VOLUME 17 MARCH, 1929 NUMBER 3

PROCEEDINGS
of
The Institute of Radio Engineers

1929 CONVENTION
Washington, D. C.
May 13-15

General Information and Subscription Rates on Page 404

Institute of Radio Engineers

Forthcoming Meetings

FOURTH ANNUAL CONVENTION
Washington, D. C., May 13–15, 1929

ATLANTA SECTION
Atlanta, Georgia, March 6, 1929

DETROIT SECTION
Detroit, Mich., March 15, 1929

LOS ANGELES SECTION
Los Angeles, Calif., March 18, 1929

NEW YORK MEETING
New York, N. Y., April 3, 1929

PHILADELPHIA SECTION
Philadelphia, Penna., March 22, 1929

PITTSBURGH SECTION
Pittsburgh, Penna., March 19, 1929

SAN FRANCISCO SECTION
San Francisco, Calif., March 20, 1929

WASHINGTON SECTION
Washington, D. C., March 14, 1929

PROCEEDINGS OF
The Institute of Radio Engineers

Volume 17 — March, 1929 — Number 3

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The Institute of Radio Engineers

GENERAL INFORMATION

The PROCEEDINGS of the Institute is published monthly and contains papers and discussions thereon submitted for publication or for presentation before meetings of the Institute or its Sections. Payment of the annual dues by a member entitles him to one copy of each number of the PROCEEDINGS issued during the period of his membership.

Subscription rates to the PROCEEDINGS for the current year are received from non-members at the rate of $1.00 per copy or $10.00 per year. To foreign countries the rates are $1.10 per copy or $11.00 per year.

Back issues are available in unbound form for the years 1918, 1920, 1921, 1922, 1923, and 1926 at $9.00 per volume (six issues) or $1.50 per single issue. Single copies for the year 1928 are available at $1.00 per issue. For the years 1913, 1914, 1915, 1916, 1917, 1918, 1924, and 1925 miscellaneous copies (incomplete unbound volumes) can be purchased for $1.50 each; for 1927 at $1.00 each. The Secretary of the Institute should be addressed for a list of these.

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Year Books for 1926, 1927, and 1928, containing general information, the Constitution and By-Laws, catalog of membership etc., are priced at seventy-five cents per copy per year.

Contributors to the PROCEEDINGS are referred to the following page for suggestions as to approved methods of preparing manuscripts for publication in the PROCEEDINGS.

Advertising rates to the PROCEEDINGS will be supplied by the Institute's Advertising Department, Room 802, 33 West 39th Street, New York, N. Y.

Changes of address to affect a particular issue must be received at the Institute office not later than the 15th of the month preceding date of issue. That is, a change in mailing address to be effective with the October issue of the PROCEEDINGS must be received by not later than September 15th. Members of the Institute are requested to advise the Secretary of any change in their business connection or title irrespective of change in their mailing address, for the purpose of keeping the Year Book membership catalog up to date.

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.

All correspondence should be addressed to the Institute of Radio Engineers, 33 West 39th Street, New York, N. Y., U. S. A.

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SUGGESTIONS FOR CONTRIBUTORS TO THE PROCEEDINGS

Preparation of Paper

Form—Manuscripts may be submitted by member and non-member contributors from any country. To be acceptable for publication manuscripts should be in English, in final form for publication, and accompanied by a summary of from 100 to 300 words Papers should be typed double space with consecutive numbering of pages. Footnote references should be consecutively numbered, and should appear at the foot of their respective pages. Each reference should contain author's name, title of article, name of journal, volume page, month, and year. Generally, the sequence of presentation should be as follows: statement of problem; review of the subject in which the scope, object, and conclusions of previous investigations in the same field are covered; main body describing the apparatus, experiments, theoretical work, and results used in reaching the conclusions conclusions and their relation to present theory and practice; bibliography. The above pertains to the usual type of paper. To whatever type a contribution may belong, a close conformity to the spirit of these suggestions is recommended.

Illustrations—Use only jet black ink on white paper or tracing cloth. Cross-section paper used for graphs should not have more than four lines per inch. If finer ruled paper is used, the major division lines should be drawn in with black ink, omitting the finer de visions. In the latter case, only blue-lined paper can be accepted. Photographs must be very distinct, and must be printed on glossy white paper. Blueprinted illustrations of any kind cannot be used. All lettering should be $^3/_{16}$ in. high for an 8 x 10 in. figure. Legends for figures should be tabulated on a separate sheet, not lettered on the illustrations.

Mathematics—Fractions should be indicated by a slanting line. Use standard symbols. Decimals not preceded by whole numbers should be preceded by zero, as 0.016. Equations may be written in ink with subscript numbers, radicals, etc., in the desired proportions.

Abbreviations—Write a.c. and d.c., kc, μf, $\mu\mu$f, emf, mh, μh, henries, abscissas, antennas Refer to figures as Fig. 1, Figs. 3 and 4, and to equations as (5). Number equations on the right, in parentheses.

Summary—The summary should contain a statement of major conclusions reached, since summaries in many cases constitute the only source of information used in compiling scientific reference indexes. Abstracts printed in other journals, especially foreign, in most cases consist of summaries from published papers. The summary should explain as adequately as possible the major conclusions to a non-specialist in the subject. The summary should contain from 100 to 300 words, depending on the length of the paper.

Publication of Paper

Disposition—All manuscripts should be addressed to the Institute of Radio Engineers, 33 West 39th Street, New York City. They will be examined by the Committee on Meetings and Papers and by the Editor. Authors are advised as promptly as possible of the action taken, usually within one month.

Proofs—Galley proof is sent to the author. Only necessary corrections in typography should be made. *No new material is to be added.* Corrected proofs should be returned *promptly* to the Institute of Radio Engineers, 33 West 39th Street, New York City.

Reprints—With the notification of acceptance of paper for publication reprint order form is sent to the author. Orders for reprints must be forwarded promptly as type is not held after publication.

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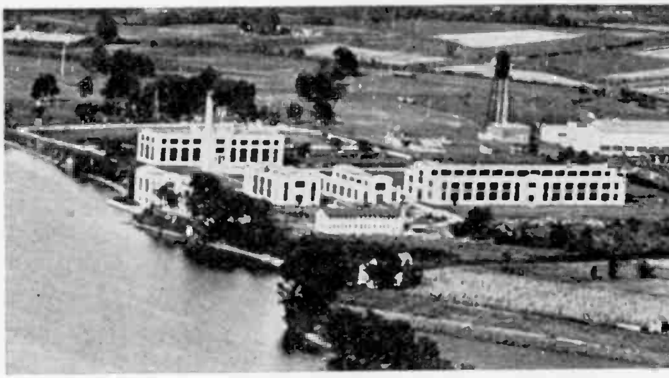
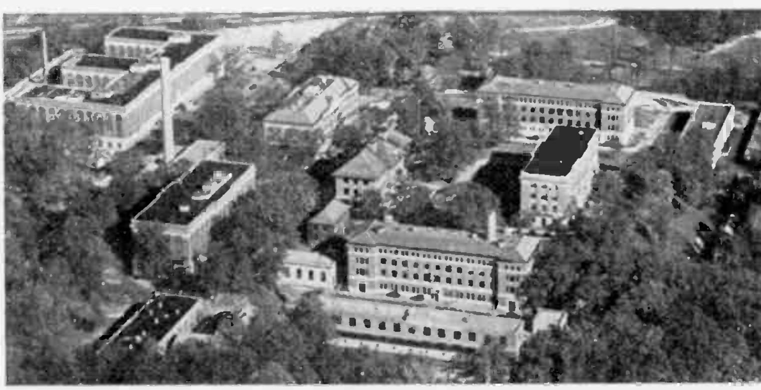


General View of Naval Research Laboratory, Anacostia, D. C.
(Several additional buildings have been added since this photo was taken.)



Airplane View of Bureau of Standards, Washington, D. C.
Radio Building at right in background.

INSPECTION TRIPS AT CONVENTION

Two full afternoons of the Fourth Annual Convention will be devoted to inspection trips to the Naval Research Laboratory and the Bureau of Standards, in Washington.

The Naval Research Laboratory is located on the Potomac River about eight miles from the center of Washington. It will be reached by buses going via the White House, Treasury Building, up historic Pennsylvania Avenue, past the Capitol, Botanical Gardens, Congressional Library, Navy Yard, and St. Elizabeth's Hospital.

The trip to the Bureau of Standards will be made by buses also. The route is to include the fine residential section of Washington, and a four-mile ride through Rock Creek Park. Returning, the convention delegates will cross the Million Dollar Bridge, past the former home of Herbert Hoover, the "S" Street home of Woodrow Wilson, and many other historic places of interest.

INSTITUTE NEWS AND RADIO NOTES

February Meeting of the Board of Direction

The February meeting of the Board of Direction of the Institute, held on the sixth of the month in the offices of the Institute in New York City, was attended by the following Board members: A. Hoyt Taylor, President; Melville Eastham, Treasurer; Arthur Batcheller, R. A. Heising, J. V. L. Hogan, L. M. Hull, C. M. Jansky, Jr., R. H. Manson, L. E. Whittemore, and J. M. Clayton, Secretary.

The following were transferred or elected to higher grades in the Institute:

Transferred to the Member grade, Harold Gray; elected to the Member grade, Lieut. H. N. Coulter and Mrs. J. D. Stewart.

One hundred and six Associate members and ten Junior members were elected.

With great regret the Board of Direction acceded to Dr. Goldsmith's request that he should not be reelected Editor of Institute Publications, a position which he has held for the past sixteen years. By unanimous vote of those members present the following resolution was adopted by the Board:

> WHEREAS: The members of the Board of Direction of the Institute of Radio Engineers are deeply appreciative of the invaluable services rendered by
>
> **Alfred Norton Goldsmith**
>
> as Editor of the PROCEEDINGS since the formation of the Institute; and
>
> WHEREAS: This contribution made by him as a pioneer in the development of the radio art is immeasurable in the light of future progress; and
>
> WHEREAS: The high standards and ethics adopted by him as Editor have earned for the PROCEEDINGS an enviable position in the field of radio engineering literature;
>
> *Therefore Be it Resolved:* That the Board of Direction, as individuals and as a whole, express to Dr. Goldsmith deep regret at the termination of his tenure of office as Editor, and profound appreciation of his untiring efforts and conscientious zeal, to which the PROCEEDINGS for the past sixteen years shall always remain a fitting testimony.

To succeed Dr. Goldsmith as Editor of Publications and Chairman of the Board of Editors, the Board appointed Dr. Walter G. Cady of Scott Laboratory, Wesleyan University, Middletown, Connecticut. Dr. Cady served on the Board of Direction for 1928 and was the recipient of the 1928 Morris Liebmann Memorial Prize. He is well known as a professor of physical science, a research worker in piezo electricity, a past associate editor of the *Physical Review*, and a contributor on numerous occasions to the PROCEEDINGS.

Radio Stations of Holland

From the Dutch Government a revised list of high-frequency assignments in Holland (1,500 kc and above) has been received by the Institute office. This is a revision of the information relating to Dutch stations contained in the list of high-frequency stations published in the November, 1928, issue of the PROCEEDINGS. Copies of the revision are available to members upon request at the Institute office.

Standard Frequency Transmissions by the Bureau of Standards

The Bureau of Standards announces a new schedule of radio signals of standard frequencies, for use by the public in calibrating frequency standards and transmitting and receiving apparatus. This schedule includes many of the border frequencies between services as set forth in the allocation of the International Radio Convention of Washington which went into effect January 1, 1929. The signals are transmitted from the Bureau's station WWV, Washington, D. C. They can be heard and utilized by stations equipped for continuous-wave reception at distances up to 1,000 miles from the transmitting station.

The transmissions are by continuous-wave radiotelegraphy. The modulation which was previously on these signals has been eliminated. A complete frequency transmission includes a "general call" and "standard frequency" signal, and "announcements." The "general call" is given at the beginning of the 8-minute period and continues for about 2 minutes. This includes a statement of the frequency. The "standard frequency signal" is a series of very long dashes with the call letter (WWV) intervening. This signal continues for about 4 minutes. The "announcements" are on the same frequency as the "standard frequency signal" just transmitted and contain a statement of the frequency. An announcement of the next frequency to be transmitted is then given. There is then a 4-minute interval while the transmitting set is adjusted for the next frequency.

Information on how to receive and utilize the signals is given in the Bureau of Standards Letter Circular No. 171, which may be obtained by applying to the Bureau of Standards, Washington, D. C. Even though only a few frequency points are received, persons can obtain as complete a frequency meter calibration as desired by the method of generator harmonics, information on which is given in the letter circular. The schedule of standard frequency signals is as follows:

RADIO TRANSMISSIONS OF STANDARD FREQUENCY; SCHEDULE OF FREQUENCIES IN KILOCYCLES

Eastern Standard Time	March 20	April 22	May 20	June 20	July 22
10:00–10:08 P. M.	1500	4000	125	550	1500
10:12–10:20	1700	4500	150	600	1700
10:24–10:32	2250	5000	200	700	2000
10:36–10:44	2750	5500	250	800	2300
10:48–10:56	2850	6000	300	1000	2700
11:00–11:08	3200	6500	375	1200	3100
11:12–11:20	3500	7000	450	1400	3500
11:24–11:32	4000	7300	550	1500	4000

Changes in Federal Radio Commission

The Institute is honored in the action of the President of the United States in appointing to the Federal Radio Commission two of its Board members:

Arthur Batcheller and C. M. Jansky, Jr.

At this writing these appointments have yet to be confirmed by the Senate. Mr. Batcheller is to succeed O. H. Caldwell from the first zone, and Professor Jansky is to succeed Sam Pickard from the fourth zone.

Mr. Batcheller was appointed to membership on the Board of Direction in 1928, and was elected to Board membership by the Institute for a three-year term beginning with 1929.

Professor Jansky was elected to membership on the Board of Direction by the Institute in the last election.

The Senate Committee has confirmed the reappointment of Judge Ira E. Robinson of the second zone, Judge Sykes of the third zone, and Mr. H. A. Lafount of the fifth zone.

Committee Work

1929 COMMITTEE CHAIRMEN

At the February 6th meeting of the Board of Direction the Board approved the appointment of committee personnel for 1929, the chairmen of the various committees being as follows:

Board of Editors, W. G. Cady; Committee on Nominations, Melville Eastham; Committee on Broadcasting, L. M. Hull; Committee on Sections, E. R. Shute; Committee on Admissions, R. A. Heissing; Committee on Constitution and Laws, R. H. Marriott; Committee on Membership, I. S. Coggeshall; Committee on Standardization, J. H. Dellinger; Committee on Meetings and Papers, K. S. Van Dyke; Committee on Publicity, W. G. H. Finch; Committee on Institute Awards, Melville Eastham.

