zi_p &= v &\quad (d)
\end{aligned}
\right\} \qquad (6)
$$

and utilizing the relation (1e), equation (5) may be written

$$\frac{e - v}{Z} = K(v)^n U_v. \qquad (7)$$

Expanding the right-hand member of (7) in a Taylor's series about the point a, again employing (1e), and collecting like powers of the function $U(v)$,

$$\frac{e - v}{Z} = G_0 U_v + G_1 U(v) + G_2[U(v)]^2 + \cdots G_m[U(v)]^m + \cdots \qquad (8)$$

or,

$$e = v + ZG_0U_v + ZG_1U(v) + ZG_2[U(v)]^2 + \cdots ZG_m[U(v)]^m + \cdots \qquad (9)$$

where the coefficients G_m are functions of the point of expansion, a, and the exponent, n, alone.

It is now assumed that the amplifier load impedance Z is of such form as to exhibit a high resistive component at the frequency of the grid exciting voltage, and negligible impedance at all other frequencies. Since those terms of (9) containing the impedance Z as a factor can then contribute terms of the exciting frequency only, it is apparent from inspection that the voltage v must be of the form

$$v = E_0 + V \cos wt. \qquad (10)$$

Inasmuch as the voltage (10) is a continuous, periodic, single valued function of time, it is possible to express functions of the type $[U(v)]^m$ appearing in (9) by trigonometric series of the form

$$[U(v)]^m = [U(v)]_0^m + [U(v)]_1^m \cos wt + \cdots [U(v)]_0^m \cos qwt \cdots \qquad (11)$$

and the function U_v by the series

$$U_v = U_{v0} + U_{v1} \cos wt + \cdots U_{vq} \cos qwt + \cdots \qquad (12)$$

the numerical subscripts associated with the U functions of (11) and (12) being employed to indicate the order of the harmonic component of those functions.

Before considering the manner of deriving the values of these various harmonic coefficients, however, it should be noted that if $E_0 < V$, the expansions (2), (3), and (8) are valid for all possible values of V if the point of expansion b involved in the coefficients B_m and C_m be given the value V in the former coefficients, and $2V$ in the latter, and if the point of expansion, a, involved in the coefficients G_m be given the value V. Then, retaining the first four terms of (2) and (3),

$$B_0 = \frac{3V}{16}; \quad B_1 \doteq \frac{1}{2}; \quad B_2 = \frac{3}{8V}; \quad B_4 = -\frac{1}{16V^3}. \qquad \text{(a)}$$
$$C_0 = \frac{1}{2}; \quad C_1 = \frac{2}{3V}; \quad C_3 = -\frac{1}{3V^3}; \quad C_5 = \frac{11}{72V^5}. \qquad \text{(b)} \qquad (13)$$

while, if the exponent n be assigned the normal value 3/2, and the first three terms of (8) be retained

$$G_0 = -\tfrac{1}{8}KV^{3/2}; \quad G_1 = \tfrac{3}{4}KV^{1/2}; \quad G_2 = \tfrac{3}{8}KV^{-1/2}. \qquad (14)$$

The values of the fundamental frequency coefficients $[U(v)]_1{}^m$ are now perhaps most readily determined by substituting (10) and (13a) in (2), and the resultant in (1d); straightforward algebraic expansion of the latter then yields expressions of the form

$$[U(v)]_1 = (0.500V + 0.564E_0 + \cdots) \cos wt$$

and,

$$[U(v)]_1{}^2 = (0.430V^2 + E_0V + 0.660E_0{}^2 + \cdots) \cos wt. \qquad (15)$$

An expression for the coefficient U_{v1} may be obtained in a similar manner by substituting (10) and (13b) in (3), and expanding to obtain the approximate value

$$U_{v1} = (0.512 - 0.667E_0{}^2/V^2 + \cdots) \cos wt. \qquad (16)$$

An equation relating the fundamental harmonic amplitudes of both members of (9) is now formed, and is given by

$$E_1 = V + Z_1G_0U_{v1} + Z_1G_1[U(v)]_1 + Z_1G_2[U(v)]_1{}^2 + \cdots \qquad (17)$$

where Z_1 denotes the impedance of Z at the exciting voltage frequency. Upon substituting (14), (15), and (16) in (17), and collecting terms of like power in V, the relation

$$E_1 = V + 0.473KZ_1V^{3/2} + 0.798KZ_1E_0V^{1/2} + 0.331KZ_1E_0{}^2V^{-1/2} + \cdots \qquad (18)$$

is obtained.

A solution for V, of sufficient accuracy for the great majority of circuits, may be derived from (18) in the following manner. Since the voltage V must lie within the interval $O < V < E_1$, and is rarely lower in value than 0.5 E_1, an expansion of the quantities $V^{3/2}$, $V^{1/2}$, and $V^{-1/2}$ about an arbitrary fractional value of E_1, such as the point $V = 0.8\ E_1$, yields the highly approximate relations

$$V^{3/2} = (0.8E_1)^{3/2} + \frac{3}{2}(0.8E_1)^{1/2}(V - 0.8E_1) + \cdots$$

$$V^{1/2} = (0.8E_1)^{1/2} + \frac{1}{2}(0.8E_1)^{-1/2}(V - 0.8E_1) + \cdots$$

$$V^{-1/2} = (0.8E_1)^{-1/2} - \frac{1}{2}(0.8E_1)^{-3/2}(V - 0.8E_1) + \cdots$$

which, when substituted in (18), permit the solution

$$V = \frac{E_1 + 0.169KZ_1E_1^{3/2} - 0.358KZ_1E_0E_1^{1/2} - 0.556KZ_1E_0^2E_1^{-1/2}}{1 + 0.635KZ_1E_1^{1/2} + 0.446KZ_1E_0E_1^{-1/2} - 0.232KZ_1E_0^2E_1^{-3/2}}. \tag{19}$$

Since it is evident from (6c), (6d), and (10) that the fundamental alternating component of plate current i_{p1}, is given by

$$i_{p1} = \frac{E_1 - V}{Z_1} \tag{20}$$

equations (19) and (20) may be employed to derive the solution

$$i_{p1} = \frac{0.466KE_1^{3/2} + 0.804KE_0E_1^{1/2} + 0.335KE_0E_1^{-1/2}}{1 + 0.635KZ_1E_1^{1/2} + 0.446KZ_1E_0E_1^{-1/2} - 0.231KZ_1E_0^2E_1^{-3/2}}. \tag{21}$$

For the case of the class B amplifier, the voltage E_0 is equal to zero, and only the first term of the numerator and the first two terms of the denominator are employed.

For the case of the class C amplifier, the number of terms employed depends in some measure upon the relative values of E_0, E_1, and Z_1. If the value of Z_1 is of the same order of magnitude as the optimum value for maximum power output and E_0 is relatively small compared to E_1, an excellent approximation to the value of i_{p1} may be obtained by employing only the first two terms of the numerator and the first three terms of the denominator.

The above solution for the fundamental component of amplifier plate current, though not perfectly rigorous nor closed in form, nevertheless converges at such a rate as to render the inclusion of higher order terms of questionable value.

The solution (21) is fundamental in character, inasmuch as the form assumed is quite independent of the several points of expansion involved in its derivation. The principal effect of variations in the latter quantities is reflected in limited variations in the values of the numerical coefficients appearing in (21).

The determination of any plate current component other than the fundamental is readily accomplished by employing the relation

$$i_{pq} = G_0 U_{vq} + G_1[U(v)]_q + G_2[U(v)]_q^2 + \cdots \tag{22}$$

where q denotes the order of the desired harmonic component, this relation being merely a summation of the *qth* harmonic components of the several terms in the right-hand member of (8). In making calculations of the type indicated by (22) it is of some assistance to note that the *qth* harmonic component of the quantity $[U(E_0+V\ cos\ wt]^r$ may be determined in the following manner.

From the relation (1e) it may be seen that the coefficient of the *qth* harmonic component of the Fourier series representing the function $[U(E_0+V\ cos\ wt)]^r$ is given by the integral

$$\frac{2w}{\pi}\int_0^T (E_0 + V\cos wt)^r \cos qwt\, dt \tag{23}$$

where the limit T, the time of plate-current cut-off referred to the time $t=0$, is given by

$$T = \frac{1}{w}\cos^{-1} - \frac{E_0}{V}. \tag{24}$$

The integral (23) is valid for all values of q except zero, in which case one half the value indicated by (23) should be employed.

The equations derived above permit the determination of the various components of amplifier plate current in terms of the operating voltages, the load impedance, and the tube constants. Attention is now directed to the determination of the optimum value of load impedance for any given set of operating conditions.

The choice of a proper value of load impedance for the class B or class C amplifier is governed by a number of factors, foremost among these being the maximum safe plate power dissipation of the tube, the desired operating angle of plate-current flow, the applied continuous grid and plate potentials, the grid exciting potential, the required over-all linearity of the amplifier output characteristic, and the nature and permissible loss in modulation products if such exist. No attempt will be made to consider these factors in detail, such a study being quite beyond the scope of this paper. It should, however, be noted that for any given set of operating conditions there exists an optimum value of load impedance which will insure maximum power output from the amplifier for any given maximum value of plate power dissipation. This optimum load impedance is usually considerably higher than the value of impedance necessary to secure the maximum power output from the tube regardless of plate power dissipation, and is determined from the following considerations.

If the angle during which the plate-current flow is to exist be fixed, the optimum load impedance becomes that value which limits the plate power dissipation to any arbitrary maximum value, while permitting the power output to attain the maximum value consistent with the limiting conditions imposed. For any fixed value of load impedance, the power output of the amplifier increases with increasing values of grid excitation until such a point is reached at which the maximum instantaneous value of grid voltage becomes equal to the minimum instantaneous value of plate voltage. Further increase in the value of grid excitation is usually accompanied by severe distortion of the plate-current wave peak and a reduction in amplifier efficiency. The equations which follow have been derived to permit the calculation of the optimum value of load impedance for either class B or class C amplifiers when the continuous plate potential, desired operating angle, and maximum plate dissipation are given. The required values of grid biasing and exciting potentials may readily be calculated when the optimum load impedance is known.

As a preliminary step in the formation of the equations for optimum load impedeance it is desirable to formulate two simple relations which permit the expression of the continuous and fundamental alternating components of plate current in terms of the angle of plate-current flow and the potential V.

From (24), the potentials E_0 and V and the plate-current cut-off angle wT are related by the equation

$$E_0 = -V \cos wT.$$

Setting $wT = \frac{\pi}{2} + \gamma$, the above expression becomes

$$E_0 = V \sin \gamma, \tag{25}$$

or, to a first order of approximation

$$E_0 = V\gamma. \tag{26}$$

Substituting (26) in (18),

$$E_1 = V + F_1 Z_1 V^{3/2} \tag{27}$$

where,

$$F_1 = K(0.473 + 0.798\gamma + 0.331\gamma^2 + \cdots). \tag{28}$$

Substituting (27) in (20),

$$i_{p1} = F_1 V^{3/2}. \tag{29}$$

A similar expression for the continuous component of plate current i_{p0}, may be derived with the aid of (22) and (23); thus, from (22),

$$i_{p0} = G_0 U_{v0} + G_1[U(v)]_0 + G_2[U(v)]_0^2 + \cdots. \tag{30}$$

Substituting the value,

$$v = E_0 + V \cos wt$$

in the U functions appearing in (30), and employing (23), the following relations are obtained:

$$U_{v_0} = \left[\frac{1}{2} + \frac{E_0}{\pi V}\right]$$

$$[U(v)]_0 = \frac{w}{\pi}\left[E_0 T + \frac{V}{w} \sin wT\right]$$

$$[U(v)]_0^2 = \frac{w}{\pi}\left[E_0^2 + \frac{V^2}{2} T + \frac{2}{w} E_0 V \sin wT + \frac{V^2}{4\pi} \sin 2wT\right].$$

Again setting $wT = \pi/2 + \gamma$, $\sin\gamma = \gamma$, and $\cos\gamma = 1 - \gamma^2/2$, and employing (26), the above equations take the approximate values

$$U_{v_0} = \left[\frac{1}{2} + \frac{\gamma}{\pi} + \cdots\right] \tag{31}$$

$$[U(v)]_0 = \frac{V}{\pi}\left[1 + \frac{\pi\gamma}{2} + \frac{\gamma^2}{2}\right] \tag{32}$$

$$[U(v)]_0^2 = \frac{V^2}{\pi}\left[\frac{\pi}{4} + 2\gamma + \frac{\pi\gamma^2}{2}\right]. \tag{33}$$

Substituting (31), (32), (33), and (14) in (30)

$$i_{p0} = F_0 V^{3/2} \tag{34}$$

where,

$$F_0 = K(0.271 + 0.574\gamma + 0.307\gamma^2 + \cdots). \tag{35}$$

With the above relations available, the derivation of an expression for optimum load impedance may be carried out in the following manner.