Committee on Admissions

A meeting of the Committee on Admissions was held on February 6th in the office of the Institute in New York City. The following members were present: R. A. Heising, chairman; H. F. Dart, George Lewis, C. M. Jansky, Jr., and E. R. Shute.

The committee considered six applications for transfer or election to the higher grades of membership in the Institute.

Institute Meetings

Proposed Lehigh Valley Section

Much interest has been expressed on the part of the Institute members residing in the vicinity of Allentown, Pa., in the organization of a Lehigh Valley section of the Institute. B. H. Eckert and F. J. Hardner have been instrumental in the preliminary organization plans which brought forth a meeting of the Institute members at Muhlenberg College, Allentown, Pa. on February 8th, 1929. At this organization meeting B. H. Eckert and C. F. Maylott presided.

The paper by R. L. Smith-Rose, "Radio Direction-Finding by Transmission and Reception," was presented by Mr. Maylott. F. J. Hardner presented a paper, "Radio Noise Finding and Its Elimination." Messrs. Maylott, Hardner, Thomas, Muthard, and Kleck participated in the discussion which followed the presentation of these papers.

Mr. Maylott was elected chairman of the temporary organization. Another meeting is to be held on the 8th of March.

New York Meeting

At the New York meeting of the Institute held on February 6th in the Engineering Societies Building, 33 West 39th Street, A. Hoyt Taylor was inaugurated as President of the Institute. Ralph Bown opened the meeting with a short speech of introduction to Dr. Taylor.

A paper by R. L. Smith-Rose, of the National Physical Laboratory, Teddington, England, on "Radio Direction-Finding by Transmission and Reception" was presented by L. M. Hull, of the Radio Frequency Laboratories, Boonton, New Jersey. Following the presentation of the paper the following participated in its discussion: A. Hoyt Taylor, L. M. Hull, Lester Jones, S. W. Dean, H. E. Hallborg, Stuart Ballantine, and others.

Three hundred and twenty-five members of the Institute and guests attended this meeting.

The April New York meeting, which is to be held on April 3rd, will consist of a symposium on frequency measurements. There will be seven contributions to this symposium by engineers intimately associated with frequency measurements and standardization.

Buffalo-Niagara Section

L. Grant Hector, of the University of Buffalo, presented a paper, "Apparent Equality of Loudspeaker Output at Various Frequencies", at the January 17th meeting of the Buffalo-Niagara Section. L. C. F. Horle, chairman, presided.

Messrs. Horle, Lidbury, Henderson, Stone, and others participated in a discussion which followed. Twenty-five members of the section attended the meeting. This paper is printed elsewhere in this issue of the Proceedings.

Cleveland Section

On January 25th a meeting of the Cleveland section was held jointly with the Cleveland Astronomical Society in the Case School of Applied Science, Cleveland, Ohio, presided over by Chairman Bruce W. David and attended by one hundred and sixty members and guests.

A paper was presented by H. T. Stetson entitled "Sunspots, Radio, and Weather." The paper showed the striking relations between solar activity and certain of the earth's meteorological conditions. Radio reception, the earth's magnetic field, and to a certain extent the weather are affected by sunspots. The paper was illustrated with lantern slides.

Los Angeles Section

The Los Angeles section held a meeting in the Elite Cafe, Los Angeles, on January 21st, attended by one hundred and twenty-five members and guests. T. F. McDonough, chairman of the section, presided.

A paper entitled "The Nature of Sound, Its Transmission and Reproduction" was presented by A. P. Hill, of the Southern California Telephone Company.

Rochester Section

The Rochester section held a meeting in the Sagamore Hotel, Rochester, N. Y., January 11th, presided over by E. C. Karker, vice-chairman of the section.

Joseph P. Maxfield, of the Victor Talking Machine Co., presented a paper on "Physical Requirements of High Quality Audio-Frequency Reproduction." By means of lantern slides and a special orthophonic victrola, the speaker demonstrated improvements that had been made recently in the art of sound reproduction. The limitations of mechanical and electrical reproduction of sound were pointed out.

This was a joint meeting with the Rochester section of the American Institute of Electrical Engineers and the Rochester Engineering Society.

San Francisco Section

A meeting of the San Francisco section was held in the Hotel Bellevue, San Francisco, January 23rd, attended by twenty-eight members. Leonard F. Fuller, chairman, and Donald K. Lippincott, vice-chairman, presided.

Harry R. Lubcke presented a paper on "Vacuum-Tube Voltmeter Design." The election of officers was held with the following results: Donald K. Lippincott, chairman; Walter D. Kellogg, vice-chairman; Paul R. Fenner, secretary-treasurer.

Proceedings of the Institute of Radio Engineers
Volume 17, Number 3 *March, 1929*

GEOGRAPHICAL LOCATION OF MEMBERS ELECTED FEBRUARY 6, 1929

Transferred to the Member grade

Ohio	Cleveland, WJAY, Schofield Bldg.	Gray, Harold E.

Elected to the Member grade

Dist. of Columbia	Washington, 406 International Bldg.	Stewart, Jessica Dee
Nicaragua	Managua U.S.S. Rochester, Balboa, C. Z.	Coulter, Howard N.

Elected to the Associate grade

Alabama	Mobile, c/o Reynolds Music House Co.	Helt, Sanford
	Mobile, P. O. Box 801	Helt, Scott
California	Oakland, 1208 E. 18th St.	Brearty, Lawrence S.
	Los Angeles, 444 Kings Road	Grosjean, G. M.
	San Francisco, 2370 Filbert St.	Smith, Herbert H.
	San Jose, 398 N. 8th St.	Kelliher, John Edward
Colorado	Colorado Springs, 920 E. Monument	Harvey, Francis M.
Dist. of Columbia	Washington, Bureau of Standards	Brattain, Walter H.
	Washington, 3706-24th St., N. W.	Day, John F.
	Washington, 401-23rd St., N. W.	Detwiler, Donald J.
Illinois	Chicago, 4134 North Richmond Ave.	Brose, Fred O.
	Chicago, 2787 Frances Place	Edwards, Charles
	Chicago, 6257 Harper Ave.	Hermanutz, Ray J.
	Chicago, 2251 E. 71st St.	Timmings, George H.
	Oak Park, P. O. Box 552	Hoffman, Walter Henry
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Kansas	Atchison, 624 U St.	Gier, Willard Marion
Massachusetts	Arlington, 68 Marathon St.	Dempsey, John P.
	Boston, P. O. Box 1678	Decker, Donald Philips
	Cambridge, 15 Holworthy Hall	Hunkins, Harold R.
	Cambridge, 112 Lakeview Ave.	Noyes, Atherton, Jr.
	Cambridge, Harvard University, Holworthy 16.	Packard, Alden C.
	Cambridge, 15 Holworthy Hall	Taylor, John Pratt
	Medford, 21 Frederick Ave.	Surette, Dennis C.
	N. Wilbraham, Cottage Ave.	Garvey, Edmond
	Springfield, 407 St. James Ave.	Chapman, Alan B.
	Springfield, 19 Elliott St.	Van Doeren, C. A.
Michigan	Detroit, 11338 Dexter Blvd.	Huber, John E. L'E.
	Detroit, 504 Commerce Bldg.	Kratokvil, Frank M.
	Detroit, 15364 Oakfield Ave.	Martin, Robert D.
	Detroit, 16508 Welland Ave.	O'Neil, John J.
	Detroit, 135 Nevada, W.	Porter, Samuel
	Jackson, 1019 First St.	Rich, C. E.
	Jackson, 434 Stewart Ave.	Riethmiller, Earl R.
Missouri	St. Louis, 6339 Marquette Ave.	Riddle, Ruston L.
Nebraska	York, 1214 Lincoln Ave.	Meyer, Albert
New Jersey	Allendale, P. O. Box 207	Asten, Oliver B.
	Atlantic City, 225 Atlantic Ave., Apt. B-6	Enderle, Jackson J.
	Irvington, 617 Grove St.	Hart, James J.
	Linden, 1104 Wood Ave.	Holetz, Alexander C.
New York	Brooklyn, 54 Wyckoff St.	Kirdahy, Emil
	Buffalo, 15 University Ave.	Schwing, Russell L.
	Great Neck, 20 Arrandale Ave.	Genner, W. Gordon, Jr.
	New York City, 336 East 5th St.	Barnueba, Richard
	New York City, 116 Broad St.	Danz, Hermann
	New York City, 273 West 113th St.	Diaz, Ernest
	New York City, 120 East 30th St.	Hastings, Gerald M.
	New York City, Elec. Research Products, Inc., 250 W. 57th	Hipp, W. S., Jr.
	New York City, 463 West St., Room 279	Kurtinaitis, John V.
	New York City, 152 Dyckman St.	Murphy, E. Edward
	New York City, Elec. Research Products, Inc., 250 W. 57th	Padden, Cecil John
	New York City, 269 W. 34th St.	Payette, Walter S.
	Riverhead, L. I., c/o Radio Corporation of America	Henery, R. S.
	Schenectady, 221 Seward Place	Biver, Carl J.
	Schenectady, 2 Eagle St.	Frink, Frederick W.

	Schenectady, 607 Chapel St.	Lynn, Roland A.
	Schenectady, Y.M.C.A. Bldg.	McLennan, Miles Ayrault
	Schenectady, 614 Campbell Ave.	Richards, Philip A.
	Schenectady, Y.M.C.A., Room 425	Tanke, Harold F.
North Carolina	Norlina, Norlina Hotel	Schulke, Enno
Ohio	Akron, 179 Ido Ave.	Smith, Paul C.
	Cleveland, 4124 Bailey Ave.	Deutsch, E. J.
	Cleveland, 3905 Svoboda Ave.	Pitonak, Joseph C.
	Cleveland, 2845 Prospect Ave.	Umbrecht, Stanton
	Lakewood, 1288 Ramona Ave.	Drummond, P.
	Marion, 360 Silver St.	Ackerman, Francis R.
	Newphiladelphia, 334 Minnich Ave.	Nolan, John
	Salem, 604 McKinley Ave.	Ludlow, Gilbert H.
	Warren, 1903 Grove Place	Wason, R. E.
Oklahoma	Tulsa, Radio Dept., Skelly Oil Co.	Rand, George L.
	Tulsa, c/o Dodge Electric Co., 318 So. Boulder	Swan, Merrill LeRoy
Pennsylvania	Allentown, 959 Turner St.	Keck, Kenneth K.
	Boyertown, 36 North Reading Ave.	Markle, J. E.
	Philadelphia, 4916 Chestnut St.	Kienzle, D. R.
	Wayne, 225 W. Wayne Ave.	Adelberger, Paul J.
South Dakota	Huron, Box 663	Griffiths, A. Elmer
West Virginia	Kingwood, 134 Price St.	Michelson, Peter
Tennessee	Saltillow	Berry, James S.
Texas	Houston, 403 Studewood	Harold, George
Virginia	Quantico, Post Radio Station, Brown Field	Beardsley, Franklin
Washington	Seattle, 4055-42nd Ave., S. W.	Mood, George T.
Wisconsin	Fond du lac, 284 Dixie St.	Eckert, Walter R.
	Madison, 1530 Jenifer St.	Hagen, Paul A.
	Milwaukee, 672 Grove St.	Frohrieb, Edward F.
Canada	Hamilton, Ont., 339 Wilson St.	Clemnts, B. D.
	Hamilton, Ont., 267 Cannon St., E.	Crofte, Cecil T.
	Hamilton, Ont., 65 Garfield Ave S.	Bain, J. R.
	Penticton, B. C.	Howse, J.
	Toronto, Ont., 67 McLean Blvd.	Clarkson, Percy W.
	Toronto, Ont., 578 Spadina Ave.	Freeman, William
	Toronto, Ont., 41 McPherson Ave.	Glassford, J. O.
	Toronto 12, Ont., 1331 Avenue Road	Kinnear, Donald R.
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China	Canton, Sun Yatsen University	Chu, Chih Teih
Denmark	Copenhagen, Vennemindevej 3, 3 Str.	Svenningsen, Karl
England	Branston, Lincoln	Sparrow, A. W.
	Cambridge, Corpus Christi College	Landale, S. E. A.
	London, Berkeley St., c/o Thomas Cook, Ltd.	Samarasekara, V. R.
	London, W1, Berkeley St., c/o Thomas Cook, Ltd.	Wijeyeratne, P. de S.
	Swindon, Wilts, 32 Prospect Hill	Mustchin, Norman
	Whitley Bay, Northumberland, 25 Marden Road South	Gow, Charles N.
Germany	Berlin, Wilmersdorf, Hildegardstr. 13 b	Lock, M. J.
	Heilbronn, Bockingen	Hertweck, C.
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Part II

TECHNICAL PAPERS

Proceedings of the Institute of Radio Engineers
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RADIO DIRECTION-FINDING BY TRANSMISSION AND RECEPTION

(With Particular Reference to Its Application to Marine Navigation)*

By

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Summary—*This paper presents a critical résumé of the performance of apparatus employed for radio direction determination either by transmission or by reception. After an historical summary of results obtained in various parts of the world, a brief description is given of the fundamental principles underlying radio direction-finding. In this section attention is drawn to the application of the principle of reversibility to this art, by the aid of which the behavior of directive radio transmitters can be largely predicted from the more numerous results and greater experience already obtained with directional receivers.*

The next two sections of the paper give a review of the results obtained in Great Britain during the course of extensive investigations into this subject during the past seven years. Observations obtained from thirteen direction-finding receiving stations, specially erected for the purpose, have been carefully analysed and the performance of the apparatus studied under a variety of conditions, including operation in daylight and darkness, and both oversea and overland. In addition, some two years have been spent in studying the performance of a rotating-loop beacon transmitter, by means of which accurate radio bearing can be obtained with any type of receiving apparatus.

The later portions of the paper deal with the application of direction-finding to marine navigation, and of the possible effect of coastal and night errors in connection therewith. The production of night errors on closed loop receivers by the horizontal component of the electric force in downcoming waves is explained, and a demonstration is given of the manner in which the Adcock aerial system gives freedom from such errors. The paper concludes with a discussion of the relative advantages of direction-finding by transmission and reception for navigation purposes. A bibliography of the subject is appended.

* Dewey decimal classification: R125.1. Original manuscript received by the Institute, November 14, 1928. An abstract of this paper was read before the meeting of the Union Radio-Scientifique Internationale held in Brussels, September 5 to 10, 1928. Presented before New York meeting of the Institute, February 6, 1929.

1. Historical

THE application of the radio direction-finder both as a navigational instrument and as a useful scientific tool in the study of the propagation of electromagnetic waves has been developing rapidly during the past few years. As a result, a number of text-books expressly devoted to the subject of directional wireless have appeared, and the reader must be referred to these[1]† and other published works for an account of the fundamental principles of the art of direction-finding and its historical development. The object of this paper is to present a critical resumé of the results of investigations which have been carried out over a period of several years into the performance of direction-finding systems, and the historical background provided in this section will be confined to this aspect of the subject.

(*a*) *The Direction-Finding Receiver*

The modern radio direction-finder undoubtedly owes its success very largely to the introduction of valve amplifiers, enabling a moderately large reception range to be obtained, and its practical development therefore dates from about 1915. Previous to this, such systems of direction-finding as were in existence were confined to short-distance working and the comparatively crude instruments then in use made accurate systematic observations difficult to obtain. As early as 1908, however, Pickard[2] observed that large errors might be obtained in the reading of coil direction-finders due to buildings, trees, and other obstacles in the neighborhood. In the diagrammatic representation of his results, the errors are shown to be approaching 90 deg. It was found also by Fessenden[3] in the years 1901–07, that errors in apparent direction of as much as 20 deg. to 45 deg. might be obtained in the indication of these instruments when receiving over a range of 100 miles. These errors were attributed to a refraction effect resulting from the difference in conductivity of land and sea-water, or even to a varying local conductivity of the ground and of vegetation. In making continuous observations day and night for a week, Fessenden was apparently the first to observe that the errors were greatest during the night, a fact which he attributed to a refraction effect of large clouds of ionized air in the path of the waves.

† See bibliography.

A method of obtaining an absolute zero of signal-strength on a small frame-coil direction-finder was described by A. H. Taylor[4], in which the "antenna effect" of the coil is compensated for by a small emf from an auxiliary frame at right angles to the first. Using this system at Washington, it was found that while readings taken in the daytime were fairly accurate those taken near sunset and at night were very erratic. While it appeared that the variations observed on continuous waves of wavelength 13,600 meters were greater than on shorter waves, they were quite serious on damped waves of 1,500 meters wavelength. These variable results were briefly ascribed to reflection and refraction effects occurring during the propagation of the electromagnetic waves over the earth's surface.

The liability of the metalwork of a ship to produce a quadrantal error in the readings of a direction-finder mounted thereon was mentioned by Blondel[5] in 1919, while the corresponding effects on an aeroplane were later described by Robinson.[6] The complete theory of the effect of the metal hull of a ship on a direction-finder was first given by Mesny[7] in 1920. Calculations from this theory, confirmed by experimental results, showed that the quadrantal error obtained may be as great as 12 deg. This error was shown to be independent of wavelength and to decrease with the height of the frame coil above the deck. Attention was also drawn in the above paper to the approximately analogous case of a direction-finder erected upon a hill or an island, and the resulting quadrantal error which may be obtained in such a case is illustrated by a curve having a maximum value of 15 deg.

The phenomenon of the refraction of electromagnetic waves in passing over a surface of suddenly changing conductivity was discussed by T. L. Eckersley[8] in 1920. Experimental observations made in Cyprus and Egypt on wavelengths between 800 and 1,100 meters showed that wireless waves in crossing a coastal boundary between sea and land might suffer a deviation of as much as 4 deg. This deviation falls to zero for normal incidence of the waves on the coast line, and it was also shown to be negligible for wavelengths exceeding 2,000 meters. In the paper there is quoted an interesting case of a bad day minimum being produced by the reception of two waves from a transmitter, the two waves arriving by different paths and with a phase difference which resulted in a rotating field.

Somewhat similar refraction effects on wireless waves passing from dry to wet ground and across a river were mentioned by Kiebitz[9] in connection with experiments on a directional transmitter. The deviations of the waves amounted to 8 deg. or 9 deg. for a wavelength of 550 meters.

Some results showing the errors to which a radio direction-finder may be subject due to local conditions were given by Hollingworth and Hoyle.[10] Masses of metalwork, tuned circuits, and overhead wires were found to produce appreciable errors in the readings.

In a most valuable paper published in 1920, Round[11] gave an account, chiefly from his personal experience, of the development and application of the direction-finder during the war. The manner in which the instrument was perfected as a useful tool for both military and naval purposes was described together with the various types of errors encountered, both by day and by night. Reference was made to the work of Adcock, Eckersley, and Wright in connection with these errors, and a brief indication was given of the means by which they might be eliminated for practical direction-finding purposes.

A large amount of experimental work on the intensity and directional properties of the electro-magnetic field radiated from an aeroplane transmitter was described by Baldus, Buchwald, and Hase in 1920,[12] while a mathematical treatment of this case was given by Burstyn.[13] The errors in the apparent bearings of an aeroplane at a ground direction-finding station were discussed in detail in their relation to the plane of polarization of the emitted waves. The experiments of Baldus and Buchwald, in particular, showed that a closed-coil direction-finder on the ground could give errors of as much as 60 deg. in the bearings of aircraft. This fact is interesting in connection with the patent filed by Adcock[14] in 1919, in which was described a means of eliminating the error of observation of the orientation of aeroplanes.

Some further observations on the variable night errors were published in 1920 by Kinsley and Soby.[15] Variations in the apparent bearings ranging up to 50 deg. were recorded on wavelengths between 960 and 17,300 meters, and for ranges of transmission from 40 up to 7,500 miles.

Towards the end of 1920, the Department of Scientific and Industrial Research in England, acting on the advice of its

Radio Research Board, began the erection of a number of directional radio receiving sets in various parts of the British Isles, attached either to Universities or to Government experimental establishments. The object of these installations was to make regular observations of the apparent radio bearings of various transmitting stations in order to obtain data on the nature, magnitude, and other characteristics of the variations of bearings which were previously known to take place. The general organization and conduct of this investigation was carried out by the author from The National Physical Laboratory, Teddington, as headquarters. Up to the time of the termination of the general investigation in September, 1926, about a quarter of a million observations had been accepted for correlation, these observations covering the range of wavelengths of 300 to 20,000 meters. A detailed record of the work, with discussion of the conclusions drawn therefrom, has formed the subject of a number of official reports published by H. M. Stationery Office, England.[16] In addition to these publications, descriptions of various investigations subsidiary to the main line of research have been published elsewhere. For example, in order to obtain accurate bearings in continuous wave working it was found necessary to prevent any mutual induction between the local oscillator and the receiving frames of a Robinson direction-finder by suitably screening the local oscillator.[17] Such screened oscillators have now been in use for several years in connection with various direction-finding work, and nowadays they find considerable application in radio measurement work.

These experiments were later extended to that of screening assemblies of amplifying and receiving apparatus to prevent the undesired direct induction of signals. Data were obtained by Barfield[18] for the screening of a complete hut containing the receiving apparatus as, for example, in the Bellini-Tosi direction-finding system. In the course of the same investigation Barfield demonstrated the properties of open wire screens, and these were later applied to the reduction of the error known as "antenna-effect" in radio direction-finding.

Various experiments were carried out in the early stages of the main investigation to ascertain the effect of local conditions such as metal-work, overhead wires, trees, etc., on the readings of direction-finders.[19,20] These experiments showed that some quite large errors, ranging up to 22 deg., can be produced by the proximity of such obstacles and emphasize the importance of exercising care in selecting a suitable site for a direction-finding installation. The difficulty in finding any approach to an ideal site was illustrated by the results obtained from the stations selected. In very few cases was the error due to local conditions less than 2 deg. It is fortunate, however, that such a type of error remains constant in value for any particular direction, so that it can be treated as of the nature of a permanent deviation, which can be ascertained periodically from a calibration of the station. In the case of the Aberdeen station, the cause of permanent errors ranging up to 15 deg. was traced to a long iron plate beneath the ground and supporting a sewer duct, over which the direction-finding installation was inadvertently erected.[20]

During the course of the main investigation each of the three practical types of direction-finder, known as the Bellini-Tosi, Robinson, and single-coil systems, respectively, has been used in some portion of the investigation: and it was naturally desirable to verify whether comparable results could be obtained with any of these systems. A simple consideration of the theory shows that there is no essential difference in the basic principle of any of the systems, for in each case the reading of the direction is made as the result of some portion of the apparatus rotating about a vertical axis being set in the position in which there is a minimum, or in the ideal case, zero emf induced by the incoming waves. This theory was discussed in a previous publication[21] which also contained a description of the results of experiments showing that each system was equally subject to variable night errors.

(b) *The Direction-Finding Transmitter*

As an alternative to the use of a special radio receiving instrument for the determination of bearings the directional property can be transferred to the transmitting station, so that its direction can be determined at a distant receiving station by the aid of some characteristic of the emitted radiation.

Both of the types of directional transmitting systems which are in use today may be said to date from the time of Hertz, since in his experimental researches Hertz used reflectors to concentrate the radiation from a straight rod aerial and also loops whose transmission or reception properties depend upon the orientation of the loop. Of recent years the properties of reflecting systems used in conjunction with linear aerials have been studied by Marconi,[22] Franklin,[23] and others,[24] and with the application of the beam system to long distance communication considerable development has been taking place in many countries. The beam system has also been adapted as a rotating beacon transmitter,[25] but practical limitations necessitate its operation on the very low wavelengths of 6 to 10 meters. Experimental beacons of this type have been installed at Inchkeith[22,23] and South Foreland,[25] but it is believed that its use among ships has not been very widespread.

The predecessor of the closed loop antenna, whether for reception or transmission, is to be found in either the inverted *L* aerial or in a pair of spaced vertical aerials. The former has developed into the Beverage aerial which is now used as one method of obtaining directional selectivity at the receiving end. A system of inverted *L* aerials giving directional transmission has been experimented with by Scheller, Buchwald,[26] and Kiebitz.[27] For navigation purposes it is also probable that the Telefunken compass[28] arrangement falls under this heading. This system made use of a series of directional aerials radiating from a central mast, these arials being excited in turn by a rotary switch operating at a speed of one revolution per minute. A non-directional aerial was also provided for the purpose of transmitting a timing signal applicable to the directive system. By noting the interval between this time signal and the reception of the signal from the directional system, the bearing of the transmitter could be estimated from a distant receiver.

The combination of the pair of spaced aerials developed first into the Bellini-Tosi system of direction-finding and later into the rotating frame coil. The transmitting equivalent of the Bellini-Tosi direction-finder is to be found in the Radiophare, several of which were in operation on the French coast prior to 1914. In the same manner the single-frame coil can be adapted to transmission since its polar radiation characteristic is the well-known figure-of-eight diagram, and thus the intensity of the radiation varies according to a cosine law with the angle between the plane of the loop and the direction of transmission. One of the great advantages of a loop transmitter is that it can be operated on the wavelengths usually employed in ship and aircraft wireless communication. Various methods of applying the rotating loop transmitter for navigation purposes were described by Erskine-Murray and Robinson in 1922,[29] while more recently Gill and Hecht[30] have recounted the development of the rotating beacon by the British Air Ministry and supplied some typical results obtained in the application of this system to the navigation of aircraft.

The use of two directional transmitting aerials sending complementary Morse signals (such as *A* and *N*) upon the same wavelength for the purpose of providing an equi-signal zone along a fixed course appears to have originated with Scheller in Germany, and to have been investigated by Buchwald[26] and Kiebitz[27] in 1920. With the substitution of closed loops for the open inverted *L* aerials previously employed, Engel and Dunmore[31] published in 1924 an account of experiments designed to illustrate the utility of this system for the navigation of both ships and aircraft. This method is not strictly one of direction-finding since the observer or navigator is not generally able to determine his bearings or position by this means, but only to locate himself along a fixed course as given by the beacon transmitter. For this reason the system is more directly applicable to the navigation of aircraft flying along fixed routes than to the navigation of ships; and it is from this point of view that considerable development of the method has recently been carried out in the United States of America. This work has been described by Dellinger and Pratt,[32] who have applied a modified form of the radiogoniometer to enable the course or equi-signal zone given by the transmitter to be oriented in any required direction. The limitation of range of the system for accurate direction indications is illustrated by the results of some experiments reported by Pratt[33] in a separate paper. In common with all closed loop transmitters and receivers for direction-finding this system becomes liable to serious errors at ranges exceeding about 100 miles, even when the receiver is some 2,000 feet above the ground.

For further detailed information on the application of radio communication to aircraft navigation, the reader may be referred to the Bibliography recently published by Jolliffe and Zandonini.[34]

2. Brief Description of Methods of Direction Determination by Radio Transmission or Reception

(*a*) *The Radio Direction-Finder*

The radio direction-finder is now well known as an instrument which can be used to determine the direction of arrival of wireless waves, and it will suffice to give the briefest outlin heree of the principles underlying this instrument. The several commercial types of direction-finder now in use employ the same fundamental principle of the reception of vertically polarized* wireless waves by a frame coil. In Fig. 1(a), for example, let C represent a plane vertical loop rotating about a vertical axis in the field of an arriving wave whose component electric and magnetic forces are as shown. From the plan view in Fig. 1(b)

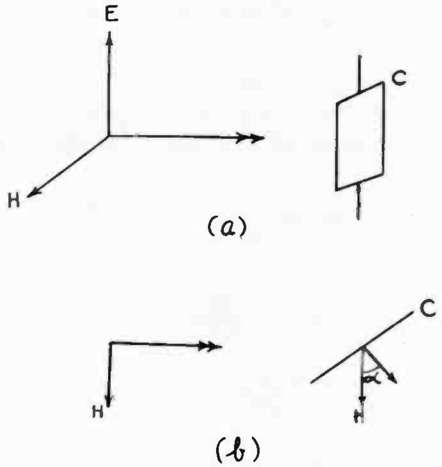

Fig. 1

it is evident that the emf induced in the loop by the arriving waves will be proportional to the cosine of the angle a between the direction of the magnetic field and the axis of the coil. The accuracy with which any definite position of the coil may be located depends upon the rate of change of emf with orientation, i.e., the accuracy is proportional to sin a. Thus the determination of the direction of arrival of the waves is most accurate when the signal emf induced by the waves is zero. This point is also illustrated by Fig. 2, which shows the theoretical polar reception diagram for a rotating loop. The strength of the signal emf induced in the loop by a wave arriving from any direction is proportional to the intercept of the vector OA made by the "figure of-eight."

The most important feature which requires attention in the design of a practical direction-finder is the avoidance of spurious

* The term "vertically polarized" is used here to indicate that the electric force of the wave lies in the vertical plane of propagation of the wave.

emf's introduced into the system from one or both of the phenomena commonly known as "antenna-effect" and "direct pick-up." The term "antenna-effect" is applied to the property possessed by a frame coil receiver of acting as an untuned vertical aerial as well as a coil for reception purposes. As a result of this, the receiving system may have induced in it an emf whose phase and magnitude are independent of the orientation of the coil. The signal heard in the telephones will be the sum of that produced by the rotating coil as such and that due to the equivalent aerial effect of the whole receiver. As the coil is rotated it is found that the signal zeros become blurred into broad minima only, and moreover, they may be displaced from their correct positions. The existence of this antenna effect in the system

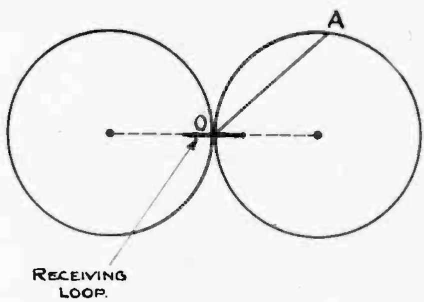

Fig. 2

therefore makes the observed directions incorrect, and also makes the determination of these directions more difficult.