It will be assumed that the desired plate-current operating angle at maximum power output and the limiting permissible value of plate dissipation are given. By way of limiting the plate-current wave form distortion under conditions of maximum power output, the maximum instantaneous value of grid potential will be chosen equal to the minimum instantaneous value of plate potential. Analytically, this condition is expressed by the equation

$$E_b - Z_1 i_{p1} = E_g + E_c. \tag{36}$$

By definition,

$$E_0 = E_b + \mu E_c.$$

Substituting this relation in (25),

$$E_c = \frac{V \sin \gamma - E_b}{\mu} \tag{37}$$

while the substitution of (29), (37), and the relation $E_g = E_1/u$ in (36) yields the equation

$$E_b - Z_1 F_1 V^{3/2} = \frac{E_1}{\mu} + \frac{V \sin \gamma}{\mu} - \frac{E_b}{\mu}. \tag{38}$$

Substituting the value of E_1 given by (27) in (38),

$$E_b - Z_1 F_1 V^{3/2} - \frac{V(1 + \sin \gamma)}{\mu + 1} = 0. \tag{39}$$

The power input to the amplifier plate circuit is

$$P_i = E_b i_{p0} = E_b F_0 V^{3/2} \tag{40}$$

while the power output at the fundamental frequency is

$$P_0 = \tfrac{1}{2} Z_1 i_{p1}^2 = \tfrac{1}{2} Z_1 F_1^2 V^3. \tag{41}$$

Then, from (40) and (41)

$$Z_1 = \frac{2E_b F_0 V^{3/2} - 2P_p}{F_1^2 V^3} \tag{42}$$

where P_p is the plate power dissipation.

Substituting (42) in (39), and multiplying by $V^{3/2}$

$$\frac{F_1(1 + \sin \gamma)}{\mu + 1} V^{5/2} + (2F_0 - F_1) E_b V^{3/2} - 2P_p = 0. \tag{43}$$

As the amplification factor of the tube becomes infinitely great the maximum desirable value of $V^{3/2}$ approaches the limiting value

$$V^{3/2} = \frac{2P_p}{E_b(2F_0 - F_1)}. \tag{44}$$

For finite values of μ, the limiting values of $V^{3/2}$ are usually considerably lower than the value given by (44), though still a function of that value. An excellent approximate solution to (43), applicable for any finite value of μ, may be obtained by replacing the term $V^{5/2}$ in (43) by a first order expansion for that quantity in terms of $V^{3/2}$ and a point of expansion, H. The latter may quite properly be made a function of the value of (44), a satisfactory relation being

$$H = \frac{P_p}{E_b(2F_0 - F_1)}. \tag{45}$$

The expansion for $V^{5/2}$ takes the form

$$V^{5/2} = H^{5/3} + \frac{5}{3} H^{2/3}(V^{3/2} - H) + \cdots$$

while the general solution for $V^{3/2}$ becomes

$$V^{3/2} = \frac{2P_p + \dfrac{2}{3}\dfrac{(1 + \sin\gamma)}{\mu + 1} F_1 H^{5/3}}{E_b(2F_0 - F_1) + \dfrac{5}{3}\dfrac{(1 + \sin\gamma)}{\mu + 1} F_1 H^{2/3}}. \tag{46}$$

When the optimum value of $V^{3/2}$ has been determined from (46), the optimum load impedance may be calculated from (42).

Experimental Verification of Theory

The theory presented in the first portion of this paper has been directed toward the establishment of an analytical theory of class B and class C power amplifier operation, utilizing tube characteristics such as are generally encountered in practice. The remainder of the paper will be devoted to the presentation of typical applications of the theory, partly by way of illustrating the use of the equations derived, and partly by way of indicating the order of agreement between the predicted and experimental results.

An experimental power tube capable of dissipating approximately 500 watts in plate heating was employed for test purposes. The pertinent constants for this tube are given by the values

$$\mu = 20; \quad n = 3/2; \quad K = 1.12 \times 10^{-5};$$

the substitution of these factors in (4) giving an expression for the plate current in amperes.

A continuous plate potential of 2900 volts, and biasing potentials varying from -115 volts to -175 volts were employed in the tests. An antiresonant tank circuit, loosely coupled to an artificial antenna system was adjusted to exhibit the desired value of load impedance at the frequency of the grid exciting potential, the latter being approximately 570 kilocycles. The peak alternating voltage developed across the load impedance was measured by means of a specially calibrated sphere gap voltmeter, provision being made to reduce automatically the value of grid excitation to a safe value as soon as breakdown of the voltmeter occurred. Values of the fundamental alternating component of plate current were computed by dividing the various voltmeter breakdown readings by the value of the antiresonant load impedance. Regenerative effects in the amplifier were eliminated by means of careful neutralization of the interelectrode capacitance of the tube and appropriate shielding of the various circuit components.

Let it now be assumed that operation of the tube as a class B amplifier is desired, the plate dissipation to be limited to 450 watts at maximum power output. The optimum value of load impedance and grid exciting potential for maximum power output are to be determined, together with the amplifier output characteristic as a function of the grid exciting potential.

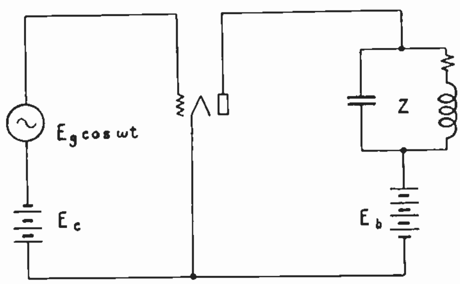

Fig. 1—Circuit schematic for class B or class C amplifier.

Since the tube will be biased to plate-current cut-off, the angle γ is equal to zero. Then, by (28) and (35),

$$F_1 = 5.30 \times 10^{-6}; \quad F_0 = 3.03 \times 10^{-6}.$$

Substituting these values, together with the known continuous plate potential and plate power dissipation in (45), we find

$$H = 2.04 \times 10^5$$

and from (46),

$$V^{3/2} = 2.785 \times 10^5,$$

or,

$$V = 4260 \text{ volts}.$$

Sufficient data are now available to enable calculation of the optimum value of load impedance, equation (42) giving

$$Z_1 \text{ (optimum)} = 1835 \text{ ohms}.$$

The substitution of this value, together with the known values of V and F_1 in (27), gives

$$E_1(\max) = \mu E_g(\max) = 6970$$

or,

$$E_g(\max) = 348.5 \text{ volts}.$$

The alternating component of plate voltage, $E_1 - V$, has an amplitude of 2710 volts, thus giving a minimum instantaneous plate voltage of 190 volts. Since the biasing potential required for plate-current cut-off in the absence of grid excitation is, from (37), equal to -145 volts, the grid attains a peak potential of $+203.5$ volts with respect to the filament, a value somewhat higher than the minimum instantaneous plate voltage.

From (40), the plate circuit power input is 2448 watts, while (41) gives the power output to the load as 2000 watts. The plate dissipation is therefore 448 watts, a figure which is in excellent agreement with the assumed maximum. The plate circuit efficiency, given by the ratio of power output to power input, is equal to 81.7 per cent.

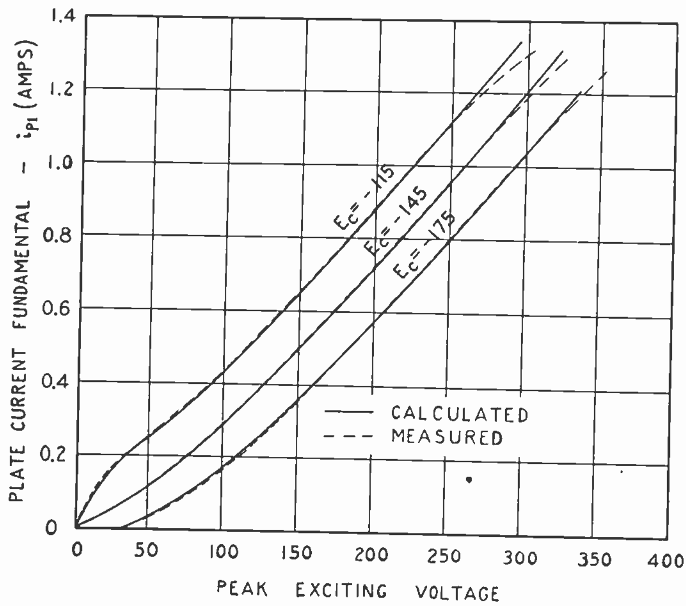

Fig. 2—Calculated and experimental output characteristics for 500-watt power amplifier. $E_b = 2900$ volts; $\mu = 20$; $K = 1.12 \times 10^{-5}$; $Z_1 = 1850$ ohms.

The value of load impedance actually employed in the experimental runs on the amplifier was 1850 ohms. Calculations for the amplifier output characteristic, employing this figure for Z_1 were made from (21), this relation taking the form,

$$i_{p1} = \frac{5.22 \times 10^{-6} E_1^{3/2}}{1 + 1.316 \times 10^{-2} E_1^{1/2}}$$

for class B operation.

Generally speaking, the difference between the calculated and experimentally determined values of i_{p1} was slightly less than two per cent for all values of grid excitation lower than that necessary to produce an approximate equality between maximum instantaneous grid voltage and minimum instantaneous plate voltage. The greatest error in the calculated values was noted at very low grid excitations when the grid biasing potential was considerably in excess of the value employed for class B operation. Fig. 2 indicates graphically the relation between calculated and experimentally determined values of i_{p1} for three values of grid biasing potential and various degrees of grid excitation. All calculations were based upon equation (21).

Conclusion

The development of any theory employing a number of series expansions, is, in a sense, somewhat of a compromise between simplicity of form and accuracy of solution. In the present instance, the accuracy of the several solutions presented is probably comparable with the general order of agreement between any actual tube characteristic and the assumed three-halves power law. Under certain conditions of operation, however, appreciable error in the predicted plate currents may obtain due to high grid currents, grid voltage wave form distortion, variation in the apparent amplification factor of the tube, or insufficient filament emission.

While the theory here presented has been particularly directed to the triode amplifier, it is possible to modify readily the fundamental plate-current equation to permit extension of the theory to the operation of screen-grid amplifiers.

Acknowledgment

In conclusion, the writer wishes to express his gratitude to the late Dr. E. M. Terry of the University of Wisconsin Department of Physics for his suggestions and kindly interest during the early portion of this work.

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GRAPHICAL HARMONIC ANALYSIS FOR DETERMINING MODULATION DISTORTION IN AMPLIFIER TUBES*

By

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In the investigations which led to the development of variable-mu amplifier tubes it was shown by Ballantine[1] and others that the envelope of a modulated sine wave would be distorted by an amplifier whose characteristic was not linear or quadratic, on the assumption that the tube operated into a selective output circuit, as is the case with most radio receiver circuits. In this case only the radio-frequency components of voltage and current having a frequency near the fundamental need be considered. The voltage passed on by such a circuit to the next amplifier tube or detector may be modulated to a different degree, usually higher, than the input voltage, and in addition is modulated with spurious side bands which produce distortion of the audio-frequency output. The ratio of the amplitudes of these spurious side bands to those of the desired side bands may be called the *modulation distortion* produced by the amplifier. It can be shown that this ratio is the same as the ratio of the various harmonics of the *modulation envelope* of the output wave (from the selective circuit) to the fundamental component of this envelope. This is the audio-frequency distortion which would appear in the output of a perfectly linear detector excited by the amplifier.

Modulation distortion is usually calculated from the dynamic characteristic of a vacuum tube by first obtaining the value of third derivative of the characteristic and substituting this value in the formula

$$\text{Per cent 2nd harmonic} = \frac{3mE^2\dfrac{f'''(E_c)}{f'(E_c)} + \dfrac{5}{8}m^3E^4\dfrac{f^V(E_c)}{f'(E_c)} + \cdots}{16 + 6\dfrac{f'''(E_c)}{f'(E_c)}\left(1 + \dfrac{m^2}{4}\right) + \cdots}$$

* Decimal classification: R148.1 Original manuscript received by the Institute May 22, 1934.

[1] Ballantine and Snow, "Reduction of distortion," Proc. I.R.E., vol. 18, no. 12, p. 2102; December, (1930).

where,

$$m = \text{modulation factor of input voltage}$$

$$E = \textit{peak} \text{ radio-frequency carrier voltage}$$

$$f'(E_c) = \frac{\partial i_b}{\partial e_c} = s_m f'''(E_c) = \frac{\partial^3 i_b}{\partial {e_c}^3}, \quad \text{etc.,}$$

and modulation rise may be obtained in a similar manner. This method is cumbersome and not strictly accurate since the effect of higher derivatives is ignored. In general, a harmonic analysis will give better results for periodic quantities than the Taylor's series method employed above even if derivatives of higher order than that of the highest harmonic considered are present. The method described below is a harmonic analysis which may be used with the static characteristic to obtain any of the components of the output of a thermionic or other system when excited with a modulated alternating voltage of the form

$$e_g = E \sin \omega t(1 + m \sin pt).$$

Assume that a modulated voltage of this form is applied to the grid of a vacuum tube. The output can be shown by substitution in a Taylor expression of the static characteristic to consist, in part, of terms of the form

$$I_p \sin \omega t[1 + m_1 \sin pt + m_2 \cos 2pt + \cdots$$
$$m_k \sin npt + m_{k+1} \cos (n + 1)pt]. \quad k \text{ odd} \quad (1)$$

where m_1 will in general not be equal to m, and $m_2/m_1 \times 100$ per cent will be the per cent second harmonic of the *modulation envelope*. When a selective tuned circuit is placed in series with the plate of the tube, the output of a *linear* detector placed across the tuned circuit will be exactly similar to this envelope and hence will be distorted to the same degree. Terms of the form

$$QI_p \sin n_1 \omega t[1 + m' \sin pt + m_2' \cos 2\omega t + \cdots] \quad n_1 > 1$$

will also occur, but will be ignored in this discussion since they will not contribute to the output *voltage*, due to the selectivity of the output circuit.

The method to be described in this paper depends upon the following principle:

When the output voltages of frequency $\omega/2\pi$ are found by a harmonic analysis for several appropriate unmodulated input voltages of the form E_g sin ωt, the values so obtained can be employed in another harmonic analysis to obtain the harmonic components of the modulation envelope *when a modulated voltage of the form* $e_g = E_g \sin \omega t\ (1 + m \sin pt)$ *is applied.*

This may be expressed otherwise by writing the static characteristic of the device as $I_p = f(E_g)$. From this equation or from a graph of this relation, I_p can be found for a number of values of E_g, for instance,

$$
\begin{aligned}
I_{p_1} &= f(E_{g_1}) \\
I_{p_2} &= f(E_{g_2}) \\
&\cdot\ \cdot\ \cdot\ \cdot\ \cdot \\
I_{p_n} &= f(E_{g_n}).
\end{aligned}
$$

Using these values of I_p, the first harmonic analysis is made to find the relation

$$i_p = F(E_g) \cdot \sin \omega t,$$

the current of frequency $\omega/2\pi$ as a function of E_g. Assigning a number of values to E_g in this expression and finding the corresponding i_p's, and performing a harmonic analysis on these, the m_1, m_2, etc., in the expression $i_p = I_p \sin \omega t\ [1 + m_1 \sin pt + m_2 \cos 2pt + \cdots]$ are found.

Any method of harmonic analysis may be used for either of these steps, but it must be remembered that the first analysis must be capable of detecting at least the third order terms, since it can be shown that modulation distortion is a third order effect, depending on the third derivative of the characteristic and hence the third harmonic of the fundamental carrier voltage. The second analysis (that of the envelope) need only be capable of giving the second harmonic if only that is wanted. Obviously a more complete analysis, using more points, is necessary if higher precision is needed or if the static characteristic is very irregular, but the method is general.

With a double application of the methods of harmonic analysis given by Espley[2] for sine wave signals, only six points need be measured, and for a 100 per cent modulated carrier these will be at the convenient intervals from the static bias point of ± 1, $\pm 1/2$ and $\pm 1/4$ times the maximum peak voltage of the modulated wave. Thus if as in Fig. 2 the maximum peak voltage is 8 volts and the bias is -10 volts the points should be taken at -10 ± 8, -10 ± 4, and -10 ± 2, that is at -2, -6, -8, -12, -14, and -18 volts.

Denoting the ordinates on Fig. 1 by subscripts corresponding to the instantaneous negative grid voltage, Espley's formula gives for the fundamental component of the radio-frequency carrier frequency current for signal = 4 volts, 8 volts, and 0 volts radio frequency:

[2] D. C. Espley, "Harmonic production in thermionic valves," Proc. I.R.E., vol. 21, no. 10, p. 1444, formula 12; October, (1933).

$J_0 = \frac{1}{3}(I_2 + I_3 - I_5 - I_6)$ = amplitude of unmodulated carrier current of *fundamental* frequency. (2)

$J_{\max} = \frac{1}{3}(I_0 + I_2 - I_6 - I_8)$ = amplitude of carrier current if double the unmodulated carrier exciting voltage is used; corresponding to the *peak* of the envelope. (3)

$J_{\min} = 0$ = amplitude of carrier frequency component of current corresponding to the *trough* of the envelope. (4)

These relative amplitudes are obviously those corresponding to 100 per cent modulation with a 4-volt carrier. (Peak carrier voltages are used throughout this paper.)

The derivation of the formulas for modulation rise and modulation distortion is analogous to the determination of the modulation of the *direct plate current* and audio-frequency distortion in an audio-frequency amplifier when the tube is operated with a signal just sufficient to reach cut-off, that is for 100 per cent modulation of the effective grid voltage.

In the audio-frequency amplifier

$$I_{DC} = \tfrac{1}{4}(I_{\max} + I_{\min} + 2I_0) = \textit{total}\text{ average current}$$

$$= \tfrac{1}{4}(I_{\max} + 2I_0) \qquad \text{if } I_{\min} = 0.$$

$$I_{\text{fundamental}} = \tfrac{1}{2}(I_{\max} - I_{\min}) = \tfrac{1}{2}I_{\max} \qquad \text{”} \quad \text{”} \quad = 0.$$

$$I_{\text{2nd harmonic}} = \tfrac{1}{4}(I_{\max} + I_{\min} - 2I_0) = \tfrac{1}{4}(I_{\max} - 2I_0) \qquad \text{”} \quad \text{”} \quad = 0.$$

$$\frac{I_{\text{fundamental}}}{I_{DC}} = \frac{\frac{1}{2}I_{\max}}{\frac{1}{4}(I_{\max} + 2I_0)} = \frac{1}{\frac{1}{2} + \frac{I_0}{I_{\max}}} \qquad \text{”} \quad \text{”} \quad = 0.$$

$$\frac{I_{\text{2nd harmonic}}}{I_{\text{fundamental}}} = \frac{\frac{1}{4}(I_{\max} - 2I_0)}{\frac{1}{2}I_{\max}} = \frac{1}{2} - \frac{I_0}{I_{\max}} \text{(usually expressed in per cent)}$$

$$\text{if } I_{\min} = 0.$$

By substituting $J_{\max}$, $J_{\min}$, and J_0 for $I_{\max}$, $I_{\min}$, and I_0, respectively, in the above, the formula for modulation of the radio-frequency carrier results in one case and that for per cent second harmonic modulation distortion in the other.

Thus the fundamental modulation factor, m_1, may be computed by means of the formula

$$m_1 = \frac{1}{\frac{1}{2} - \frac{J_0}{J_{\max}}}.$$

This value of modulation is understood to be the factor m_1 in (1), given above, and is twice the ratio of either of the side band currents of frequency $\omega \pm p/2\pi$ to the current of carrier frequency $\omega/2\pi$. The second harmonic distortion of envelope of fundamental radio-frequency output $= \frac{1}{2} - J_0/J_{max}$.

Referring to Fig. 1 and equations (2) and (3) one obtains

$$\frac{J_0}{J_{max}} = \frac{(I_2 - I_6) + (I_3 - I_5)}{(I_2 - I_6) + (I_0 - I_8)}.$$

The values of BF, CE, and AG may be easily measured from the static characteristic with a pair of dividers, making possible a very rapid analysis of the tube's performance.

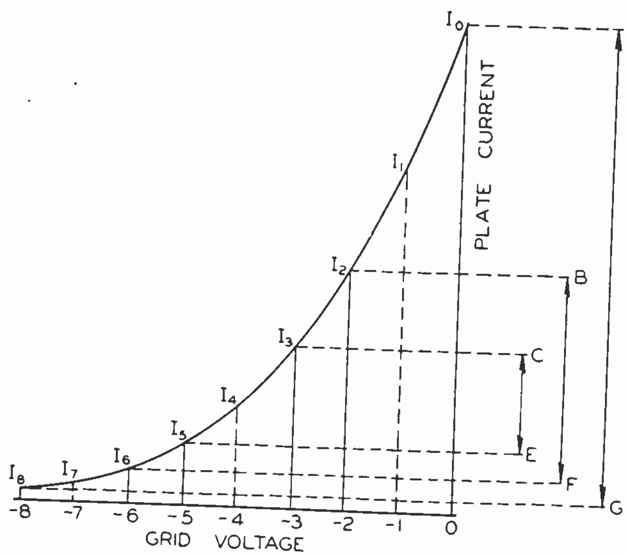

Fig. 1

The curve of Fig. 2 is a graph of the cubic equation $1000 I_b = (E_c + 26)^3$ and the exact values of the required ordinates are as follows:

E_c	I_b
-2	13.824
-6	8.000
-8	5.832
-10	4.096

E_c	i_b
-12	2.744
-14	1.728
-18	0.512

Then the modulation distortion by the harmonic analysis

$$= \frac{1}{2} - \frac{8 - 1.728 + 5.832 - 2.744}{8 - 1.728 + 13.824 - 0.512}$$

$$= \frac{1}{2} - \frac{9.360}{19.584} = 2.206 \text{ per cent}$$

of the fundamental component of the envelope.

For this cubic curve the exact values are 271/266 = 101.88 per cent modulation and 6/271 = 2.214 per cent second harmonic distortion as may be shown by an algebraic substitution. The error in the value of modulation obtained by the harmonic analysis is due to the fact that the three-point analysis of the *envelope* for the fundamental does not allow for the third harmonic of modulation which exists to the

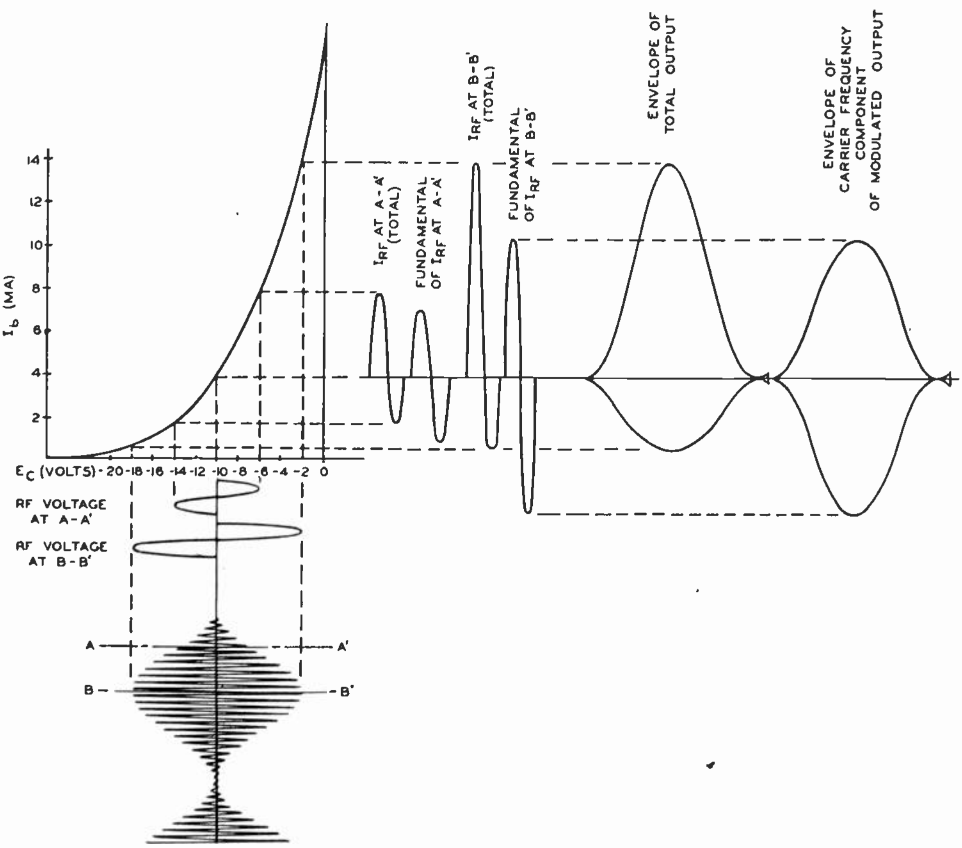

Fig. 2

extent of one sixth of the second harmonic. A more accurate analysis of the envelope using more points could be made, but the following correction is usually sufficiently accurate:

By dividing the above value of $m_1 = 1.0226$ by $1 + \frac{\%\text{ 3rd harmonic}}{100} =$

$1 + \frac{1}{6}\,\frac{\%\text{ 2nd harmonic}}{100} = 1.00368$ the correct value of 1.0188 is obtained for m_1. Multiplying the value of per cent second harmonic,

$x = 2.206$ per cent, by 1.00368 also gives a closer approximation to the true value of the second harmonic, but this error in the per cent second harmonic may be safely ignored. With any other value of m, say M, the per cent second harmonic is equal to M times that for $m = 1$.

The final formulas are then

$$\% \text{ 2nd harmonic} = \left(\frac{1}{2} - \frac{J_0}{J_{\max}}\right) \times M \;(M \text{ expressed in } \%).$$

Modulation of output (input 100 per cent modulated)

$$= \frac{1}{\dfrac{1}{2} + \dfrac{J_0}{J_{\max}}} \times \frac{1}{1 + \dfrac{1}{6}\,\dfrac{\% \text{ 2nd harmonic (for } m = 1)}{100}}.$$

$$\text{Modulation rise} = \frac{m_1 - m}{m} = m_1 - 1 \quad \text{if } m = 1.$$

Or, referring to Fig. 1

$$\% \text{ 2nd harmonic} = \frac{1}{2} - \frac{BF + CE}{BF + AG} \times M \times 100 \text{ per cent}$$

where BF, CE, and AG are conveniently scaled off with dividers from the dynamic characteristic, and if $m = 100$ per cent,

$$m_1 = \frac{1}{\left(\dfrac{1}{2} + \dfrac{BF + CE}{BF + AG}\right)\left[1 + \dfrac{1}{6}\left(\dfrac{1}{2} - \dfrac{BF + CE}{BF + AG}\right)\right]}.$$

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THE DETECTION OF FREQUENCY MODULATED WAVES*

By

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Summary—The comparative ease with which pure frequency modulation can be produced in electron oscillators at ultra-high frequencies has led to an examination of the problem of detecting a frequency modulated wave. In this region of frequencies the high ratio of frequency shift to modulating frequency gives rise to a very large number of side bands in the spectrum representing the modulated wave. Detection is usually accomplished by distorting the spectrum by means of a selective network and then impressing the output voltages upon the grid of a detector. This process is treated analytically and formulas are given which permit the calculation of low-frequency detection products in terms of the transmission characteristic of the distorting network and the maximum frequency shift during modulation.