Somewhat similar results may be produced by the second of the two causes mentioned above, viz. "direct pick-up." This last term implies that portions of the receiving system, such as the tuning circuits and the amplifier, are having emf's induced in them directly by the incoming waves. These emf's will obviously be independent of the orientation of the main receiving frame, and they will be effective in adding to or subtracting from the signal strength finally heard in the telephones. It must be appreciated that while these stray emf's may be small compared with the main emf picked up by the rotating frame-coil in its maximum position, they become of very great importance when the coil is turned into its minimum position.

The methods adopted for overcoming the effects of these spurious emf's are based on the use of somewhat elaborate screening arrangements, with or without the addition of a compensating condenser for the antenna effect. The application of these methods to the practical arrangement of single-coil direction-finders has been described by Kolster,[35] Dunmore,[36] Long,[1(g)] Mesny,[(f)] and the author;[37] and the reader must be referred to these descriptions for further details of such apparatus.

With the object of enabling the incoming signal to be clearly audible throughout the whole process of taking a bearing, a crossed-coil arrangement was described by Robinson[38] in 1920. This system was, at one time, particularly favored for use on aircraft, but with some modification described by Bainbridge-Bell,[39] it now finds widespread application to marine navigation.

Before the development of valve amplifiers made possible the use of rotatable multi-turn loops, Artom in 1903 and Bellini and Tosi in 1907 suggested and used large frames of a triangular shape, with the ends open at the top apex, for directional wireless communication. The arrangement developed from this and now generally known as the Bellini-Tosi system was fully described in 1908.[40] The large, fixed closed loops employed in this system are connected to a radiogoniometer, an instrument which reproduces in miniature the directive properties of the external field of the waves. Recent developments of this system for use in ships have resulted in the employment of smaller multi-turn loops, which are more conveniently fixed on board. The development and use of the Bellini-Tosi system during the war was described by Round[11] in 1920, while Horton,[41] Slee,[42] and Mesny[43] have dealt with some more recent developments.

(*b*) *The Rotating Loop Transmitter*

As an alternative to the direction-finding schemes outlined above, the directional part of the wireless system may be transferred from the receiving to the transmitting end. This is effected in the rotating loop beacon system, which has been developed to a high degree in Great Britain by the Royal Air Force, and which employs a vertical closed loop transmitter arranged to rotate about a vertical axis at a uniform speed of one revolution per minute. The polar radiation diagram of such a loop will be of the same figure-of-eight form as that shown in Fig. 2 for a loop receiver. Thus as the loop rotates the field radiated in any given direction will vary according to a cosine law, passing through successive maximum and minimum values at intervals of fifteen seconds. When the plane of the coil is perpendicular to the geographical meridian a characteristic signal is emitted by the beacon which may be termed the N point. An observer at a distant receiving station upon hearing this signal starts a chronograph. As the beacon rotates the intensity of the received signal varies and will ultimately pass through a minimum or zero value, at which instant it is known that the plane of the transmitting loop is at right angles to the great circle joining transmitter and receiver. If the reading of

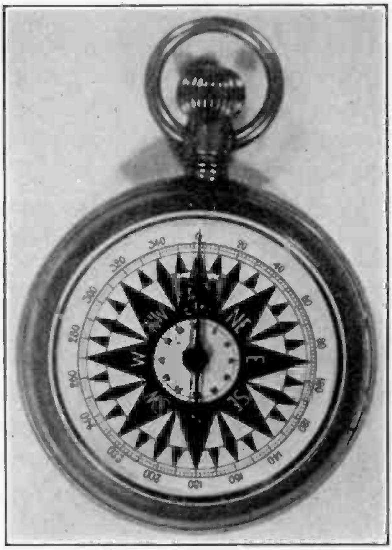

Fig. 3—Stop Watch Fitted with Special "Compass-Card" Dial for Use in Taking Bearings from a Rotating Beacon.

the chronograph is observed at this instant of minimum signal intensity it is evident that the bearing of the transmitter from the receiver can be obtained by a simple calculation. To provide for the case in which the observer is due north or south of the beacon, when the N signal would probably be inaudible, another characteristic signal is emitted after a 90 deg. rotation to the corresponding E point. Bearings observed from this signal as a starting point are evidently subject to a correction of 90 deg. It is to be noted that since the radiation from the coil is symmetrical about its plane, a second minimum will be obtained after a rotation of 180 deg. from the first. With the beacon making one revolution per minute, therefore, a line bearing is obtainable in the above manner every half-minute. To fix the position of a receiving station it is necessary to obtain line bearings in this manner from two or more beacons.

Since the timing process mentioned above is but an intermediate step in taking a bearing, it is convenient to provide a stop-watch or chronograph used for the purpose, with a dial specially engraved in degrees and points of the compass as illustrated in Fig. 3. If the center second-hand of such a watch is started on the *N* signal from the beacon, the indication of the hand at the occurrence of the signal minimum will give the true bearing of the observer. Examples of other dials suitable for working from the *E* point, and on beacons with different times of rotation, have been described elsewhere.[44(a)]

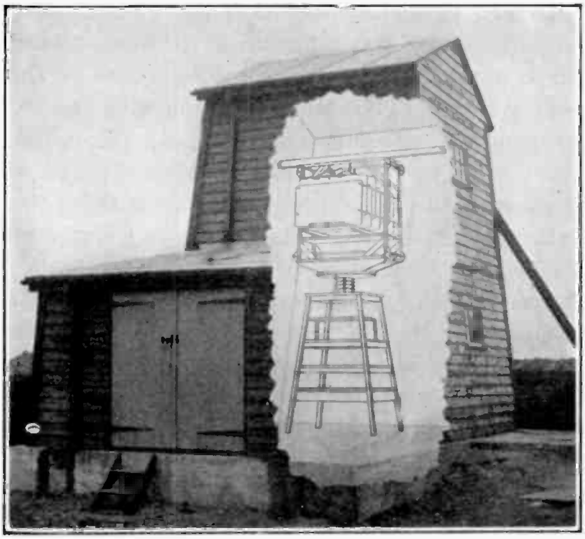

Fig. 4—View of Rotating Beacon inside Hut at Fort Monckton, Gosport.

The development and initial testing of this rotating beacon system by the Royal Air Force have naturally been confined to a study of its advantages over the direction-finding receiver for the navigation of aircraft.[30] During the past few years, however, the author has been privileged to investigate the performance of a rotating beacon station, especially set up for the purpose in England, and particularly to ascertain its advantages and reliability as an aid to marine navigation.[44] A sketch photograph of this beacon is shown in Fig. 4.

(c) The Reversibility of Direction-Finding

From the brief description of fundamental principles given in the two previous sections it will be gathered that wireless direction-finding can be carried out by rotating a closed loop at either the transmitting or receiving end of a communication link. The directional property is given by the rotating closed loop and the other station can employ any type of wireless transmitter or receiver connected to any type of aerial system. It will probably aid the reader in understanding the performance of each system and their relative merits for any given purpose, if attention is drawn here to the reversibility of the communication system between an open aerial and a closed loop.

The reference of the reciprocal theorem to radio communication has been enunciated by Lorentz, Pfrang, and Sommerfeld,[45] who discussed its application to transmission between open aerials, closed loops, or a combination of these. The theorem may be briefly stated in the following terms: if an antenna A_1 transmits to another antenna A_2, the signal intensity in A_2 is the same as that which would be received in A_1 if A_2 transmitted with the same power and at the same frequency as was previously used by A_1. This equality of signal intensity in the two cases is independent of the electromagnetic properties of the medium and of the shapes of the antennas. This means that transmissions from a rotating loop beacon being received on an open antenna should produce errors of the same type as those experienced when the antenna is employed for transmitting to a loop direction-finder. The utility of this theorem in studying the performance of the two systems will become evident in succeeding sections of the paper, and the author has referred elsewhere to the possibilities of investigating local errors in this manner.[46] On theoretical grounds, the reversibility of the Adcock direction-finding system as a means of avoiding night errors has also been established by the present author.[72] In the above cases a reservation must be made as to any irreversible effects which may be produced by the influence of the earth's magnetic field upon wireless waves travelling through ionized regions of the earth's atmosphere. The possibility of such a departure from the reciprocity relation was pointed out by Appleton in 1925.[47]

TABLE I

Summary of Observations Taken at Newcastle from February 28, 1921 to March 4, 1922

(1)	(2)	(3)	(4)	(5)	(6)				(7)			
					Day Observations				Night Observations			
Transmitting Station	Type and wave-length	Time of trans-mission	Distance	True bearing	No.	Extent of variation	Error of mean	Max. varia-tion from mean	No.	Extent of varia-tion	Error of mean	Max. varia-tion from mean
	(km)		(miles)	(degs.)		(degs.)	(degs.)	(degs.)		(degs.)	(degs.)	(degs.)
Aberdeen	C.W. 3.3	I	154	352.0	100	10.5	−0.2	− 6.8	37	17.0	+0.1	−11.1
Aranjuez	S. 3.5	I	1,034	184.6	65	1.7	+2.0	− 1.1	102	5.6	+1.6	± 2.8
Budapest	S. 3.0	I	1,026	111.6	45	3.5	−1.3	− 1.8	527	29.5	−1.1	+18.5
Chelmsford	C.W. 3.8	I	240	158.1	126	5.0	−0.8	+ 2.7	256	4.0	−0.7	+ 2.6
Cleethorpes	S. 3.0	17.00	118	147.2	—	—	—	—	87	4.2	−0.9	+ 2.2
Cleethorpes	C.W. 4.6	I	118	147.2	72	9.3	−0.8	− 5.2	134	12.0	−1.5	− 7.2
Clifden	S. 5.8	I	355	256.2	64	2.2	−1.4	+ 2.8	4	6.0	−3.4	+ 3.7
Clifden	C.W. 5.8	I	355	256.2	95	7.5	−0.3	+ 0.1	182	33.0	−0.1	−18.1
Coltano	S. 4.2	I	948	140.6	141	3.1	−1.9	+ 1.7	60	7.6	−0.7	+ 5.7
Horsea	C.W. 6.0	12.00 20.00	287	175.5	204	6.5	−0.9	+ 3.4	392	14.5	−0.5	+ 8.0
Karlsborg	S. 4.5 2.5	12.15 20.00	650	62.4	33	6.7	−1.4	+ 3.5	441	37.0	+1.7	+25.9
Karlsborg	S. 4.2	I	650	62.4	207	10.2	−1.2	− 6.4	128	23.0	+0.7	−12.1
Karlsborg	C.W. 4.5	I	650	62.4	27	2.3	−0.6	− 1.3	9	4.0	−2.3	+ 2.4
Moscow	S. 4.8	I	1,521	71.8	18	2.4	−0.4	− 1.3	1,838	34.0	+0.8	+23.4
Nantes	S. 2.5	08.00 21.00	538	180.4	2	0.3	0.0	− 0.2	8	7.6	+0.2	− 4.4
Nantes	S. 4.2	08.15 21.30	538	180.4	6	1.3	−2.9	+ 0.9	5	2.0	+0.4	+ 1.2
Nauen	S. 3.9 3.2	11.50	612	99.2	269	3.4	−2.5	− 2.0	—	—	—	—
Nauen	C.W. 4.7	I	612	99.2	50	13.5	−3.1	+ 6.9	27	13.5	−2.4	− 7.3
Nicolaieff	S. 4.0	I	1,546	96.3	160	5.8	−0.7	+ 4.4	106	12.8	+1.0	+ 7.2
Paris	S. 2.6	08.15	454	156.9	202	3.0	−2.2	− 1.7	—	—	—	
Paris	S. 2.6	09.20 10.40	454	156.9	1138	4.3	−2.2	− 2.9	—	—	—	
Paris	S. 2.6	11.30	454	156.9	605	3.1	−2.3	− 1.7	—	—	—	
Paris	S. 2.6	19.20 21.10	454	156.9	—	—	—		448	8.5	−2.1	+ 4.7
Paris	S. 3.2	11.00 12.00	454	156.9	537	3.0	−0.5	− 1.9	—	—	—	
Poldhu	S. 2.8	09.30 21.30	374	205.6	365	5.2	+0.3	+ 2.8	172	32.5	−1.0	−20.6
Poldhu	S. 2.8	I	374	205.6	14	1.5	+0.3	− 0.9	17	26.2	−4.5	−21.1
Sofia	S. 3.2	I	1,400	116.8	7	2.8	−2.2	± 1.4	166	11.5	+0.4	+ 5.8
Warsaw	S. 2.0	I	942	92.0	60	4.0	+0.8	+ 2.2	23	5.6	+0.2	+ 3.3

I = Irregular transmission.

3. Analysis of the Performance of Wireless Direction-Finders

Attention has already been drawn in Section 1 to the carrying out of a large investigation in wireless direction-finding by the Radio Research Board in the British Isles during the years 1920-1926. In the course of this investigation, thirteen direction-finding stations were used in various parts of the work, which covered a range of wavelengths of from 300 to 20,000 meters. The precise distribution of these stations and the detailed results of the whole investigation will be found in a series of official reports to which reference has already been made.[16] It is considered to be useful here, however, to give a very brief resumé of these results with the conclusions drawn therefrom. Apart from the errors due to local conditions at each direction-finding station, which were studied separately and which could be corrected for when necessary, it was found that the apparent bearings of the various transmitting stations observed varied in a very erratic manner under certain conditions. In the work of tabulating and correlating the results it was found convenient to adopt an arbitrary division of the times of observation into day and night periods. The border lines between these periods were taken at one hour after sunrise at the westerly end of the path of transmission and one hour before sunset at the easterly end.