Measured detection products produced in such a system are compared with values calculated by means of the formulas which are given, and the results are shown to be in substantial agreement over the region in which certain simplifying assumptions are justified.

Introduction

THE analysis of a frequency modulated wave was given by Carson in 1922 and has since been covered rather fully by a number of writers.[1] The problem of the detection of such a wave is of considerable complexity from a theoretical standpoint. When the degree of modulation is low the wave can be represented by a carrier and a relatively small number of side bands, and the products of detection can be evaluated in a straightforward manner. The degree of pure frequency modulation which can be produced in oscillators operating at frequencies in common commercial use is, in general, rather limited, and since the ratio of frequency shift to rate of modulation is not very great the number of side bands in the modulated wave is small. Furthermore, as a result of the comparative ease with which amplitude modulation can be effected, the latter system is employed almost exclusively in commercial installations at the present time.

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[1] J. R. Carson, "Notes on the theory of modulation," Proc. I.R.E., vol. 10, pp. 57–83; February, (1922).
Balth. van der Pol, "Frequency modulation," Proc. I.R.E., vol. 18, pp. 1194–1206; July, (1930).
Hans Roder, "Amplitude, phase, and frequency modulation," Proc. I.R.E., vol. 19, pp. 2145–2177; December, (1931).

In the ultra-high-frequency region of the radio spectrum the Barkhausen-Kurz type of oscillator is often employed as a source of energy. The fact that the frequency of this device is dependent to a large extent upon its operating voltages makes it possible to produce a very considerable degree of pure frequency modulation. Furthermore, pure amplitude modulation becomes difficult for the same reason. Hence it becomes of interest to inquire into the mechanism of the detection of frequency modulated waves with particular reference to the region of ultra-high frequencies. As a result of the high ratio of frequency change to modulating frequency encountered in this region the modulated wave can contain a very large number of side bands and it becomes impractical to evaluate detection products by giving individual consideration to each component of the wave.

In what is to follow there will be given an analytical treatment of the problem together with experimental verification of its validity.

General Discussion

In order to determine the result of applying a frequency modulated wave to a detecting system it is first necessary to obtain a clear concept of the spectrum representing the wave.

Consider a generator of high-frequency oscillations producing a voltage

$$e = A \cos \omega_0 t. \tag{1}$$

If in some manner the frequency of the generator is made to vary sinusoidally at a rate $q/2\pi$ so that its instantaneous radian frequency becomes

$$\omega = \omega_0(1 + k \cos qt) \tag{2}$$

then it can be shown[1] that the resultant voltage wave becomes[2]

$$e = A \sum_{n=-\infty}^{\infty} J_n(x) \cos (\omega_0 + nq)t \tag{3}$$

where $J_n(x)$ is the Bessel coefficient of the first kind of order n and argument x, and where $x = k\omega_0/q = \Delta\omega/q$.

The above expression defines a spectrum of frequencies consisting of a "carrier" having the same frequency as the unmodulated generator and differing from the unmodulated amplitude by the factor

[2] This form may be obtained directly from van der Pol's[1] equation (14) by recalling that

$$J_{-n}(x) = (-1)^n J_n(x).$$

$J_o(x)$. Symmetrically disposed about the carrier at intervals equal to the modulating frequency are pairs of side bands having the general form

$$AJ_{\pm n}(x) \cos (\omega_0 \pm nq)t. \tag{4}$$

While theoretically the spectrum is of infinite extent, practically it is very definitely limited by the fact that the coefficient $J_n(x)$ approaches zero when n becomes greater than x, so that the spectrum contains approximately $2x$ side bands. Furthermore since x is the ratio of the maximum frequency deviation during modulation to the rate of modulation, the total width of the spectrum is approximately

$$2\left(\frac{\Delta f}{f_0}\right)f_0 = 2\Delta f \qquad (x \gg 1) \tag{5}$$

where f_o is the modulating frequency.

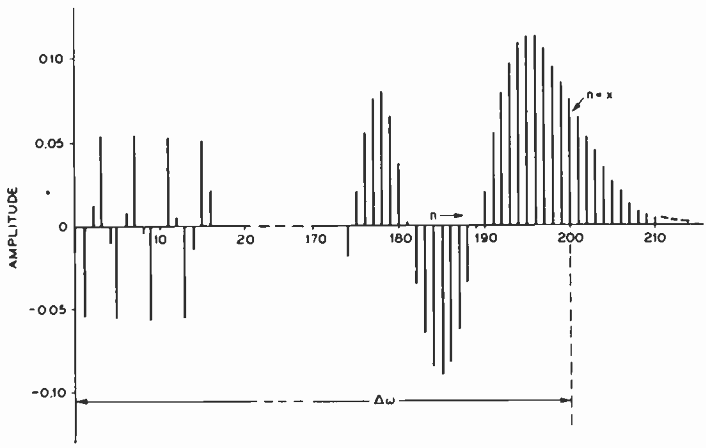

Fig. 1—Upper half of the spectrum of a frequency modulated wave where $x=200$. Amplitude of the unmodulated signal $=1$.

In the case of generators of moderately high frequency the absolute magnitude of the frequency change which can be produced is small and only moderately large values of x are encountered. At ultra-high frequencies, the same percentage change in frequency will yield a correspondingly higher value of x and consequently a greater number of side bands which must be dealt with in attacking the problem of detection. For instance a Barkhausen-Kurz oscillator operating at a wavelength of about half a meter may easily have its frequency varied several hundred kilocycles without sensible change in output by a moderate change in plate voltage. Thus if the frequency is varied ± 200 kilocycles at a rate of 1000 cycles per second, x will be 200, and we shall have somewhat over 400 side bands in the resulting wave. Fig. 1 shows the upper half of the spectrum of this wave where the amplitude of the unmodulated signal voltage is taken as unity. The lower half is similar except that the negative odd order terms have experienced a reversal of sign.

Consideration of the effect of applying this spectrum to the grid of a square-law detector shows that the detection product of fundamental frequency consists of the net effect of the beating together of all adjacent pairs of components throughout the entire spectrum. The carrier and first pair of side bands have practically lost their usual significance, and their complete elimination would scarcely be noticed.

Similarly, a second harmonic will result from the beating together of alternate pairs of components, a third harmonic from the interaction of components differing in order by the factor three, and so on.

It can be shown that the summation of all of these various cross products is zero in each case, and that the sum of the squares of the components is unity. Hence the application of such a spectrum to the grid of a square-law detector results, as far as low-frequency products are concerned, in nothing but an increase in the space current of detector of the same magnitude as that produced by the unmodulated wave. In order to obtain a useful signal it is necessary to distort the spectrum in order to prevent the complete cancellation of the various cross-products which takes place in the absence of distortion. The ideal form of distortion is that produced by a network in which the transmission and phase shift characteristics are linear functions of frequency. These characteristics are usually approximated by means of simple antiresonant circuits, the signal being tuned so that the carrier falls at a point part way down from the peak of the resonance curve. Now the phase and transmission characteristics of such a system are approximately linear only over limited regions. Curvature of the transmission characteristic gives rise to amplitude distortion and the production of harmonics of the modulating frequency. Its effect can be taken care of analytically. The evaluation of the effect of curvature of the phase characteristic, while it could undoubtedly be included in the mathematical treatment, is unnecessary in dealing with the very high-frequency case. The reason for this will be evident from the following considerations. Each of the individual cross-products which must be summed up to give the total fundamental output may be considered as a vector. Each may be shown to be phased with respect to the original modulating signal by an amount equal to the difference in the phase shift introduced by the circuit between adjacent components in the high-frequency spectrum of the wave. If curvature is present in the phase characteristic of the circuit these vectors will not all have the same phase. However, in dealing with the large number of side bands encountered at ultra-high frequencies the difference in phase shift between successive side bands will be very small, and even though the slope of the phase characteristic varies considerably over the region embraced by the spectrum, the vector sum of the cross-products will not differ sensibly from the algebraic sum. The approximation is further improved in the case of a simple tuned circuit by the fact that in the region where the slope of the phase characteristic is changing most rapidly the components have suffered the greatest relative attenuation. As a result their contribution is small compared with that from the other end of the spectrum where the characteristic is more nearly linear.

Similar reasoning can be applied to the summations which yield the harmonics of the modulating frequency. The phase angle which must remain small is the difference in phase shift between components separated by the number of intervals corresponding to the order of the harmonic under consideration. In general, the effect of phase distortion can be neglected at ultra-high frequencies except in cases where the modulating frequency is extremely high, or where the order of the harmonic under consideration is excessive. In the former case the number of side bands is small and it is possible to resort to a step-by-step method of evaluating the products of detection.

Turning next to the effect of the transmission characteristic of the conversion circuit (so called for the reason that it effectively converts frequency into amplitude modulation), it is necessary to define its shape rather accurately over the region embraced by the high-frequency spectrum. This is particularly true where we are concerned with the evaluation of harmonics of the modulating frequency. The most general expression for this characteristic is a power series. Usually the curve has the general characteristics of a simple resonance curve. The point at which the carrier falls on this curve is conveniently taken as the origin, and it is in general considerably removed from the peak of the curve. In order to define the entire extent of such a characteristic by means of power series it is necessary to include a large number of terms. However, it is known from experience that if the frequency shift during modulation is sufficiently great to produce important side bands which lie beyond the peak of the curve, severe distortion will occur. Hence, if we limit the region over which the series is to give adequate representation to that portion of the characteristic lying to one side of the peak and exclude the very small region close to the peak where the slope undergoes rapid changes, it is usually possible to obtain a satisfactory representation by means of a series ending with a term of the third degree.

More specifically, we shall write the gain-frequency characteristic of the radio receiver as a function of its gain at the carrier frequency and δf, the amount by which we depart from this point. Thus,

$$\text{Gain} = a_0 + a_1\delta f + a_2\overline{\delta f^2} + a_3\overline{\delta f^3}. \tag{6}$$

A simple and convenient method of determining the coefficients of an experimentally determined curve is given in Appendix A.

Having determined the equation of the characteristic of the conversion circuit it is then possible to write a general expression for the amplitude of any component of the spectrum. The appropriate cross-product is then formed and the resulting expression is subjected to the process of summation over the entire spectrum. The actual carrying out of this process involves the use of certain mathematical devices which will be treated in a later section. The final results are of comparatively simple form and are readily applied to specific cases once the coefficients of the circuit characteristic have been determined.

The formulas by means of which the magnitudes of certain low-frequency detection products can be determined under the conditions outlined above are as follows:

$$\begin{aligned}\Delta i_p = \frac{A^2\alpha}{2}\Bigg[& a_0^2 + \overline{\Delta f^2}\left(a_0a_2 + \frac{a_1^2}{2} + a_1a_3f_0^2 + \frac{a_2^2}{2}f_0^2 + \frac{a_3^2}{2}f_0^4\right)\\ & + \overline{\Delta f^4}\left(\frac{3}{8}a_2^2 + \frac{3}{4}a_1a_3 + \frac{15}{8}a_3^2f_0^2\right)\\ & + \overline{\Delta f^6}\left(\frac{5}{16}a_3^2\right)\Bigg].\end{aligned} \tag{7}$$

$$\begin{aligned}\text{Fundamental} = A^2\alpha\Bigg[& \Delta f(a_0a_1 + a_0a_3f_0^2)\\ & + \overline{\Delta f^3}\left(\frac{3}{4}a_1a_2 + \frac{3}{4}a_0a_3 + \frac{3}{2}a_2a_3f_0^2\right)\\ & + \overline{\Delta f^5}\left(\frac{5}{8}a_2a_3\right)\Bigg]\cos qt.\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Second Harmonic} = A^2\alpha\Bigg[& \overline{\Delta f^2}\left(\frac{a_0a_2}{2} + \frac{a_1^2}{4} + \frac{a_1a_3}{2}f_0^2 - \frac{a_2^2}{4}f_0^2 + \frac{a_3^2}{4}f_0^4\right)\\ & + \overline{\Delta f^4}\left(\frac{a_2^2}{4} + \frac{a_1a_3}{2} + \frac{a_3^2}{2}f_0^2\right)\\ & + \overline{\Delta f^6}\left(\frac{15}{64}a_3^2\right)\Bigg]\cos 2qt.\end{aligned} \tag{9}$$

$$\text{Third Harmonic} = A^2\alpha\left[\overline{\Delta f}^3\left(\frac{a_0a_3}{4}+\frac{a_1a_2}{4}-\frac{a_2a_3}{2}\,f_0^2\right)\right.$$
$$\left.+\overline{\Delta f}^5\left(\frac{5}{16}\,a_2a_3\right)\right]\cos 3qt. \tag{10}$$

In the above expressions

A = amplitude of the unmodulated signal voltage impressed upon the input to the receiver.

Δf = maximum frequency shift during modulation.

f_o = rate of modulation $= q/2\pi$

α = detection coefficient of the square-law detector.

Δi_p = increase in detector space current.

a_0, a_1, etc. = coefficients of the conversion circuit characteristic as expressed by (6).

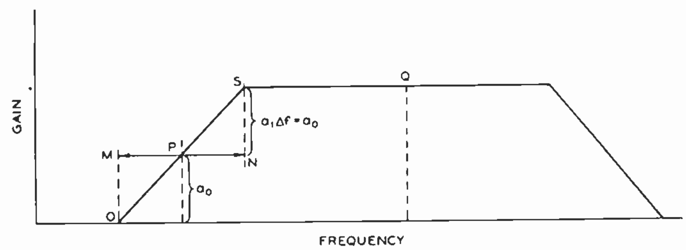

Fig. 2—Assumed form of receiver gain-frequency characteristic.

These relations are simple functions of the circuit coefficients and the maximum frequency shift during modulation. They are suggestive of the equations encountered in ordinary vacuum tube problems involving a nonlinear characteristic, with the term Δf replacing the usual amplitude factor. It will be noted that certain terms are proportional to some power of f_0. Normally these terms are very small and can be neglected entirely.[3]

It is interesting to compare a system utilizing frequency modulation with one in which pure amplitude modulation is employed. If at the transmitter an oscillator of the Barkhausen-Kurz type is used, it is necessary to take into consideration the fact that during frequency modulation the oscillator is adjusted for maximum output. On the other hand if amplitude modulation is used it is necessary to operate at reduced output so that reserve power may be available during modulation. Thus if complete modulation is to be produced under the latter system it is necessary to reduce the amplitude of the unmodulated signal to one half of its maximum value.

For simplicity, assume that the receiver has the characteristic shown in Fig. 2. Then assuming that either type of modulation can be

[3] Terms of similar form are encountered in the amplitude modulation case when the high-frequency spectrum is distorted in a corresponding manner.

produced at the transmitter, the carrier will be tuned to point P during frequency modulation and at point Q if amplitude modulation is employed. In the first case if Δf is adjusted so that the spectrum of the modulated wave embraces the region MN, the equivalent of complete modulation will be secured.

The region of the receiver characteristic between O and S can be written

$$\text{Gain} = a_0 + a_1 \delta f. \tag{11}$$

If the transmitter when adjusted for maximum output impresses a voltage E upon the input to the receiver, then by (8) the amplitude of the fundamental at the output terminals of the receiver will be

$$\alpha E^2 \Delta f a_0 a_1. \tag{12}$$

If Δf is now adjusted to give the equivalent of complete modulation we may write

$$a_1 \Delta f = a_0 \tag{13}$$

so that (12) becomes

$$\alpha E^2 a_0{}^2. \tag{14}$$

Suppose now that the transmitter is adjusted to give complete amplitude modulation and that the signal is tuned to point Q. Then since the amplitude of the unmodulated signal from the transmitter has been halved, the voltage impressed upon the detector will be

$$2a_0\left(\frac{E}{2}\right)\sin \omega t(1 + \sin qt). \tag{15}$$

Calculating the amplitude of the detection product of fundamental frequency, we again obtain (14). Thus the two systems give identical results.

If the conventional type of oscillator had been employed, the transmitter could not have been operated continuously at peak output during frequency modulation. In this case the unmodulated output of the transmitter would have been the same in the two instances, and the amplitude modulation system would have produced four times as much fundamental amplitude as the other system. This disparity could be remedied by increasing the high-frequency gain of the receiver by six decibels.

One of the fundamental differences between the two systems of modulation is the following:

In amplitude modulation the variations in the energy associated with the high-frequency wave which occur during modulation are primarily supplied by the source which energizes the transmitter.

In a system employing frequency modulation the energy in the high-frequency wave remains constant during modulation, and the energy which is associated with the useful output of the detector is supplied by the source which energizes the receiver.

Experimental Investigation

In order to obtain experimental evidence of the existence of a spectrum represented by (3), a comparatively low-frequency source of frequency modulated waves was employed. It was desired to produce a moderately high degree of modulation so that the spectrum would contain a number of components, preferably separated in frequency by

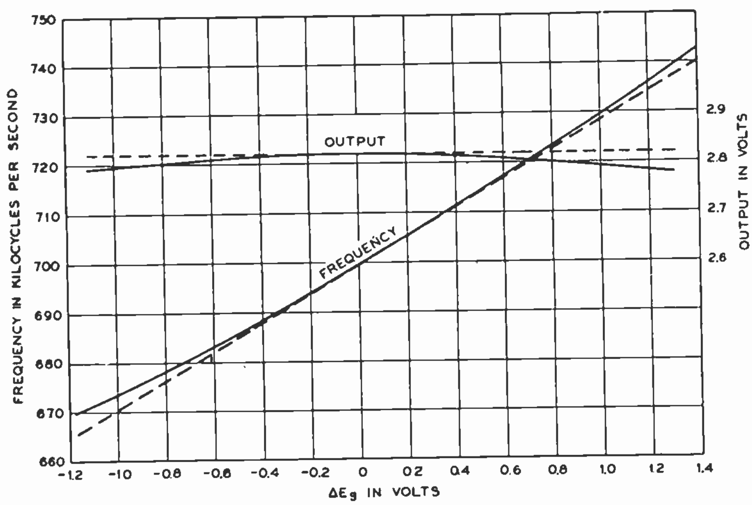

Fig. 3—Frequency and output of multivibrator as a function of grid voltage change.

an amount sufficient to facilitate the measurement of their individual amplitudes. This required that the source undergo a very considerable percentage change in frequency during modulation. It was further necessary that the frequency of the source should be linearly related to the modulating voltage, and that its amplitude remain constant during modulation. These requirements were approximately fulfilled by a multivibrator modulated by means of an alternating voltage applied to the grids of the vacuum tubes. The frequency and amplitude characteristics which were obtained with this device are shown by the solid curves in Fig. 3.

Measurement of the amplitudes of the various side bands was accomplished in the following manner. Voltage from an adjustable heterodyne oscillator and the output voltage of the multivibrator were impressed simultaneously upon the grid of a detector. Following the detector was a highly selective 800-cycle amplifier and indicating device. Then as the frequency of the heterodyne oscillator was varied through the spectrum a series of audible beat notes could be observed at the output of the detector. At the output of the selective amplifier two equal indications were observed as the frequency of the beating oscillator passed through the immediate vicinity of each component. These indications served as a measure of the relative amplitudes of the side bands.

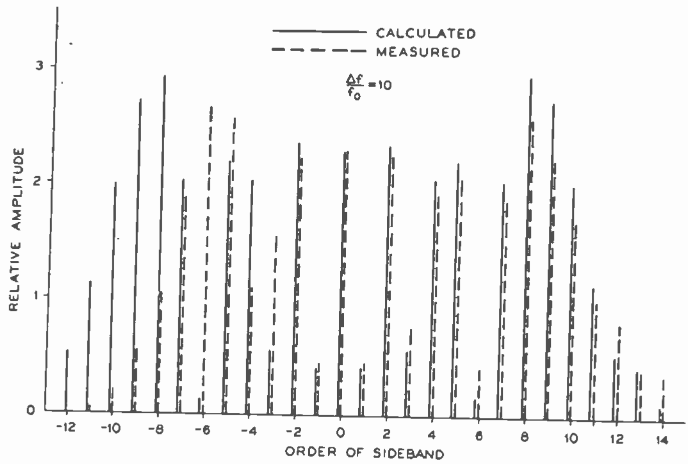

Fig. 4—Observed and calculated spectrum of frequency modulated wave where $x = 10$. Calculated values are proportional to $|J_n(10)|$.

Fig. 4 shows the result of a measurement of the spectrum produced by modulating the multivibrator so as to produce a frequency shift of $\pm$ 30 kilocycles at a rate of 3000 cycles per second. This corresponds to a value of $x = 10$. While the interval between adjacent side bands

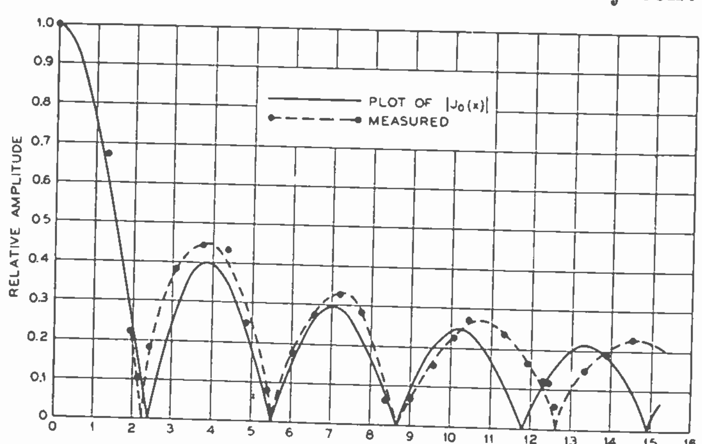

Fig. 5—Magnitude of carrier as a function of x during frequency modulation.

could not be determined accurately with the equipment employed in this experiment, a measurement of the average interval over the spectrum gave a value of 3.01 kilocycles.

For comparison the theoretical values of the side bands (on a relative basis) are also plotted. While the correspondence between experimental and theoretical amplitudes is fairly close in the upper half of the spectrum, there is considerable discrepancy in the lower frequency region. This is probably due to the fact that there was considerable curvature in the frequency characteristic of the source, as well as an appreciable amount of concomitant amplitude modulation.

A second series of observations is shown in Fig. 5. The amplitude of the carrier, or zero order component of the spectrum was observed for various values of frequency shift during modulation. The modulating frequency was 3000 cycles as before. Taking the amplitude of the

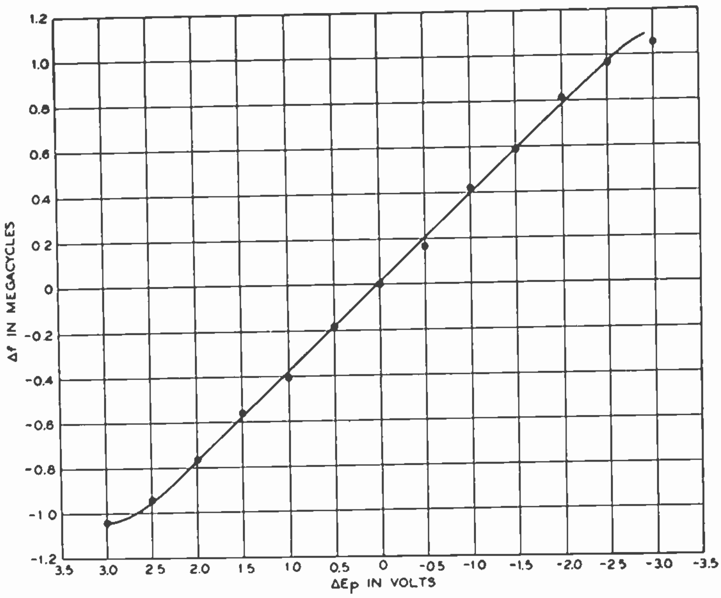

Fig. 6—Frequency change versus plate voltage change for a certain electron oscillator. $\lambda = 56$ centimeters.

unmodulated signal voltage as unity, the absolute magnitude of the carrier during modulation should be equal to $|J_o(x)|$. This is seen to be approximately true. As might be expected from the characteristics of the multivibrator the agreement is best for the smaller values of x.

For the purpose of demonstrating the validity of equations (7) to (10) a practically pure source of frequency modulated waves, capable of a degree of modulation corresponding to rather large values of x, is required. An electron oscillator of the Barkhausen-Kurz type fulfills these requirements very satisfactorily. The manner in which the frequency of a certain oscillator of this type, operating at a wavelength of 56 centimeters, was influenced by changes in plate voltage is shown in Fig. 6. Over the region shown no change in the amplitude of oscillation could be detected.