(a) *General Nature of Variations in Observed Bearings*

As illustrating the results generally obtained, a summary of the observations recorded at Newcastle on wavelengths between 2,500 and 6,000 meters during the years 1921–23 is reproduced in Tables I and II, while in Table III is reproduced a summary of the results obtained at Orford from 1922 to 1924 on wavelengths of 450 and 600 meters. With the mode of separation into day and night periods thus adopted it was found that the extreme error experienced in the day periods was usually about 4 deg. for any wavelength and distance of transmission, but during the winter months this limit was considerably exceeded on the higher wavelengths, apparently because of an extension of the night conditions until three or four hours after sunrise. As an example of this phenomenon Fig. 5 shows graphs of the daily bearings observed at Slough on the transmissions from the two stations at Leafield and Nantes. The observations were made on the U.R.S.I. signals sent by these stations at 1400 and 1415 G.M.T.,

TABLE II
Summary of Observations Taken at Newcastle from March 6, 1922 to March 31, 1923

(1) Transmitting Station	(2) Type and wave-length	(3) Time of trans-mission	(4) Distance	(5) True bearing	(6) Day Observations No.	Extent of variation	Error of mean	Max. varia-tion from mean	(7) Night Observations No.	Extent of varia-tion	Error of mean	Max. varia-tion from mean
	(km)		(miles)	(degs.)		(degs.)	(degs.)	(degs.)		(degs.)	(degs.)	(degs.)
Aberdeen	C.W. 3.3	08.30–09.30 17.00	154	352.0	189	17.5	+0.7	−11.4	125	33.8	+0.8	+18.0
Aberdeen	C.W. 3.3	21.00	154	352.0	—	—	—	—	111	37.2	+0.5	−19.7
Air Ministry	C.W. 4.1	I	252	162.5	247	10.3	−1.2	+ 6.9	252	30.7	−0.8	+17.5
Berne	C.W. 3.4	I	676	140.8	530	5.1	−1.5	− 4.3	217	56.0	−0.6	+34.3
Budapest	S. 3.0	I	1,026	111.6	48	4.0	−2.0	+ 2.4	26	7.1	0.0	+ 4.0
Chelmsford	C.W. 3.8	I	240	158.1	76	4.4	−1.6	+ 2.9	70	2.5	−1.9	+ 1.3
Cleethorpes	C.W. 4.3	08.00	118	147.2	118	12.0	−1.5	− 6.2	—	—	—	—
Cleethorpes	C.W. 4.3	I	118	147.2	116	8.5	−2.3	− 4.9	187	21.0	−0.3	−11.9
Clifden	S. 5.8	09.50 21.50	355	256.2	85	1.5	−1.4	− 0.8	66	12.5	−2.5	− 7.7
Clifden	C.W. 5.8	I	355	256.2	316	2.3	−0.5	+ 1.4	594	26.0	−0.4	+14.2
Coltano	S. 4.2	I	948	140.6	169	3.3	−1.9	− 2.2	244	10.8	−1.6	± 5.4
Horsea	C.W. 5.0	I	287	175.5	193	13.6	−0.8	+ 8.8	98	15.6	−1.3	− 9.3
Karlsborg	S. 2.5	12.15 20.00	650	62.4	171	6.6	+0.1	+ 3.5	485	57.5	+5.1	−31.5
Karlsborg	S. 4.2	I	650	62.4	125	6.2	−0.5	− 4.3	53	26.3	+0.1	+15.0
Karlsborg	C.W. 3.9	I	650	62.4	503	10.5	+2.2	− 7.1	237	55.0	+3.8	+38.8
Konigswusterhausen	C.W. 5.2	I	658	100.0	501	8.3	−2.6	− 4.2	260	32.4	−3.3	−20.7
Moscow	S. 4.8	I	1,521	71.8	421	5.5	−1.6	+ 2.8	945	39.0	−0.8	+26.5
Nantes	S. 2.5	08.00 21.00	538	180.4	21	0.6	−0.8	+ 0.4	94	11.9	−0.2	− 6.6
Nantes	S. 4.2	08.10 21.30	538	180.4	84	4.5	−0.2	− 3.0	93	15.7	−1.0	+10.0
Nantes	S. 2.5	12.15	538	180.4	60	5.2	−2.4	− 3.0	—	—	—	—
Nauen	S. 3.2	11.50	612	99.2	250	4.0	−2.8	− 2.4	—	—	—	—
Nauen	C.W. 4.7	I	612	99.2	1421	87.0	−2.5	+60.8	1471	78.2	−0.8	−40.4
Ongar (GLA)	C.W. 2.9	I	238	160.2	904	11.0	−0.1	− 6.1	979	59.5	−0.2	+30.0
Ongar (GLB)	C.W. 3.8	I	238	160.2	1239	7.5	−0.8	− 9.1	859	34.4	−1.2	−17.4
Ongar (GLO)	C.W. 4.4	I	238	160.2	252	9.5	−1.4	+ 5.7	321	23.9	−1.7	−13.0
Paris	S 2.6	08.15	454	156.9	277	2.4	−2.8	+ 1.4	—	—	—	—
Paris	S. 2.6	09.20 19.20	454	156.9	1486	5.5	−3.1	− 3.8	432	5.8	−2.7	− 4.0
Paris	S. 2.6	11.30 21.55	454	156.9	516	2.4	−2.7	+ 1.3	162	13.2	−4.0	− 7.[illegible]
Paris	S. 3.2	12.00	454	156.9	114	1.5	−1.1	− 0.8	—	—	—	—
Poldhu	S. 2.8	09.50 21.50	374	205.6	42	2.9	+0.4	− 1.5	37	30.0	−1.9	−21.7
Sofia	S. 3.2	I	1,400	116.8	—	—	—	—	163	48.0	−1.8	−31.5
Whitehall	C.W. 3.3	09.00	247	164.9	43	6.9	+0.9	+ 4.3	37	7.1	+1.8	+ 3.8
Whitehall	C.W. 3.3	17.00 21.00	247	164.9	—	—	—	—	30	12.0	−0.3	− 6.1

I = Irregular transmission.

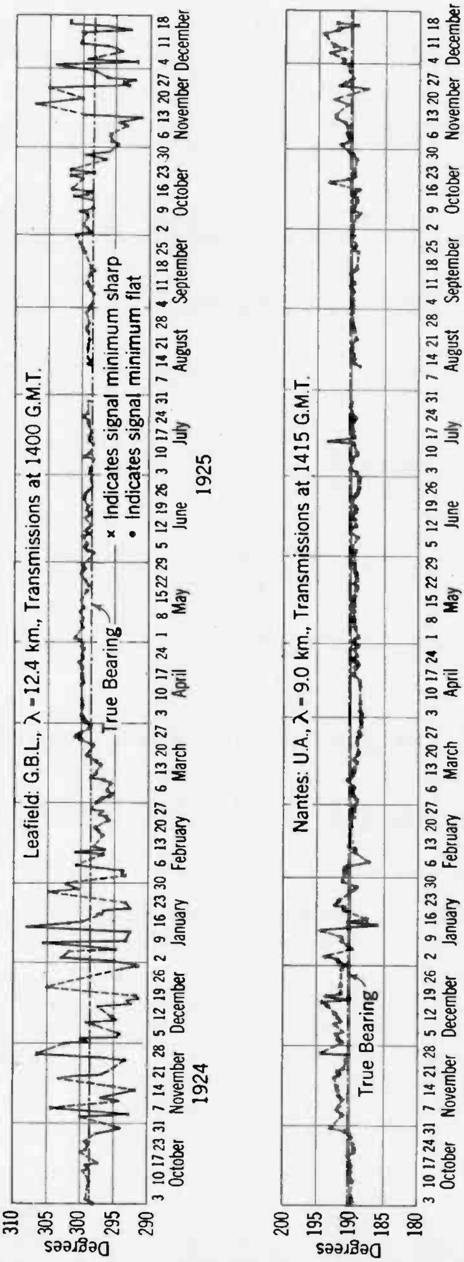

Fig. 5—Graphs Showing the Daily Observations of Bearings Taken at Slough on the U.R.S.I. Transmissions from Leafield and Nantes. October, 1924 to December, 1925.

respectively, and thus always took place in daylight. The results are plotted as the weekly extreme bearings over a period of fifteen months from October, 1924 to December, 1925. It is evident from this diagram that during the summer months the observed bearings are steady and fairly accurate, while during

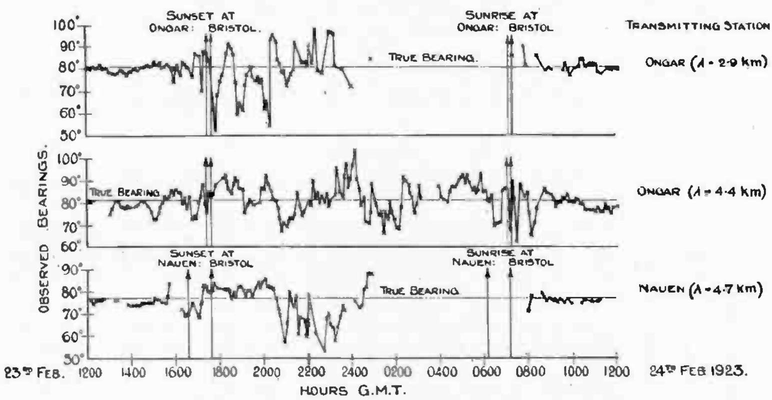

Fig. 6—Graphs of Observed Bearings of Ongar (undamped waves, $\lambda = 2.9$ and 4.4 km) and Nauen (undamped waves, $\lambda = 4.7$ km) taken at Bristol over a 24-hour period.

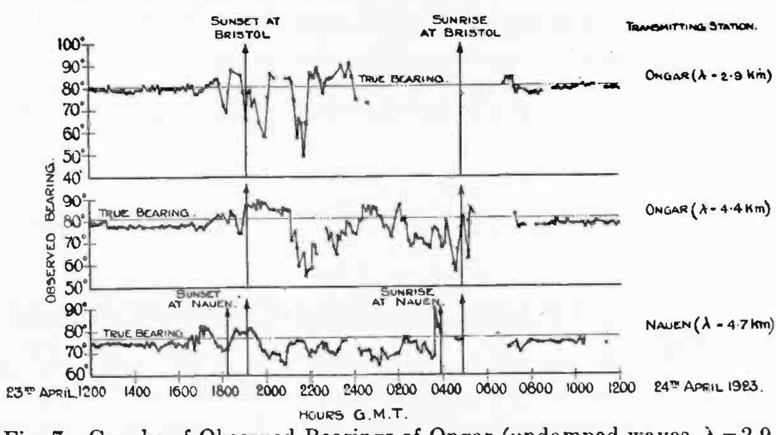

Fig. 7—Graphs of Observed Bearings of Ongar (undamped waves, $\lambda = 2.9$ and 4.4 km) and Nauen (undamped waves, $\lambda = 4.7$ km) taken at Bristol over a 24-hour period.

the winter months the daily errors assume appreciable proportions, particularly in the case of Leafield.

The general nature of the variations can be understood from the graphs given in Figs. 6 and 7, which show the apparent bearings of some fixed transmitting stations as observed every

TABLE III

Summary of Observations Taken at Orford from November 13, 1922 to March 29, 1924

(1)	(2)	(3)	(4)	(5)				(6)			
				Day Observations				Night Observations			
Transmitting Station	Type and wavelength	Distance	True bearing	No.	Extent of variation	Error of mean	Max. variation from mean	No.	Extent of variation	Error of mean	Max. variation from mean
	meters	(miles)	(degs.)		(degs.)	(degs.)	(degs.)		(degs.)	(degs.)	(degs.)
Amsterdam	S. 450	143	81.1	46	3.0	+0.6	−1.7	9	1.0	+1.2	+ 0.7
Antwerp	S. 600	136	114.9	152	3.0	+0.5	+1.6	94	30.0	+0.9	−15.8
Berwick	S. 450	285	332.0	161	2.5	+0.2	+2.3	106	20.0	+0.6	+12.4
Borkum	S. 450	237	62.3	65	3.0	+0.3	−1.6	127	14.0	+0.1	− 7.4
Boulogne	S. 450	95	178.2	519	3.5	−0.3	+2.1	341	15.0	0.0	+11.8
Cherbourg	S. 450	220	219.9	344	5.5	−0.2	+2.8	294	90.0	+1.0	+59.1
Cullercoats	S. 600	236	330.0	142	4.0	−0.3	−1.7	110	45.0	+0.5	+24.5
Dieppe	S. 450	151	188.0	206	6.0	+0.4	−3.4	—	—	—	—
Dunkirk	S. 450	83	154.1	294	3.0	+0.4	±1.5	193	32.0	+0.9	+20.0
Dunkirk	S. 600	83	154.1	90	2.0	+0.4	±1.0	85	15.0	+0.3	− 9.4
Flamborough	S. 450	155	334.8	331	2.5	−0.4	−1.4	258	45.0	−1.5	−28.3
Flushing	S. 450	98	116.0	936	4.0	+0.7	+2.3	173	30.0	+0.6	−16.6
Grimsby	S. 600	123	328.0	149	4.0	−0.5	+2.5	212	20.0	+0.8	+11.2
Havre	S. 450	188	200.0	977	5.5	−0.6	+3.1	563	75.0	+1.5	+58.5
Havre	S. 600	188	200.0	25	3.0	−0.6	−1.6	—	—	—	—
Helder	S. 450	148	65.0	544	4.0	−0.3	−2.2	108	11.0	+0.2	+ 9.8
Lizard	S. 450	327	246.2	—	—	—	—	194	25.0	+2.7	−13.9
Mok	S. 450	149	64.0	155	3.0	−1.3	−1.7	—	—	—	—
Niton	S. 600	161	230.5	81	5.5	−4.3	−3.2	40	20.0	−4.6	−15.9
North Foreland	S. 600	49.5	185.8	380	2.5	−1.2	+2.4	404	15.0	−1.2	+10.4
Ostend	S. 600	84	135.2	312	4.0	+0.1	+1.7	232	24.0	+0.1	+13.7
Parkeston Quay	S. 450	16.5	230.5	401	3.0	−2.9	−1.6	350	4.0	−3.2	− 2.3
Parkeston Quay	S. 600	16.5	230.5	10	0.5	−2.8	+0.3	10	1.0	−2.9	− 0.6
Portland	S. 450	204	239.4	20	7.0	−0.5	−3.9	47	35.0	+7.6	−22.0
Rochefort	S. 600	440	195.8	—	—	—	—	106	20.0	+2.8	+11.4
Scheveningen	S. 600	117	89.2	110	6.5	−0.5	+3.8	52	25.0	−1.1	−13.1
Scheveningen	S. 1,800	117	89.2	139	5.5	−0.4	−3.8	68	35.0	−0.3	−18.9
Teddington	S. 450	93	240.6	712	4.5	−2.6	+2.5	551	125.0	+1.7	+82.7
Teddington	S. 500	93	240.6	72	2.5	−3.2	−1.4	135	13.0	−3.1	+12.5
Teddington	S. 750	93	240.6	129	2.5	−3.1	−2.0	498	25.0	−2.7	+12.1
Teddington	I.C.W. 750	93	240.6	134	2.5	−3.0	+1.9	264	17.0	−2.7	+ 9.1
Teddington	C.W. 750	93	240.6	147	2.5	−3.1	+1.5	444	20.0	−2.4	+11.8
Teddington	S. 1,000	93	240.6	34	0.2	−2.6	+0.2	101	0.5	−3.0	+ 0.4
Teddington	I.C.W. 1,000	93	240.6	34	1.0	−2.6	±0.5	76	2.2	−3.1	+ 2.2
Teddington	C.W. 1,000	93	240.6	134	2.0	−2.5	±1.4	221	10.0	−2.1	+ 6.5
Teddington	S. 1,800	93	240.6	92	2.5	−1.8	−1.3	120	6.0	−2.1	− 3.5
Teddington	C.W. 1,800	93	240.6	196	3.5	−1.7	+2.1	328	30.0	−1.4	+15.8
Teddington	C.W. 2,600	93	240.6	65	2.5	−1.4	−1.7	123	35.0	−2.1	+21.5
Treguier St. Gonery	S. 450	307	224.9	15	3.5	−2.6	−2.3	12	13.0	+3.9	− 6.8
Ushant	S. 450	386	231.9	19	5.0	+0.2	+2.9	548	60.0	+2.0	+36.1
Wilhelmshaven	S. 450	293	67.8	304	4.0	−0.6	−2.2	323	35.0	−1.9	+19.1

few minutes over periods of 24 hours at one observing station. It is to be noticed that the day bearings are much steadier in the summer than in the winter months, but that in either case the approach of sunset is accompanied by an increase in the magnitude and frequency of the variable errors which continues throughout the night until sunrise. During the bulk of the investigations carried out on wavelengths between 450 and 12,000 meters these variable errors in bearing ranged up to, but very rarely exceeded, 90 deg. as illustrated in the above tables.