The process of detecting the modulated ouput of this source was studied by means of a double detection type of receiver. It was assumed that the shape of the over-all response characteristic of the receiver was that of its intermediate frequency amplifier, shown in Fig. 7. A calibrated reference oscillator was arranged to supply a small intermediate-frequency voltage along with the signal after its first detection process. Thus an audible beat note could be observed in the output of the receiver when the beating oscillator was so adjusted

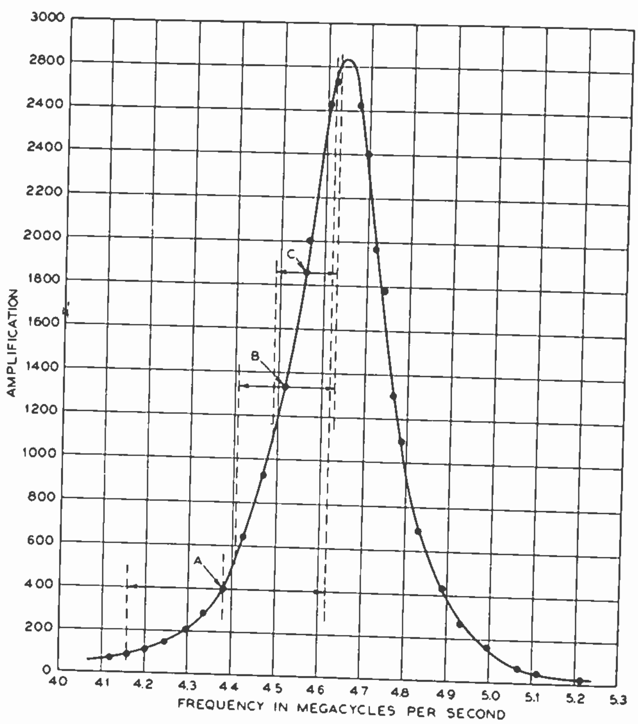

Fig. 7—Intermediate amplifier characteristic of double detection receiver.

as to bring about an approximate correspondence between the frequencies of the reference oscillator and the intermediate-frequency signal. In this manner the unmodulated signal could be set quite accurately at any desired point on the receiver characteristic without disturbing the transmitter in any way. This point will be termed the operating point.

The relative values of the fundamental, second, and third harmonics of the modulating frequency at the output of the second detector were determined by means of a highly selective amplifier-voltmeter. An attenuator between the receiver and the amplifier permitted the measurement of the demodulation products to be read directly in decibels with respect to some convenient reference level.

In modulating the transmitter a 1000-cycle source was arranged to impress two volts upon the plate of the oscillator through a standard attenuator. From Fig. 6 it is indicated that the maximum frequency shift during modulation was ± 570 kilocycles per volt impressed upon the plate of the oscillator.

Fig. 8 shows the results of a series of measurements in which the operating point was fixed at point A in Fig. 7, and the modulation voltage was varied over a wide range of values. Starting at a very low value of modulating voltage the fundamental output of the receiver is seen to increase linearly with increasing modulation over a

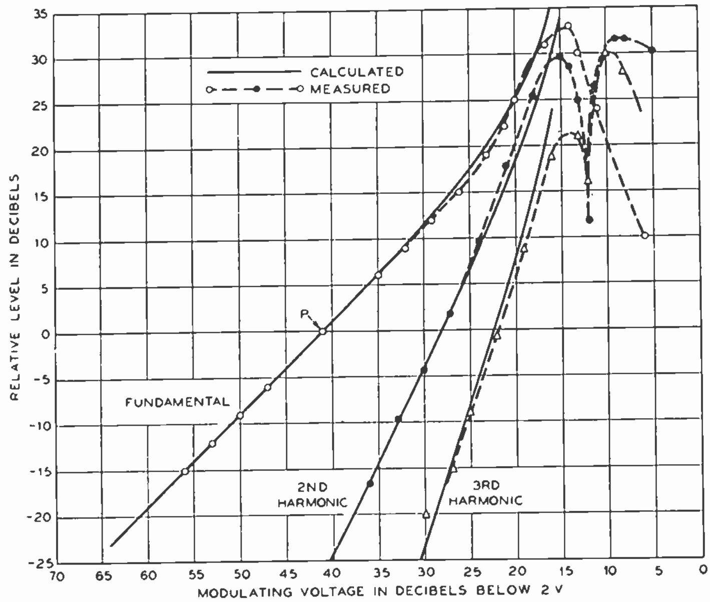

Fig. 8—Detection products resulting from operation at point A in Fig. 7.

considerable region. Further increase in modulation produces a distinct departure from linearity in a direction which is not ordinarily encountered in overloaded systems. The point at which maximum fundamental is obtained corresponds to a frequency shift embracing the region shown at A in Fig. 7, which extends practically to the peak of the resonance curve.

As might be expected from an examination of the shape of the conversion circuit, the second and third harmonic levels are rather high except in the region of very low modulation. In general they will be seen to increase in accordance with the second and third powers, respectively, of the modulating voltage.

The curves drawn in solid lines show the results of the calculated values of fundamental, second, and third harmonics. The equation of the circuit characteristic was obtained by the method described in

Appendix A. Calculation of amplitudes was then carried out on a purely relative basis by means of equations (8) to (10), following which calculated and measured levels of the fundamental output were brought into agreement at point P (Fig. 8). Over a considerable range of modulating voltage the agreement is well within the limits of experimental accuracy. The effect of neglecting the higher order terms which would have been necessary in (6) to define the peak of the resonance curve, is clearly shown.

Fig. 9 shows data obtained in a similar manner with the operating point fixed at B in Fig. 7. This represents a much more desirable oper-

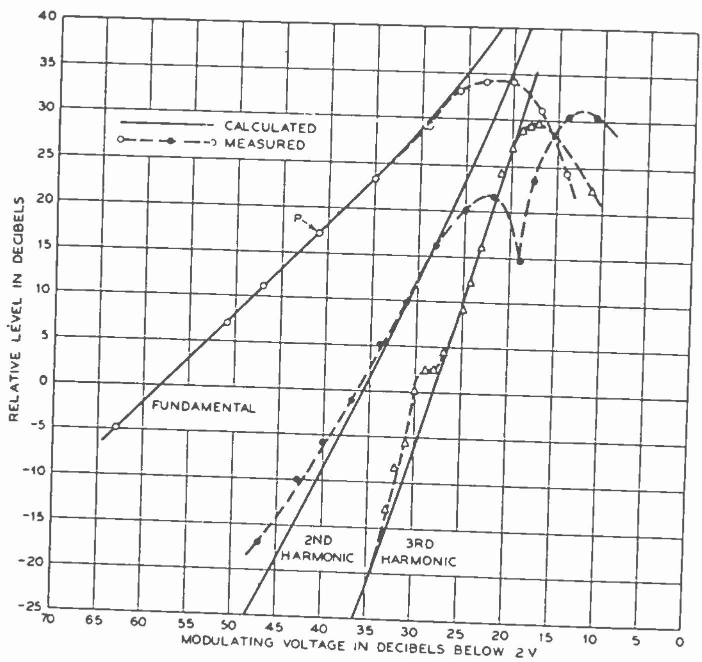

Fig. 9—Detection products resulting from operation at point B in Fig. 7.

ating condition and leads to considerably less distortion than was observed in the first case. Calculated values obtained in the same manner as before show an agreement which is consistent with the degree of approximation involved. As before, the experimental and calculated values of fundamental output were brought into agreement at point P.

The curves shown in Fig. 10 were obtained by varying the operating point while keeping the modulating voltage at a fixed level 30 decibels below two volts. The condition yielding a maximum of fundamental is shown at C in Fig. 7. This operating point is approximately a point of inflection on the circuit characteristic, and would be expected to yield the best ratio of fundamental to second harmonic.

In performing the calculations for this set of conditions it was necessary to obtain a new set of coefficients for each operating point. In certain regions of the resonance curve, the neglecting of higher order terms resulted in a certain lack of consistency in the calculated results. Some of the points on the calculated curves are therefore somewhat scattered. In general, all of the tendencies exhibited by the calculated values are present in the experimental curves.

While there is a reasonable degree of consistency between the data in Figs. 8 to 10, there is a possible discrepancy of several decibels

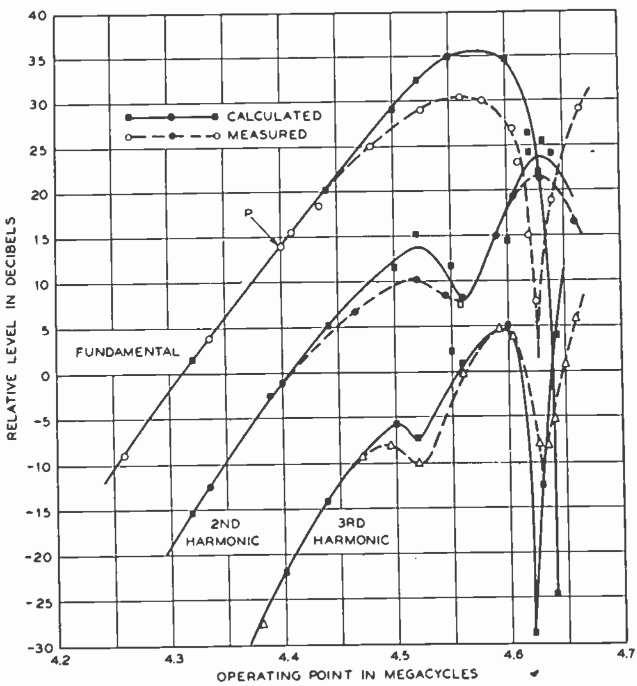

Fig. 10—Detection products as a function of the location of the operating point on the curve in Fig. 7. Modulating voltage held constant at a value 30 decibels below two volts.

between the scale of ordinates in the three sets of data. This is due to the fact that the output of the transmitter did not remain strictly constant over a long period of time. The curves in any one group are felt to be consistent among themselves since frequent checks were made of the output level under some convenient reference condition.

The above data give a general idea of the amount of distortion produced by a conversion circuit of typical form for various operating conditions, and show that the formulas which have been given are sufficiently accurate for most engineering purposes.

Mathematical Treatment

Suppose that a series of voltages

$$\sum_{p=0}^{\infty} e_p \cos(\omega_p t + \theta_p) = e_g \tag{16}$$

be impressed upon the grid of a detector having the characteristic

$$i_p = i_0 + \alpha e_g^2. \tag{17}$$

Then the resulting current may be written

$$i_p = i_0 + \frac{\alpha}{2} \sum_{m=0}^{\infty} \sum_{p=0}^{\infty} \epsilon_m e_p e_{p+m} [\cos(\omega_{p+m} t + \omega_p t + \theta_{p+m} + \theta_p) + \cos(\omega_{p+m} t - \omega_p t + \theta_{p+m} - \theta_p)] \tag{18}$$

where ϵ_m is Neumann's factor $=1$ when $m=0$, and 2 when $m \neq 0$.

If the voltages e_p and e_{p+1} differ in frequency by a constant amount $q/2\pi$ we may write

$$\omega_{p+m} = \omega_p + mq. \tag{19}$$

Then,

$$i_p = i_0 x \frac{\alpha}{2} \sum_{m=0}^{\infty} \sum_{p=0}^{\infty} \epsilon_m e_p e_{p+m} [\cos[(2\omega_p + mq)t + \theta_{p+m} + \theta_p] + \cos[mqt + (\theta_{p+m} - \theta_p)]]. \tag{20}$$

The low-frequency detection products are given by the second series of cosine terms in the above expression. Current of frequency $mq/2\pi$ will be

$$i_m = \frac{\alpha}{2} \epsilon_m \sum_{p=0}^{\infty} e_p e_{p+m} \cos(mqt + [\theta_{p+m} - \theta_p]). \tag{21}$$

Let us now replace the general series of voltages in (16) by the spectrum representing a frequency modulated wave as defined by (3), and modified by the conversion circuit. Each of the components of this spectrum will be modified in amplitude by some factor b_n, and each will have experienced a phase shift θ_n depending upon its position in the spectrum. We may then write

$$i_m = \frac{\alpha}{2} \epsilon_m A^2 \sum_{n=-\infty}^{\infty} b_n b_{n+m} J_n(x) J_{n+m}(x) \cos(mqt + [\theta_{n+m} - \theta_n]). \tag{22}$$

In the absence of phase distortion in the conversion circuit the term $\theta_{n+m} - \theta_n$ will be a constant. In general, however, it will be a function of n, so that

$$i_m = \frac{\alpha}{2} \epsilon_m A^2 \sum_{-\infty}^{\infty} b_n b_{n+m} J_n J_{n+m} (\cos mqt \cos \theta' - \sin mqt \sin \theta') \tag{23}$$

where $\theta' = \theta_{n+m} - \theta_n$. If θ' is small as it ordinarily is in cases where n is large, and when m is not too great, we may make the approximation

$$\cos\theta' = 1$$
$$\sin\theta' = 0$$

and finally obtain the following expressions for the products of demodulation:

$$\Delta i_p = \frac{\alpha}{2} A^2 \sum_{-\infty}^{\infty} b_n^2 J_n^2 \tag{24}$$

$$\text{Fundamental} = \alpha A^2 \sum_{-\infty}^{\infty} b_n b_{n+1} J_n J_{n+1} \cos qt \tag{25}$$

$$m^{\text{th}} \text{ Harmonic} = \alpha A^2 \sum_{-\infty}^{\infty} b_n b_{n+m} J_n J_{n+m} \cos mqt. \tag{26}$$

The final form of the amplitude factors will depend upon the shape of the conversion circuit characteristic. If this is defined in terms of a power series as given in(6) the quantity δf can be replaced by nf_0 since f_0, the modulating frequency, represents the intervals between succession components in the spectrum. Then in general

$$b_{n+m} = a_0 + a_1[(n+m)f_0] + a_2[(n+m)f_0]^2 + a_3[(n+m)f_0]^3. \tag{27}$$

After forming the appropriate product $b_n b_{n+m}$ it becomes necessary to evaluate a summation of the general type

$$\sum_{n=-\infty}^{\infty} [A + Bn + Cn^2 + \cdots Gn^6] J_n J_{n+m}. \tag{28}$$

The evaluation of this summation has been accomplished by the aid of a group of forms due to S. A. Schelkunoff, the derivation of which is outlined in Appendix B. The equations of interest in the present connection are the following:

$$\sum_{n=0}^{\infty} J_n J_{n+m} = \frac{x}{2m}(J_0 J_{m-1} + J_1 J_m) \quad (m \neq 0) \tag{29}$$

$$= \frac{1}{2} + \frac{J_0^2}{2} \qquad \text{when } m = 0.$$

$$\sum_{n=0}^{\infty} \epsilon_n^{2\kappa} [J_{n+\kappa}(x)]^2 = \frac{x^{2\kappa}}{2^{2\kappa}(\kappa!)^2}$$

$$\sum_{n=0}^{\infty} \epsilon_n^{2\kappa+1} J_{n+\kappa}(x) J_{n+\kappa+1}(x) = \frac{x^{2\kappa+1}}{2^{2\kappa+1}\kappa!(\kappa+1)!}$$

$$\cdots\cdots\cdots\cdots$$

$$\sum_{n=0}^{\infty} \epsilon_n^{2\kappa+r} J_{n+\kappa}(x) J_{n+\kappa+r}(x) = \frac{x^{2\kappa+r}}{2^{2\kappa+r}\kappa!(\kappa+r)!} \tag{30}$$

where,

$$\epsilon_n{}^m = \frac{(2n + m)(n + m - 1)!}{m!n!} \quad (m \neq 0)$$

$$\epsilon_n{}^0 = \text{Neumann's factor.}$$

This coefficient may be considered a generalized form of Neumann's factor. In general it is expressible as a polynomial in n. For instance,

$$\epsilon_n{}^3 = \frac{2n^3 + 9n^2 + 13n + 6}{3!}.$$

Formulas (29) and (30) are not directly applicable to the solution of (28). For this purpose we need the series of summations

$$\sum_{n=-\infty}^{\infty} n^p J_n(x) J_{n+m}(x). \tag{31}$$

This series is most readily obtained from the original forms by first performing the transformations indicated below. These may be readily verified.

$$\begin{aligned} \sum_{n=-\infty}^{\infty} n^p J_n{}^2 &= 2 \sum_{n=0}^{\infty} n^p J_n{}^2 && \text{when } p \text{ is even} \\ &= 0 && \text{when } p \text{ is odd.} \\ &= 1 && \text{when } p = 0. \end{aligned} \tag{32}$$

$$\begin{aligned} \sum_{n=-\infty}^{\infty} n^p J_n J_{n+1} &= \sum_{n=0}^{\infty} [n^p + (-1)^{p-1}(n+1)^p] J_n J_{n+1} \\ & \qquad \text{when } p \geqq 1 \\ &= 0 \qquad \text{when } p = 0 \end{aligned} \tag{33}$$

$$\begin{aligned} \sum_{n=-\infty}^{\infty} n^p J_n J_{n+2} &= \sum_{n=0}^{\infty} [n^p + (-1)^p(n+2)^p] J_n J_{n+2} + (-1)^{p-1} J_1{}^2 \\ & \qquad \text{when } p \geqq 2 \\ &= 0 \qquad \text{when } p < 2 \end{aligned} \tag{34}$$

$$\begin{aligned} \sum_{n=-\infty}^{\infty} n^p J_n J_{n+3} &= \sum_{n=0}^{\infty} [n^p + (-1)^{p-1}(n+3)^p] J_n J_{n+3} \\ &\quad + (-1)^p(2^p - 1) J_1 J_2 \\ & \qquad \text{when } p \geqq 3 \\ &= 0 \qquad \text{when } p < 3. \end{aligned} \tag{35}$$

It is then possible to identify the expressions on the right-hand side of the above equations in terms of (29) and a modified form of (30). This modification consists in replacing the variable n in (30) by $(n-\kappa)$ so as to obtain expressions of the form

$$\sum_{n=0}^{\infty} \epsilon_u{}^v J_{n'} J_{n+m} = f(x). \tag{36}$$

The evaluation of (31) has been carried out in this manner for values of m from zero to three and for powers of n through the sixth, and the results are given in Table I. With these it is possible to solve directly the appropriate form of (28), and hence of (26). Then upon replacing x by its value $\Delta f \div f_0$, formulas (7 to 10) given in the second section of the paper, are obtained.

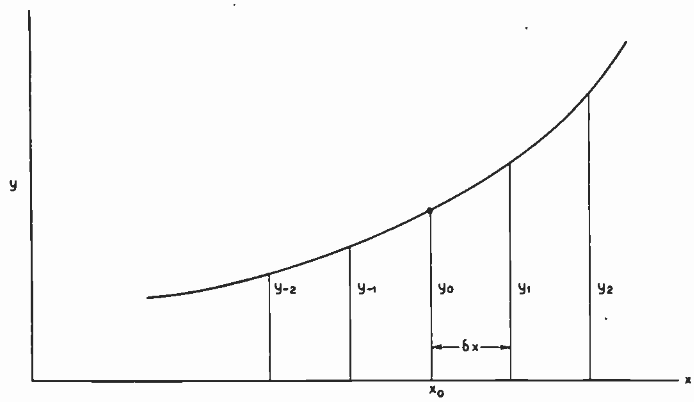

Fig. 11—Method of drawing ordinates for the determination of the equation of an empirical curve.

Acknowledgment

The writer wishes to express his appreciation for the work of Mr. S. A. Schelkunoff who contributed the basic material contained in Appendix B, and who made many helpful suggestions. He is also indebted to Messrs. E. A. Krauth and O. E. DeLange for assistance in obtaining the experimental data.

Appendix A

The following is a simple and convenient method of finding the equation of an experimentally determined curve. The equation is expressed in terms of the departure of the value of the independent variable from some fixed value. The coefficients in (6) are readily determined by this method.

Having plotted the experimental curve as shown in Fig. 11, ordinates are drawn at equal intervals of x on either side of x_0 as shown. The use of a schedule involving a total of n ordinates will yield an equation of degree $n-1$. Since it is thereby assumed that the true equation of the curve does not contain terms of order greater than $n-1$, the result will be in error if this is not the case. Actually the use of a very large number of ordinates is of doubtful value unless the curve has been determined to a rather high degree of accuracy.

The use of five ordinates as shown in the accompanying diagram will yield an equation of the form

$$y = a_0 + a_1\,\delta x + a_2\overline{\delta x}^2 + a_3\overline{\delta x}^3 + a_3\overline{\delta x}^4. \tag{37}$$

Having completed the construction the values of the ordinates are arranged in a column as shown below.

$$\begin{array}{ccccc}
y_2 & & & & \\
 & \Delta_2 & & & \\
y_1 & & \Delta_1{}^2 & & \\
 & \Delta_1 & & \Delta_1{}^3 & \\
y_0 & & \Delta_0{}^2 & & \Delta_0 \\
 & \Delta_{-1} & & \Delta_{-1}{}^3 & \\
y_{-1} & & \Delta_{-1}{}^2 & & \\
 & \Delta_{-2} & & & \\
y_{-2} & & & &
\end{array} \tag{38}$$

Then the differences between adjacent ordinates are taken and arranged in a second column. This column is next treated in the same manner and the column of second differences (Δ^2) is entered. The process is then repeated until the fourth difference $\Delta_0{}^4$ is obtained. Thus, for instance

$$\begin{aligned}
\Delta_1{}^2 &= \Delta_2 - \Delta_1 \\
\Delta_1{}^3 &= \Delta_1{}^2 - \Delta_0{}^2 \\
\Delta_0{}^4 &= \Delta_1{}^3 - \Delta_{-1}{}^3.
\end{aligned} \tag{39}$$

The values of the various coefficients may then be determined from the table of differences by means of the following relations:

$$\begin{aligned}
a_0 &= y_0 \\
a_1 &= \frac{\Delta_1 + \Delta_{-1}}{2(\delta x)} - \frac{\Delta_1{}^3 + \Delta_{-1}{}^3}{12(\delta x)} \\
a_2 &= \frac{\Delta_0{}^2}{2(\delta x)^2} - \frac{\Delta_0{}^4}{24(\delta x)^2} \\
a_3 &= \frac{\Delta_1{}^3 + \Delta_{-1}{}^3}{12(\delta x)^3} \\
a_4 &= \frac{\Delta_0{}^4}{24(\delta x)^4}.
\end{aligned} \tag{40}$$

The degree of the equation representing any given curve may be determined by taking a somewhat larger number of ordinates and forming the table of differences. Ultimately a column will be found in which all of the terms are of the same value. The order of the differences represented by this column corresponds to the order of the equation which will give an accurate definition of the curve over the region embraced by the ordinates. Thus if Δ_0^4 in (38) is zero, a cubic equation will accurately represent the curve in the region $x=x_2$ to $x=x_{-2}$.

Appendix B

Formulas (29) and (30) are based upon the following developments, for which I am indebted to Mr. Schelkunoff.

It may be readily verified by direct differentiation that

$$\frac{d}{dx}\left[x^{m-k}\sum_{n=0}^{\infty} a_n J_{n+k}(x) J_{n+m}(x)\right]$$
$$= x^{m-k}\sum_{n=0}^{\infty}(a_n - a_{n-1})J_{n+k}(x)J_{n+m}(x). \tag{41}$$

Without loss of generality we can assume $m \nless k$. Integrating (41) we obtain

$$\sum_{n=0}^{\infty} a_n J_{n+k}(x) J_{n+m}(x)$$
$$= x^{k-m}\int_0^x x^{m-k}\sum_{n=0}^{\infty}(a_n - a_{n-1})J_{n+k}(x)J_{n+m-1}(x)dx + Ax^{k-m} \tag{42}$$

where,

$$A = 0 \text{ if } m > k$$
$$= a_{-k} \text{ if } m = k.$$

Let,

$$b_n = a_n - a_{n-1}$$

so that,

$$a_n = b_0 + b_1 + \cdots + b_n. \tag{43}$$

Then assuming $k=0$ in (42) we obtain the special reduction formula

$$\sum_{n=0}^{\infty} a_n J_n J_{n+m} = x^{-m}\int_0^x\left[x^m\sum_{n=0}^{\infty} b_n J_n J_{n+m-1}\right]dx. \tag{44}$$

Putting $a_n=1$, so that $b_0=1$, and $b_1=b_2=\cdots=0$

$$\sum_{n=0}^{\infty} J_n J_{n+m} = x^{-m}\int_0^x [x^m J_0 J_{m-1}]dx \tag{45}$$
$$= \frac{x}{2m}(J_0 J_{m-1} + J_1 J_m) \quad (m \neq 0). \tag{46}$$

For the special case where $m=0$, we place $m=k=0$ in (42), and with $a_n=1$ as before

$$\sum_0^\infty J_n{}^2 = \int_0^x [J_0J_{-1}]dx + 1 \tag{47}$$

$$= \frac{J_0{}^2}{2} + \frac{1}{2}. \tag{48}$$

Equations (46) and (48) correspond to (29) in the text.

The manner in which (30) is obtained can be illustrated as follows:

$$\text{Assume } b_0 = b_1 = 1, \quad b_2 = b_3 = \cdots = 0.$$

Then a becomes the Neumann number

$$a_n = \epsilon_n, \quad \epsilon_0 = 1, \quad \epsilon_1 = \epsilon_2 = \cdots = 2.$$

Putting $k=m=0$ in (42) we obtain

$$\sum_0^\infty \epsilon_n J_n{}^2 = \int_0^x (J_{-1}J_0 + J_0J_1)dx + 1 \tag{46}$$

$$= 1.$$

Now let $b_n=\epsilon_n$. Then a_n assumes the values 1, 3, 5, 7, $\cdots$ for $n=0, 1, 2, 3, \cdots$. A typical number of this sequence will be designated by the symbol $\epsilon_n{}^1$. Then placing $k=0$ and $m=1$ in (42)

$$\sum_0^\infty \epsilon_n{}^1 J_n J_{n+1} = x^{-1}\int_0^x x \sum_0^\infty \epsilon_n J_n{}^2 dx \tag{47}$$

$$= x^{-1}\int_0^x x\,dx = \frac{x}{2}. \tag{48}$$

In the same manner by letting $b_n=\epsilon_n{}^1$, a_n assumes the values 1, 4, 9, 16, $\cdots$ which we shall call $\epsilon_n{}^2$. Then by putting $m=k=1$ in (42) we find that

$$\sum_0^\infty \epsilon_n{}^2 J_{n+1}{}^2 = \frac{x^2}{4}. \tag{49}$$

Proceeding in this fashion (30) may be established.