In some of the later work the observations have been extended into the broadcasting band of wavelengths. A summary of the results obtained is given in Table IV, and this shows that in the

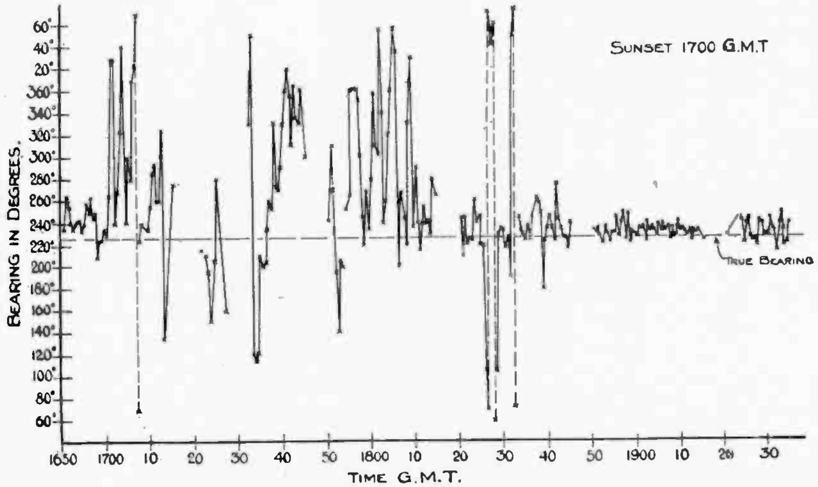

Fig. 8—Graphs of Observed Bearings of Bournemouth (undamped waves, $\lambda = 386$ m) taken at Ditton Park, Slough. October 20, 1926.

case of the observations at Slough taken on the transmissions from Bournemouth, the maximum error is given as ± 180 deg. This indicates that a single minimum has been followed round the direction-finder scale through this angle and indeed on several occasions a rotation of the apparent bearing through more than 360 deg. has been observed. Instances of this effect are illustrated in Fig. 8. A somewhat similar phenomenon has been previously recorded by Wright and Smith,[48] but on the much longer wavelength of 6,000 meters.

Another mode of illustrating the variable errors due to night conditions is that adopted in Fig. 9. This diagram refers to

TABLE IV

Summary of Observations Taken at Slough from May 28 to December 17, 1925

(1)	(2)	(3)	(4)	(5)				(6)			
				Day Observations				Night Observations			
Transmitting Station	Wave-length	Distance	True bearing	No.	Extent of varia-tion	Error of mean	Max. varia-tion from mean	No.	Extent of varia-tion	Error of mean	Max. varia-tion from mean
	(meters)	(miles)	(degs.)		(degs.)	(degs.)	(degs.)		(degs.)	(degs.)	(degs.)
Birmingham	479	88	319.1	201	3.0	+2.0	+1.9	1378	105.0	+3.4	−67.5
Bournemouth	386	77	227.6	76	6.2	+0.4	+4.2	1346	>360.	+5.3	±180.
London	365	18	83.5	—	—	—	—	803	7.5	+1.3	− 4.8
Newcastle	404	245	350.2	—	—	—	—	537	75.0	−1.4	+51.4

(The transmissions were all on telephony of which the carrier wave was treated as c.w. for reception purposes.)

TABLE V
Showing Percentage Variations of Bearings from the Annual Mean at Newcastle, 1922–23.

(1)	(2)	(3)	(4)		(5)		(6)		(7)		(8)	
Transmitting Station	Type and wave-length	Time of trans-mission	Total number of observations		Percentage Variations from Annual Mean							
					Over 2 deg.		Over 5 deg.		Over 10 deg.		Over 20 deg.	
			Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Aberdeen	C.W. 3.3 (km)	08.30 17.00	189	125	37.0	63.1	6.3	28.0	0.5	13.6	0.0	0.0
Aberdeen	C.W. 3.3	21.00	—	111	—	82.0	—	49.5	—	10.1	—	0.0
Air Ministry	C.W. 4.1	I	247	252	17.0	33.3	0.8	8.3	0.0	1.6	0.0	0.0
Berne	C.W. 3.4	I	530	217	3.2	61.3	0.4	32.7	0.0	10.6	0.0	1.8
Budapest	S. 3.0	I	48	26	2.1	15.4	0.0	0.0	0.0	0.0	0.0	0.0
Chelmsford	C.W. 3.8	I	76	70	9.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cleethorpes	C.W. 4.3	08.00	118	—	30.5	—	2.5	—	0.0	—	0.0	—
Cleethorpes	C.W. 4.3	I	116	187	12.9	61.0	0.0	13.9	0.0	0.5	0.0	0.0
Clifden	S. 5.8	09.50 21.50	85	66	0.0	28.8	0.0	9.1	0.0	0.0	0.0	0.0
Clifden	C.W. 5.8	I	316	594	0.0	6.9	0.0	3.4	0.0	1.2	0.0	0.0
Coltano	S. 4.2	I	169	244	1.0	16.4	0.0	1.0	0.0	0.0	0.0	0.0
Horsea	C.W. 5.0	I	193	98	23.8	39.8	2.6	10.2	0.0	0.0	0.0	0.0
Karlsborg	S. 2.5	12.15 20.00	171	485	20.5	83.5	0.0	42.5	0.0	20.2	0.0	1.9
Karlsborg	S. 4.2	I	125	53	6.4	50.9	0.0	18.9	0.0	7.5	0.0	0.0
Karlsborg	C.W. 3.9	I	503	237	11.3	40.0	0.6	16.9	0.0	8.5	0.0	2.1
Konigswusterhausen	C.W. 5.2	I	501	260	14.2	49.6	0.0	18.1	0.0	4.2	0.0	0.4
Moscow	S. 4.8	I	421	945	0.5	21.9	0.0	6.6	0.0	1.7	0.0	0.2
Nantes	S. 2.5	08.00 21.00	21	94	0.0	26.6	0.0	5.3	0.0	0.0	0.0	0.0
Nantes	S. 4.2	08.10 21.30	84	93	2.4	35.5	0.0	8.0	0.0	1.1	0.0	0.0
Nantes	S. 2.5	12.15	60	—	6.7	—	0.0	—	0.0	—	0.0	—
Nauen	S. 3.2	11.50	250	—	2.0	—	0.0	—	0.0	—	0.0	—
Nauen	C.W. 4.7	I	1421	1471	17.7	52.7	6.8	23.9	2.2	5.9	0.3	0.6
Ongar	C.W. 2.9	I	904	979	19.3	50.2	0.1	24.9	0.0	5.9	0.0	0.6
Ongar	C.W. 3.8	I	1239	859	2.1	34.7	0.1	14.8	0.0	2.7	0.0	0.0
Ongar	C.W. 4.4	I	252	321	4.7	24.0	0.4	10.6	0.0	1.6	0.0	0.0
Paris	S. 2.6	08.15	277	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Paris	S. 2.6	09.20 19.20	1486	432	3.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0
Paris	S. 2.6	11.30 21.55	516	162	0.0	23.4	0.0	2.5	0.0	0.0	0.0	0.0
Paris	S. 3.2	12.00	114	—	0.0	—	0.0	—	0.0	—	0.0	—
Poldhu	S. 2.8	09.50 21.50	42	37	0.0	65.0	0.0	27.0	0.0	8.1	0.0	5.4
Sofia	S. 3.2	I	—	163	—	45.4	—	16.5	—	3.7	—	0.6
Whitehall	C.W. 3.3	09.00 17.00	43	37	30.2	46.0	0.0	0.0	0.0	0.0	0.0	—
Whitehall	C.W. 3.3	21.00	—	30	—	40.0	—	10.0	—	0.0	—	0.0

records by several observers of the apparent bearings of Karlsborg during its daily transmissions from 2000 to 2030 on a wavelength of 2,500 meters. The observations were summarized in weekly batches and the graphs show the extremes of the bearings for individual weeks over a period of two years. It is very noticeable that the bearings show little variation so long as they are taken before sunset at the receivers, even though

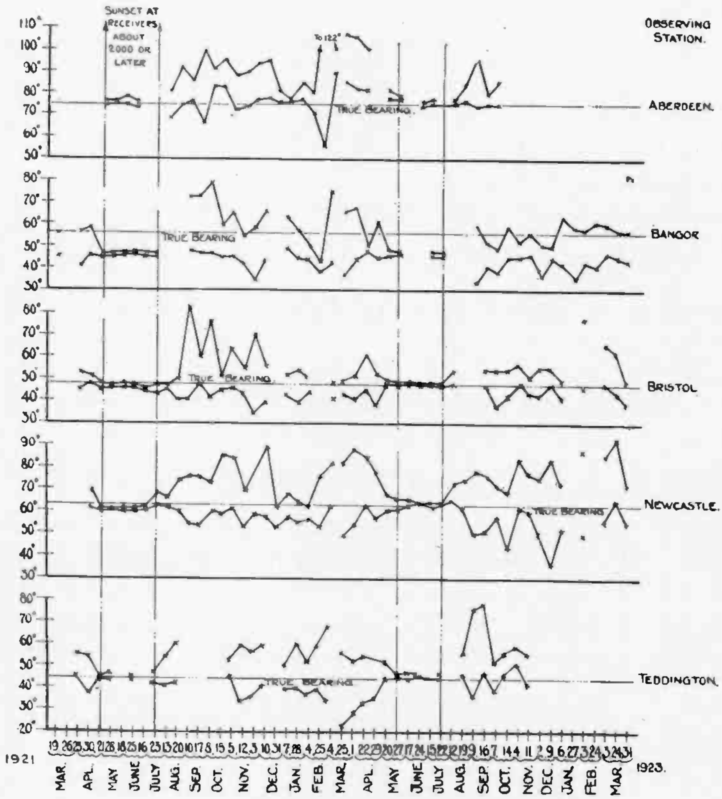

Fig. 9—Graphs of Weekly Extreme Bearings of Karlsborg (damped waves, $\lambda = 2.5$ km) observed on the transmissions at 2000 G.M.T. during the two years, March, 1921 to March, 1923.

darkness has prevailed over a portion of the path of transmission for some time.

In spite of the large variations in apparent bearings described and illustrated above, it is noteworthy that during the night periods the observed bearings show no signs of a definite systematic error, and so the variations are on the whole equally distributed about the mean value. Another feature to be observed in connection with the magnitude of the night variations is the comparative rarity of the larger errors. A summary of the results obtained at Newcastle during the last year of operation is given in Table V, arranged in such a manner as to show the proportion of the observed bearings which differ by various fixed amounts from the mean day bearing. From this mode of expressing the results it will be seen that it is not often that more than 10 per cent of the night results give an error exceeding 10 deg. This fact, combined with the absence of a systematic error at night, is of great importance in the practical application of wireless direction-finding.

It thus appears that the chief effects to be observed in radio direction-finding are generally as follows. In the summer time in those latitudes in which the United Kingdom is situated the observed bearings in daylight are fairly constant and, with the exception of the permanent errors already mentioned, they approximate quite accurately to the true geographical bearing of the transmitting station. Under certain conditions of transmission to be referred to below this accuracy is maintained at all times and seasons. When these conditions do not prevail, however, the observed bearings show signs of variable errors as the setting of the sun approaches the path of transmission. These variations then prevail throughout the night, but decrease to a negligible extent soon after sunrise. As the seasonal conditions are changed gradually from summer to winter the variations in the daytime increase somewhat; and the night conditions begin an appreciable time before sunset and continue until some time after sunrise. In the midwinter conditions represented by January, the change from day to night effects is very much more gradual and the difference is only distinguishable by the difference in magnitudes of the variations. At this time of year it appears that on the longer wavelengths the variations may have an amplitude of the order of 10 deg. or more during the daylight hours, and this increases rapidly at about one hour before sunset to the night value of 50 deg. or 70 deg., and so continuing in the most erratic manner until one hour or so after sunrise.

It has now been satisfactorily established that these variations in apparent bearing are due to the arrival at the receiver of waves from the upper atmosphere polarized with their electric force in a horizontal plane. This explanation was first put forward by T. L. Eckersley[49] in 1921 and supported by experimental results. Of recent years considerable direct confirmation of the theory has been provided,[50,51,52] and the study of the propagation of electromagnetic waves through the ionized regions of the atmosphere now forms the subject of large numbers of papers published in all parts of the world.

(b) *Effect of Various Factors upon Variations in Bearings*

From time to time throughout the investigation the results have been carefully considered to ascertain if there is any definite relation between the wavelength of transmission and the nature, frequency, and magnitude of the variations in apparent bearings experienced. Over the band of wavelengths from 300 to 20,000 meters no marked difference has been observed in the extreme variations recorded, after due allowance has been made for the distance and the geographical conditions over the path of transmission. The outstanding exception to this statement is the case of Bournemouth observed at Slough, as mentioned above, in which exceedingly violent variations have been recorded. It is probable that this occurrence is due to a coincidence of wave length and distance, and the relative magnitudes of the downcoming and direct waves. The conclusion that, within wide limits, the wavelength has no effect upon the amplitude of the variations observed over a period is to be distinguished from the fact that when the wavelength of transmission is changed instantaneously the error in bearing due to night effect also changes appreciably. Excellent examples of this occurrence have been obtained in observing on the transmissions from arc stations, such as Leafield, which employ for signalling purposes a marking and spacing wave differing in length by about 1 per cent. The errors in bearing taken in rapid succession on the marking and spacing waves differed at times by 20 deg. to 30 deg.