TABLE I

In the following expressions $\sum_{-\infty}^{\infty} J_n \equiv \sum_{n=-\infty}^{\infty} J_n(x)$

$$\sum_{-\infty}^{\infty} J_n{}^2 = 1$$

$$\sum_{-\infty}^{\infty} n^2 J_n^2 = \frac{x^2}{2}$$

$$\sum_{-\infty}^{\infty} n^4 J_n^2 = \frac{3x^4}{8} + \frac{x^2}{2}$$

$$\sum_{-\infty}^{\infty} n^6 J_n^2 = \frac{5x^6}{16} + \frac{15x^4}{8} + \frac{x^2}{2}$$

$$\sum_{-\infty}^{\infty} n^p J_n^2 = 0 \text{ when } p \text{ is odd.}$$

. . . .

$$\sum_{-\infty}^{\infty} J_n J_{n+1} + 0$$

$$\sum_{-\infty}^{\infty} n J_n J_{n+1} = \frac{x}{2}$$

$$\sum_{-\infty}^{\infty} n^2 J_n J_{n+1} = -\frac{x}{2}$$

$$\sum_{-\infty}^{\infty} n^3 J_n J_{n+1} = \frac{3x^3}{8} + \frac{x}{2}$$

$$\sum_{-\infty}^{\infty} n^4 J_n J_{n+1} = -\frac{3x^3}{4} - \frac{x}{2}$$

$$\sum_{-\infty}^{\infty} n^5 J_n J_{n+1} = \frac{5x^5}{16} + \frac{15x^3}{8} + \frac{x}{2}$$

$$\sum_{-\infty}^{\infty} n^6 J_n J_{n+1} = -\frac{15x^5}{16} - \frac{15x^3}{4} - \frac{x}{2}$$

. . . .

$$\sum_{-\infty}^{\infty} J_n J_{n+2} = 0$$

$$\sum_{-\infty}^{\infty} n J_n J_{n+2} = 0$$

$$\sum_{-\infty}^{\infty} n^2 J_n J_{n+2} = \frac{x^2}{4}$$

$$\sum_{-\infty}^{\infty} n^3 J_n J_{n+2} = -\frac{3x^2}{4}$$

$$\sum_{-\infty}^{\infty} n^4 J_n J_{n+2} = \frac{x^4}{4} + \frac{7x^2}{4}$$

$$\sum_{-\infty}^{\infty} n^5 J_n J_{n+2} = -\frac{5x^4}{4} - \frac{15x^2}{4}$$

$$\sum_{-\infty}^{\infty} n^6 J_n J_{n+2} = \frac{15x^6}{64} + 5x^4 + \frac{31x^2}{4}$$

. . . .

$$\sum_{-\infty}^{\infty} J_n J_{n+3} = 0$$

$$\sum_{-\infty}^{\infty} n J_n J_{n+3} = 0$$

$$\sum_{-\infty}^{\infty} n^2 J_n J_{n+3} = 0$$

$$\sum_{-\infty}^{\infty} n^3 J_n J_{n+3} = \frac{x^3}{8}$$

$$\sum_{-\infty}^{\infty} n^4 J_n J_{n+3} = -\frac{3x^3}{4}$$

$$\sum_{-\infty}^{\infty} n^5 J_n J_{n+3} = \frac{5x^5}{32} + \frac{25x^3}{8}$$

$$\sum_{-\infty}^{\infty} n^6 J_n J_{n+3} = -\frac{45x^5}{32} - \frac{45x^3}{4}.$$

BOOK REVIEWS

Air Law—Outline and Guide to Law of Radio and Aeronautics, by Howard S. LeRoy. Published by Randolph Leigh Publishing Company, 725 15th Street, N.W., Washington, D.C. 120 pages, price $3.00.

This book contains a classified list of references to international, federal, state and other laws relating to radio and aeronautics. It gives references also to decisions and opinions of courts and administrative agencies. While the total number of references must run into the thousands, they are classified in such a way as to make it fairly easy to find any one of the various groups of citations. In spite of this classification, the intermingling of groups of radio and aeronautic references is somewhat confusing for the person who may be interested in only one of these two subjects. It is to be hoped that if another edition of this booklet is issued, the author will see fit to simplify the reference system employed in the alphabetical index. There appears to be no reference to the somewhat important case involving arbitration between two companies engaged in international radiotelegraph communication which was discussed in the "Journal Telegraphique" for May, 1932.

* L. E. Whittemore

Die Patente der Funkempfangstechnik, by Curt Borchardt, consulting radio engineer, Charlottenburg-Berlin, 109 pages. Press of the Union Deutsche Verlagsgesellschaft Zweigniederlassung, Berlin, 1934.

This book is a survey of German patents (a total of approximately 1600) relating to radio receivers. The subject is divided into about a dozen main classifications, each with numerous subdivisions, and in each of these subdivisions the treatment is chronological. The author's purpose is to provide a work of reference for all those professionally interested in the subject with respect to questions of infringement or patentability. At the same time it is a valuable source of material for one who wishes to obtain a bird's-eye view of the historical development, as revealed by patents, of any particular phase of radio receiver technique. The discussion consists merely of a very brief statement, usually in a single sentence, of the principal feature of each patent, with the date of application. At the end of the book there is a table of all German patents in effect on January 1, 1934, with their expiration dates.

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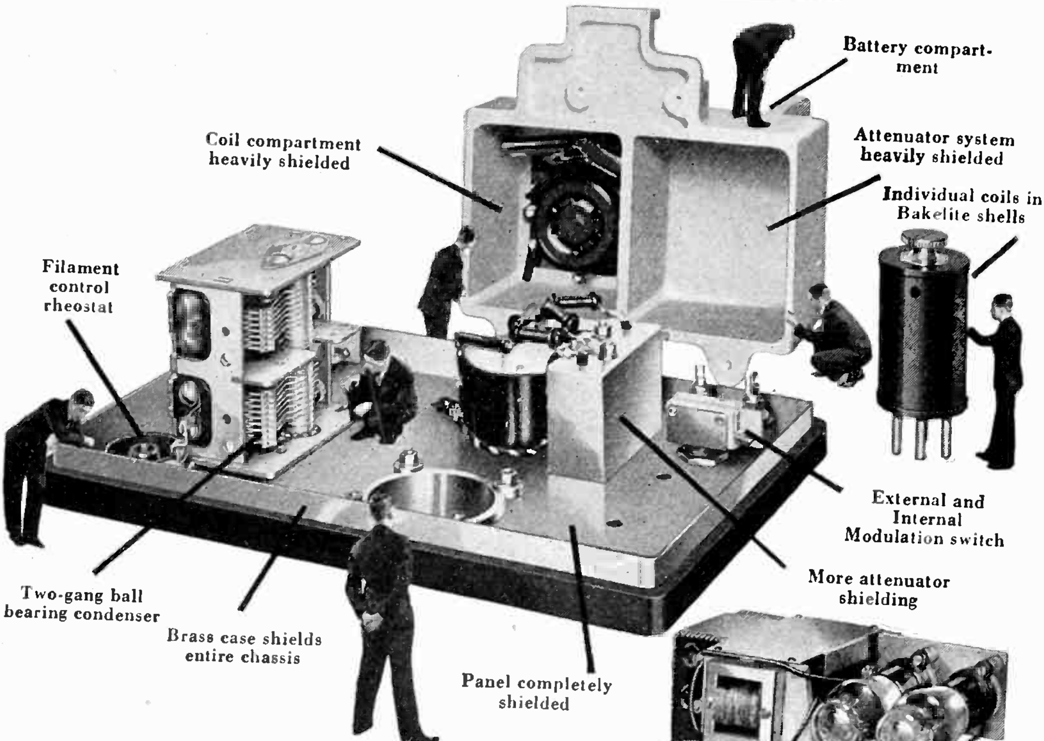

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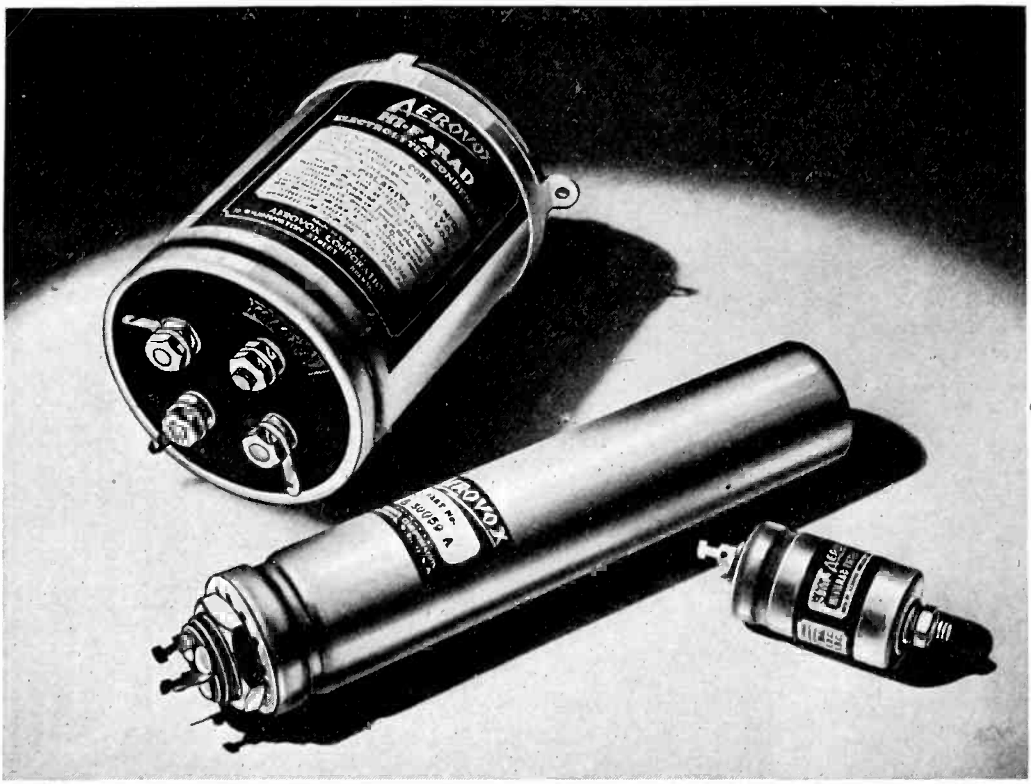

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INSTITUTE SUPPLIES

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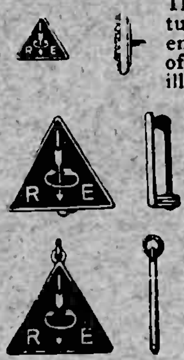

Three styles of emblems are available to members of the Institute only. They are all of 14k gold with gold lettering on an enameled background, the color of which indicates the grade of membership. The approximate size of each emblem is as illustrated.

The lapel button is supplied with a screw back having jaws which fasten it securely to the coat. The price is $2.75, postpaid, for any grade.

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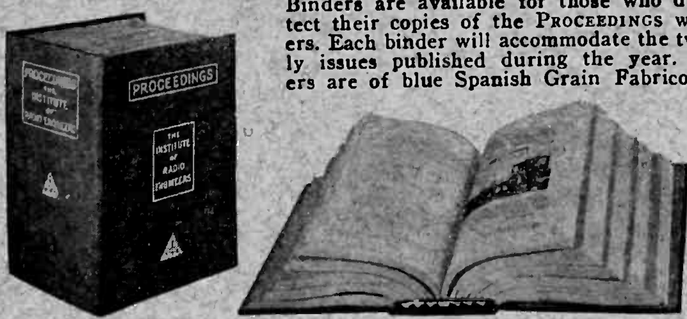
Binders are available for those who desire to protect their copies of the PROCEEDINGS with stiff covers. Each binder will accommodate the twelve monthly issues published during the year. These binders are of blue Spanish Grain Fabricoid with gold lettering, and will serve either as temporary transfers or as permanent binders. They are so constructed that each individual copy of the PROCEEDINGS will lie flat when the pages are turned. Copies can be removed from the binder in a few seconds and are not damaged by their insertion. They are priced at $1.50 each, and the member's name or PROCEEDINGS Volume Number will be stamped upon the binder in gold for $0.50 additional.



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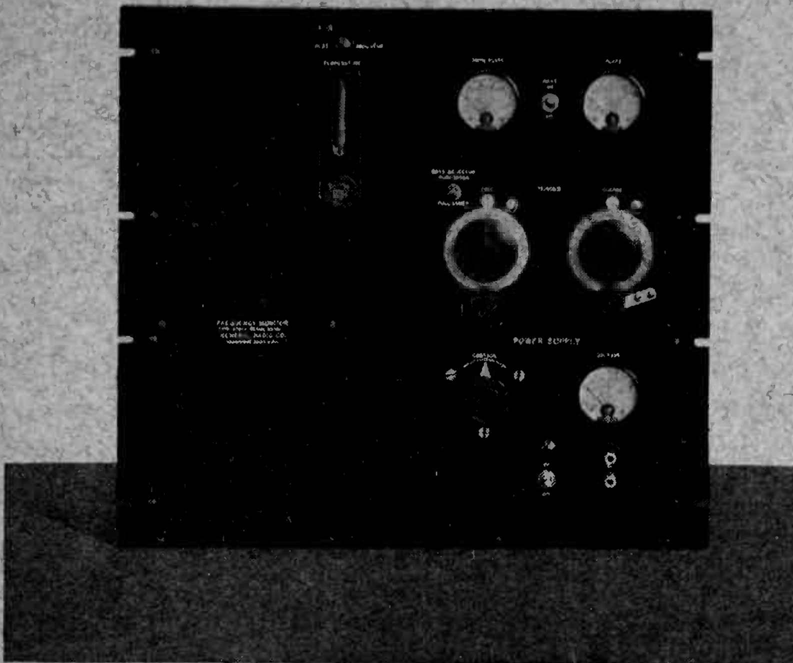

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