The experience of the author obtained in Great Britain that the wavelength itself does not have a very marked effect upon the magnitude of the variations would appear to differ from that of Austin,[53] who states that in the United States of America the variations on the shorter wavelengths are considerably less than on the longer wavelengths. This conclusion does not, however, appear to be consistent with the results obtained by

TABLE VI

Summary of Observations Taken at Teddington during 24-hour Test from January to June, 1926

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)			
Transmitting Station	Wave-length	Distance	True bearing	No. of obser-vations	Extent of varia-tion	Error of mean bearing	Max. varia-tion from mean	Percentage of Bearings differing from Mean by more than:			
								2 deg.	5 deg.	10 deg.	20 deg.
	(meters)	(miles)	(degrees)		(degs.)	(degrees)	(degs.)				
Bordeaux LY	18 940	452	181.8	316	33.0	−0.2	−19.1	63.3	32.6	5.4	0.0
Carnarvon MUU	14 200	200	307.3	139	7.7	+1.3	− 4.6	36.9	0.0	0.0	0.0
Karlsborg SAQ	18 050	760	44.4	219	19.8	+2.9	−11.6	55.7	11.9	0.9	0.0
Long Island WQK	16 460	3,403	287.9	547	7.4	+2.3	+ 3.4	6.4	0.0	0.0	0.0
Rugby GBR	18 900	75	330.4	147	34.5	−1.3	+27.9	85.8	47.7	11.6	4.8
St. Assise UFT	14 290	237	146.3	416	34.0	−3.9	−22.4	83.7	35.4	9.4	0.3
Tuckerton WCI	16 800	3,521	287.3	192	3.7	+2.4	+ 2.0	0.0	0.0	0.0	0.0

Merritt,[54] Bidwell,[55] and Reich[56] at Cornell University, which show variations in bearings exceeding 100 deg. on wavelengths of 380 to 500 meters. The difficulty of drawing very definite conclusions from observations made on available transmissions from commercial stations within range is illustrated by Table VI, which is intended to show the decrease in magnitude of the bearing variations when the range of transmission is over 3,000 miles. The results given in this table were obtained at Teddington, England, during a series of continuous tests each lasting 24 hours, in which observations were made of the apparent bearings of various European and American stations transmitting on wavelengths between 14,000 and 19,000 meters. These experiments have shown that over similar distances the variations experienced on the wavelengths 2,000 to 9,000 meters are of the same order as those on the higher wavelengths, and also that the actual amplitudes of the variations decrease considerably for a range of transmission exceeding 3,000 miles. In fact, on the American transmitting stations the variations in

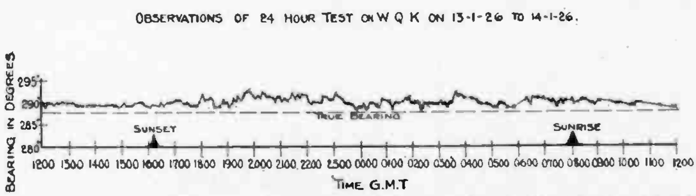

Fig. 10—Graph of Observed Bearings of Long Island (WQK, $\lambda = 16.5$ km) taken at Teddington during a 24-hour period, January 13 to 14, 1926.

bearings show no marked distinction between day and night periods. As illustrated in Table VI, observations taken over several 24-hour periods show a maximum error in bearing of about 3 deg. for the American stations, while on nearer European stations the night error may range up to nearly 30 deg. From Table VI it is seen that of the two American stations observed one gave 94 per cent and the other 100 per cent of bearings correct within 2 deg. during the whole series of tests; whereas of the European stations the best example, Carnarvon, gave only 63 per cent of bearings correct to within this limit. The contrast of the observations on the stations at different distances is illustrated by Figs. 10 and 11 which are typical of the results obtained on transmissions from the American and European stations. The error of the daylight readings is in each case attributable to local conditions at the direction-finder.

While discussing the effect of distance on the errors in observed bearings it may be mentioned that Pickard[57] published in 1922 some results, of which a very noticeable feature was that the apparent bearings of European stations observed at Maine, U. S. A., showed much smaller variations than the bearings of some American stations. This difference was attributed to the fact that the transmission from the former was mostly over sea, whereas in the latter case it was entirely over land. It can be shown from theoretical considerations, however, that this is probably not the correct explanation.[16(d)] Mesny[58] has also found that the bearings on some American stations observed in France show only a very small variation as compared with bearings taken on the nearer European stations. Experiments carried out in Shanghai by Gherzi[59] during 1923–24 have also shown that while large night errors are observed for distances of transmission

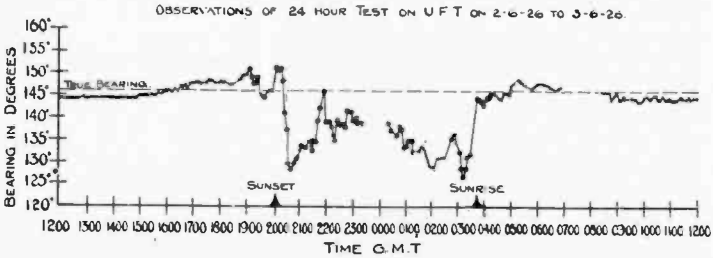

Fig. 11—Graphs of Observed Bearings of Ste. Assise (UFT, $\lambda = 14.3$ km) taken at Teddington during a 24-hour period, June 2 to 3, 1926.

of less than 5,000 km (3,000 miles) these errors have an extreme value of about 6 deg. when the range of transmission is from 5,000 to 12,000 km (3,000 to 7,500 miles).

The effect of the incidence of sunlight upon the upper regions of the earth's atmosphere can also be demonstrated during a solar eclipse. Fig. 12 shows the results of observations made at Slough on the transmissions from the Manchester broadcasting station during the solar eclipse of June 29, 1927. Although the normal night variations had ceased at about one hour after sunrise, it is seen that the variations were temporarily restored during the period of obscuration of the sun. A discussion of these and other wireless observations made during the eclipse will be found in the official published report.[60]

In concluding this section it may be repeated that it is only intended to be a general summary of the results obtained from the co-ordination of a large quantity of data. Anyone who is interested in obtaining more exact information on any portion of the work may be referred to the official reports containing the tabulated results in detail and published by the Radio Research Board. As far as the actual nature and magnitude of the effects observed are concerned, the author believes he is correct in stating that his results obtained in the British Isles are in complete agreement with the observations made in other countries, such as by Mesny and others in France;[58,61,62] by Stoye in Germany;[63] Austin,[64] Bidwell,[54,55] and Pickard[57] in America; and by Gherzi[59] in China.

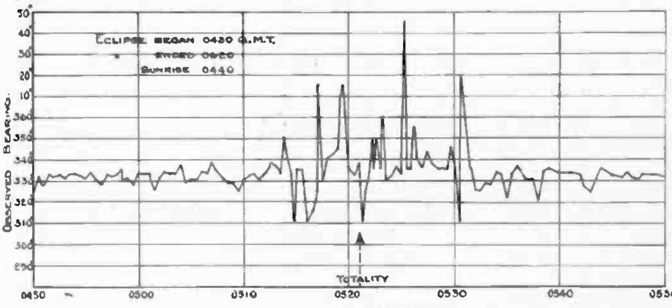

Fig. 12—Observations of Apparent Bearings of Manchester (2ZY) at Slough during the Solar Eclipse, June 29, 1927.

4. Analysis of the Performance of a Rotating Beacon

If the application of the principle of reversibility in direction-finding as stated in Section 2 be accepted, then it is evident that the performance of a rotating loop beacon transmitter can be largely predicted from the results and experience obtained with receiving loop direction-finders. Thus a rotating loop beacon when erected on the same site as a direction-finder will give bearing observations at a distant receiver, which will be subject to the same type of local error and night variations, for example, as the bearings observed on the direction-finder when the distant receiving aerial is used for transmission. Such deductions as these have been confirmed by the author during the past two or three years in the investigation of the performance of a rotating beacon erected at Fort Monckton, near Gosport, England.[44] Bearings observed on this beacon in certain directions were found to be subject to a small permanent error, which was of an approximately quadrantal nature, and which decreased in magnitude with increase of the working wavelength.[46] This error was of the same order as that experienced with a wireless direction-finder set up in proximity to the beacon, and was found to be most probably due to some underground power cables. In the choice of sites for future beacons it is evident that a portable direction-finder can be usefully employed in ascertaining the suitability of the site and its liability to produce local errors.

In order to ascertain the reliability of this type of rotating beacon as an aid to marine navigation, a number of tests were carried out on ships crossing the English Channel between Southampton and Havre, and Southampton and Jersey. Using the ship's ordinary wireless receiver observations of the bearing of the beacon were made at intervals during each trip and compared with the bearing as given by the Captain of the ship.

A typical log of one of these tests is given in Table VII, while the chart in Fig. 13 shows a comparison between the ship's "dead reckoning" and the wireless course in three other tests. As a result of tests conducted on these lines it was found that in the majority of cases the estimated and observed bearings agreed within from 2 deg. to 4 deg., although at times this difference ranged up to 12 deg. Signs of night effects in the shape of indistinct signal minima and wandering bearings were observed at distances exceeding 50 miles, but these were not always coincident with the above differences which sometimes occurred in daylight. In many cases at night and during misty weather, when visibility was very poor, the ship had to be navigated by dead reckoning so that the estimated bearing of the beacon from the ship may be subject to some suspicion.

In order to study these night variations in a more satisfactory manner, a number of tests were arranged in which observations were made continuously over a period of twelve hours or more from various fixed positions. The places of observation were selected so as to provide a variety of ranges and also to show the difference between transmission over sea and over land. Some of the observations were carried out in ships moored in dock or alongside a light vessel, while other observations with transmission entirely overland were carried out at Slough and Teddington.

An analysis of the readings obtained in this manner in daylight shows that for ranges up to 56 miles the maximum departure of the observed bearings from their mean or correct value was 3 deg., while up to the maximum range of 119 miles the greatest deviation was 6 deg. In most cases over 90 per cent of the observations were correct within 2 deg. When the observations were carried out at night, the above accuracies were maintained for distances overland of 14 miles and oversea of 23 miles. At distances of 92 miles entirely oversea the night errors experienced ranged up to a maximum value of 18 deg., but it is to be noted that in these cases over 84 per cent of the bearings were cor-

TABLE VII

Summary of Observations Obtained on a Return Voyage from Southampton to Havre, September 22 to 24, 1926.

Continuous Wave Transmission. $\lambda = 525$ m

Date	G.M.T.	From information supplied by Captain of ship				Wireless bearing from beacon	Remarks
		Position and how obtained		From Fort Monckton			
				Distance	Bearing		
22.9.26	2240	Southampton.	A.	miles 14.3	degs. 127	degrees 126	Mean of several readings.
23.9.26	0102	Beyond Nab.	V.B.	17.5	324	323	
	0132		D.R.	26.0	328	329	
	0202		D.R.	35.	330	331	
	0232		D.R.	43.	331	331	
	0302		D.R.	51.	332	332	
	0332		D.R.	60.	333	334	
	0532		D.R.	85.	335	335	
	0602		D.R.	94.	334	335	Night effect observed
	0632		D.R.	96.	330	331	
	0722	Havre.	A.	105.	328	330	
	1702	Havre	A.	105.	328	329	Mean of several readings.
24.9.26	0012		D.R.	95.	330	331	
	0032		D.R.	88.	330	329	Night effect observed.
	0102		D.R.	79.	329	327	
	0132		D.R.	69.	329	325	Night effect observed.
	0202		D.R.	60.	329	325	
	0232		D.R.	52.	329	325	
	0402		D.R.	24.	329	326	
	0432		V.B.	15.	325	326	
	0442	2 miles from Nab.	V.B.	11.5	324	323	

Notes.— (1) A = moored in dock, V.B. = visual bearings, D.R. = dead reckoning. (2) Night effect observed at 60 miles and over. (3) Maximum difference between estimated and observed bearings = 4 deg. at night. (4) Sea moderate throughout.

rect to within 5 deg. When the oversea distance exceeded 100 miles the errors became more serious. For overland transmission the errors were much larger, and at a distance of 55 miles errors up to 32 deg. were experienced, while only 66 per cent of the observed bearings were correct to within 5 deg. In spite of such large errors, however, it was found that the mean bearing of the beacon from any position was practically the same by day or night. This implies that the systematic error of the night variations is very small, so that the effect of errors of individual ob-

At each site a simple receiver with a vertical aerial was employed for the reception of the signals from the rotating beacon. Adjacent to this, but at a sufficient distance to avoid mutual interference, a single-frame coil direction-finder was set up for the purpose of taking ordinary direction-finding bearings while the beacon loop was fixed with its plane approximately in the direction of the receiver. As a further precaution against producing a spurious reading on the direction-finding set the vertical aerial was disconnected during the taking of bearings on the direction-finder. A few tests carried out on land showed that apart from the occurrence of local errors due to the site selected, the two systems gave observed bearings of similar accuracy. In order to study the variations in bearings experienced with the two systems over extended periods, further experiments were carried out on a ship at Jersey and on land at Slough. The analysis of a large number of readings taken in this manner confirmed the similarity in accuracy of the two systems, and showed also that results obtained with continuous wave transmission were similar to those obtained with interrupted continuous waves.

At night time the variations in observed bearings were quite serious in all cases. The extent of the variation ranged from 20 deg. to 57 deg. in the case of the rotating beacon bearings, and from 69 deg. to 130 deg. in the case of the direction-finding bearings. Under these conditions, however, over 86 per cent of the bearings taken on the rotating beacon were in error by less than 10 deg. while in the case of the direction-finding bearings over 62 per cent were in error by less than 10 deg. As already mentioned it is now well-known that these errors are due to the reception of waves from the transmitter deflected in the upper atmosphere, and it is realized that in the results quoted above the variations on the direction-finder are exaggerated by the fact that the loop transmitter radiates very much more to the upper atmosphere than is the case with a vertical aerial.

Comparison Tests at Sea

Some of the test runs made on ships between Southampton and Jersey, discussed above, were carried out in a ship which is fitted with a Marconi direction-finder using fixed frame coils on the Bellini-Tosi system; and the opportunity was thus provided of comparing the two systems of obtaining wireless bearings under actual sea-going conditions. The results obtained on one trip, in which observations were made successively on the rotating beacon and on the direction-finder with the beacon fixed in the maximum signal position, are given in Table VIII.

Considering first the results in Table VIII it is seen that with two exceptions the direction-finding bearings agree with

TABLE VIII

Summary of Observations Obtained of a Return Trip between Southampton and Jersey, September 14 to 16, 1927

Date	G.M.T.	From information supplied by Captain of ship				Wireless Bearings:		Type of trans-mis-sion	Re-marks
		Position and how obtained		From Fort Monckton		from bea-con	by D.F.		
				Dis-tance	Bear-ing				
				miles	degs	degs.	degs.		
14.9.27	2340	Off Egypt Point.	V.B.	9.	90.	92.	88.	I.C.W.	
15.9.27	0010	Off Yarmouth Pier.	V.B.	16.	78.	74.	75.	C.W.	
	0040	nr. Needles	V.B.	22.	68.	65.	67.	I.C.W.	Sea
	0610	At Guernsey	A.	110.	34.	36.	33.	C.W.	
	0710	St. Martin's Pt.	D.R.	111.	31.	34.	33.	C.W.	rough
	0740	nr. Groznez Pt.	V.B.	114.	27.	30.	37.	I.C.W.	
	1540	At Jersey	A.	116.	21.	22.	26.	I.C.W.	Means
	1610	At Jersey	A.	116.	21.	22.	24.	C.W.	of sev-
	1640	At Jersey	A.	116.	21.	22.	25.	I.C.W.	eral read-ings
16.9.27	0710	nr. LaCorbière.	V.B.	119.	25.	28.	Sigs. too weak	C.W.	
	0940	nr. Casquets	V.B.	96.	35.	39.	36.	I.C.W.	
	1010	beyond Casquets	V.B.	88.	39.	36.	36.	C.W.	
	1040	49° 54′ N. 2° 17′ W.	D.R.	78.	40.	38.	42.	I.C.W.	
	1110	50° 2′ N. 2° 9.5′ W.	D.R.	68.	41.	38.	41.	C.W.	Sea
	1140	50° 9.5′ N. 2° 2.5′ W.	D.R.	55.	43.	39.	41.	I.C.W.	smooth
	1310	Outside Needles	V.B.	30.	52.	48.	57.	C.W.	
	1340	Inside Needles	V.B.	20.	71.	70.	71.	I.C.W.	
	1410	Lepe Middle	V.B.	14.	82.	82.	93.	C.W.	
	1440	Beacon Buoy.	V.B.	10.	119.	121.	119.	I.C.W.	

Notes.—(1) A = moored in dock, V.B. = visual bearing, D.R. = dead reckoning. (2) Maximum difference between estimated and observed bearings on beacon = 4 deg. in daylight. The observed bearings have been corrected for land errors in accordance with the previous calibration of the beacon in the area occupied by the ship. (3) Maximum difference between estimated and D.F. bearings = 11 deg. in daylight. Part of this difference is probably due to land effects for which a correction is not readily applicable.

the estimated bearings to within 5 deg. Of the two exceptions, one shows an error of 10 deg. at a range of 114 miles, while the second shows an error of 11 deg. at 14 miles distance, when the ship was proceeding up the Solent. It is thought that a portion of these errors, but probably not more than 3 deg. or 4 deg., is due to a land deviation effect which is difficult to compensate for on a ship direction-finding set. During the same run, the rotating beacon bearings, after correction for the 1 deg. or 2 deg. of error in some positions from the calibration curve, show a maximum departure from the estimated bearing of 4 deg.

In searching for an explanation of the direction-finding errors above, it is to be remembered that the direction-finding bearing is observed relative to the ship's head and that, therefore, the accuracy of the bearing is limited to the accuracy with which the ship's compass indicates the *instantaneous* direction of the ship's head. On the ship in question the direction-finding set is operated from the wireless room and on a signal being given to the bridge the compass reading is taken by one of the ship's officers. In anything but a very calm sea it is naturally difficult to keep the ship's head steady to within one or two degrees, and in a rough sea the swing may amount to five degrees or more. Also there is probably a lag between the actual direction of the ship's head and the reading of the compass. Finally, unless it is calibrated at frequent intervals, it is doubtful if the reading of a magnetic compass is accurate to within 2 deg. or 3 deg. over all parts of the scale. These considerations may result in the accuracy of a ship direction-finder installation being appreciably inferior to that of a similar apparatus on land. The errors due to the above cause will probably decrease with an increase in the size of the ship, but the ship mentioned above is probably typical in size to many which will, in the future, utilize wireless bearings for navigation. It is also to be remarked that the ship direction-finding set is subject to a quadrantal error, for which correction or compensation is necessary.

On the other hand the rotating beacon method of obtaining wireless bearings is free from all these objections. Except for the interfering effects of noise and general vibration, the accuracy of the observed bearings is the same whether the ship is in dock or at sea.

Reception of Beacon Transmissions on Loop and Aerial

Since it may sometimes be required to receive and observe signals from a rotating beacon on a closed loop or direction-finding set instead of on an open aerial, it was considered to be useful to make a brief comparison between the two cases. When working in daylight or under such conditions at night as to be free from night variations, it has been found that the bearings observed on a loop agree with a maximum departure of one degree, with those observed on an aerial. When operating under conditions of night variations, however, the errors encountered on the loop receiver are greater than those observed on the aerial. This effect is due to the fact that with downcoming waves arriving at the earth's surface the resultant horizontal magnetic field (operating on the loop) is of greater intensity than the vertical electric field (operating on the vertical aerial).[50,52] These results have been confirmed for both continuous wave and interrupted continuous wave transmission.

Night Errors Experienced Under Strictly Reversible Conditions

Reference has been made in one or two places in this paper to the application of the reciprocal theorem to wireless direction-finding. While the form of comparison of the rotating beacon and the direction-finder adopted in the tests described above is the correct one for determining the relative advantages of the two systems for marine navigation purposes, it does not constitute a strict reversibility of the system, aerial to loop. By erecting a direction-finder in close proximity to the rotating beacon and using a distant aerial either to transmit to the direction-finder or to receive from the beacon this reversibility is achieved. In this manner it was shown that both local and night errors are of the same order on the two systems and a graph of bearing taken at night under these conditions is shown in Fig. 14.

5. Conditions Affecting Direction-Finding as an Aid to Navigation

In the application of a direction-finding system to either marine or aerial navigation it is important to understand clearly the exact conditions under which the observed bearings are accurate, and in other conditions to appreciate the order of magnitude of the possible errors involved and the means of mitigating these where possible. It is generally conceded nowadays that an accuracy of 2 deg. in observed bearings is suitable for navigation purposes, particularly when it is borne in mind that the observations may be repeated at frequent intervals.

An important factor to be noted from a navigational point of view is that of any effect of fog on direction-finding, since it

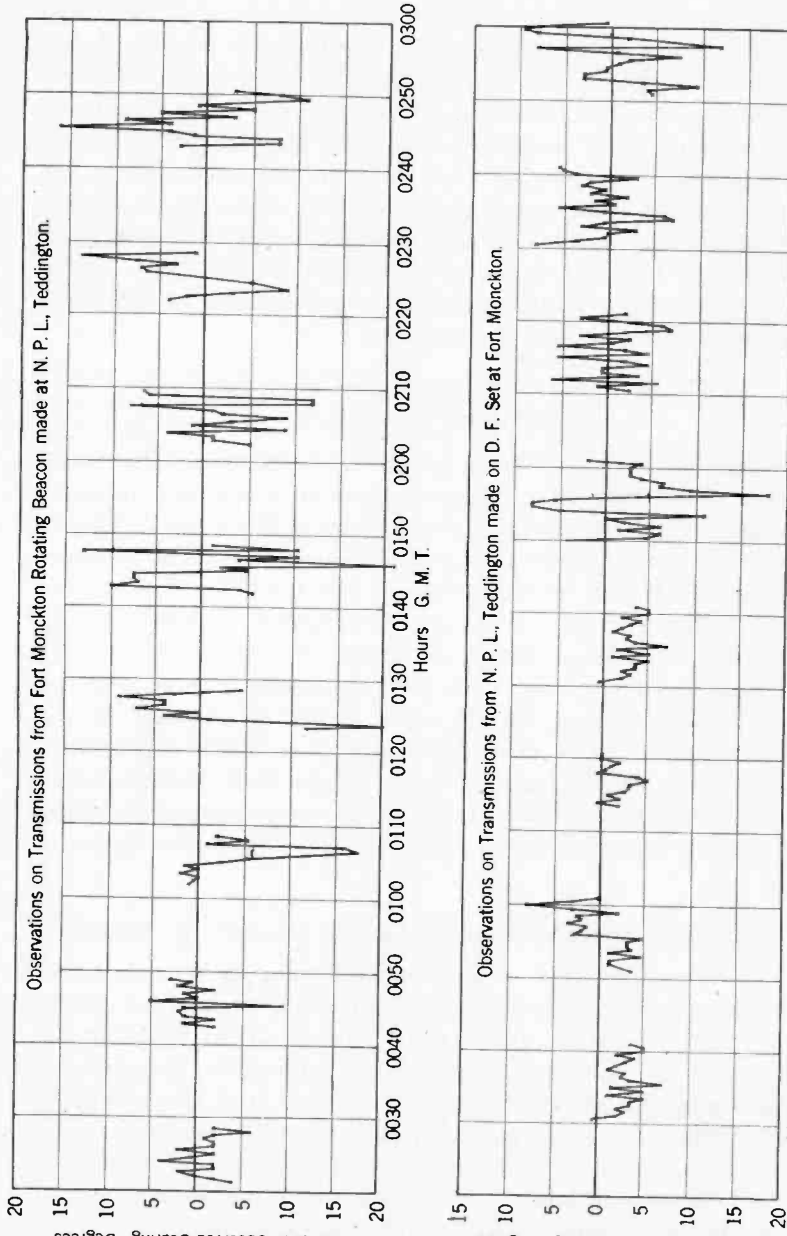

Fig. 14—Comparison of Night Observations on Rotating Beacon and on Direction Finder, March 22, 1928 (undamped waves, $\lambda = 525$ meters).

is chiefly during foggy weather that the majority of direction-finding stations are called into action. On several occasions the author has taken particular notice of the existence of fog at times when observations were in progress with a negative result. On one occasion in particular the fog was spread over the British Isle and a large portion of Western Europe, but the directional variations showed nothing beyond the usual day and night effects. These results form a confirmation to the observations of Rothé,[66] who concluded that no variations in ordinary atmospheric conditions would account for the small variations in bearings observed in the daytime.

During the course of the many experiments carried out with the direction-finder and the rotating beacon it has been found that the type of wave transmission employed has no effect upon the bearings observed, and that the errors and effects encountered are of the same order for damped, undamped, and interrupted undamped waves.[67,44]

(a) *Errors Due to Local Conditions*

In Sections 2 and 3 above it has been mentioned that various conditions may be present in the neighborhood of either a direction-finding station or a rotating beacon to cause an error in the bearing observed on a distant station. From various detailed investigations into the causes of such errors it is known that the most prominent effects are due to masses of metalwork and wires, either above or below the earth's surface, and to trees.[19,20] In most cases where the directional station is situated on land it is possible to select a site which is largely if not entirely immune from such effects, and provided that the residual errors do not exceed 2 deg. or 3 deg. in magnitude they can be definitely ascertained by a calibration at short distances, and a correction obtained for application to other observed bearings. In the case of the use of a direction-finder on board ship it is impossible to be clear of the metalwork of the ship itself and the resulting bearings are subject to a quadrantal error, which can either be compensated by circuit adjustment or corrected for from a chart.[41,42,43]

(b) *Coastal Errors*

Another type of error (which might be classified as one due to local conditions, but which, on account of its importance in the application of direction-finding to marine navigation deserves a special section) is that due to the deviation of wireless waves in crossing a coast-line, when the path of the waves lies approximately parallel to the coast. In the experimental work carried out at Orford, Suffolk, the coastal error on wavelengths of 450 and 600 meters was found to be of the order of 3 deg. or 4 deg. when the direction of transmission was within 20 deg. of the coast-line. In one instance, in which the wavelength was systematically increased from 500 to 2,600 meters, the corresponding error decreased from 3.2 deg. to 1.4 deg. On higher wavelengths the observed coastal error was less than one degree. In every instance the error was such as to indicate a bending of the waves towards the normal to the coast-line, in passing from the sea to the land side of the boundary. These experimental results are in complete agreement with those previously obtained by Eckersley[8] but, as already pointed out,[68] they are inconsistent with the explanation of the deviation as a coastal refraction effect due to the difference in the superficial velocity of wireless waves over land and sea. For the theoretical aspect of the problem would appear to indicate a deviation much smaller than that actually observed, and also in the opposite direction.

More recently some experiments on the propagation of waves across a coastal boundary have been made by Baümler and Zenneck.[69] Their results generally confirm those given above as to the magnitude and direction of the deviation of the waves in passing from sea to land. They further showed that the deviation at the coast is unaltered by the change in sea-level from high to low tide. Worlledge[70] has also given brief details of some experiments carried out at a direction-finding station in which indications were given of the reflection of wireless waves from the landward side of a coastal boundary. As a result of this phenomenon errors in observed bearing and indistinct minima due to interference may be produced at a direction-finding station when observing on transmissions emanating from a station on the same side of the boundary.

In connection with these coastal errors it is worthy of note that, with the accumulation of experience of the use of direction-finders on board ship, it is now becoming customary to mark out on charts the "arcs of good bearings" of various transmitting stations, within which the results of observations are found to be reliable.[71] Similar arcs can, of course, be provided for shore direction-finding stations or rotating beacons; and their boundaries would be found in the initial calibration of the station for the permanent local errors.

(c) Night Errors and Their Elimination

As the result of the analysis of a large quantity of data obtained with wireless direction-finders it can be stated that the minimum distance at which night variations have been consistently experienced is about 30 miles for overland working, observations taken at closer ranges than this showing a maximum error of only 2 deg. or 3 deg. Mesny[58] has stated that night variations may occur for ranges of transmission as small as 15 miles, but according to the author's experience night errors are small at such distances. For example, observations of the bearings of the London broadcasting station taken at Slough, 18 miles away, have shown a maximum error of less than 5 deg. during many months (see Table IV). Similarly, the bearings of the Air Ministry in London, at Teddington, distance 17 miles, have shown a maximum error of 4.5 deg. while 99 per cent of the readings were within 2 deg. of the mean bearing. On the other hand, Ongar, which is 30 miles away, gave an error up to 8 deg. at the same observing station, and only 14 per cent of the readings differed from the mean by less than 2 deg. When, however, the path of transmission is entirely oversea, as was the case in the observations carried out at Orford on the transmissions from various ships, the above minimum distance is increased to about 80 or 90 miles.[65] This fact is of great importance in the application of direction-finding to marine navigation, and it is perhaps fortunate that the usual conditions connected therewith are that the path of transmission is entirely oversea and that the observed bearings should be accurate at distances which are usually less than 50 miles and never greater than 100 miles. It is now known that under such conditions direction-finding is sufficiently accurate for navigational purposes.

The explanation of the greater range freedom from directional errors due to the diminished attenuation of the direct wave travelling oversea was first given by Wright[73] in 1920. An exactly similar result has been obtained from the experiments carried out at sea in the observation of bearings from a rotating beacon.[44] Even in the presence of night errors their effect can be largely mitigated with either system of direction-finding by taking a series of observations in succession over a period of a few minutes, when the mean bearing so obtained will be much more accurate than a single reading.

As already mentioned in a previous section it is now well known that the night errors experienced in the use of closed-

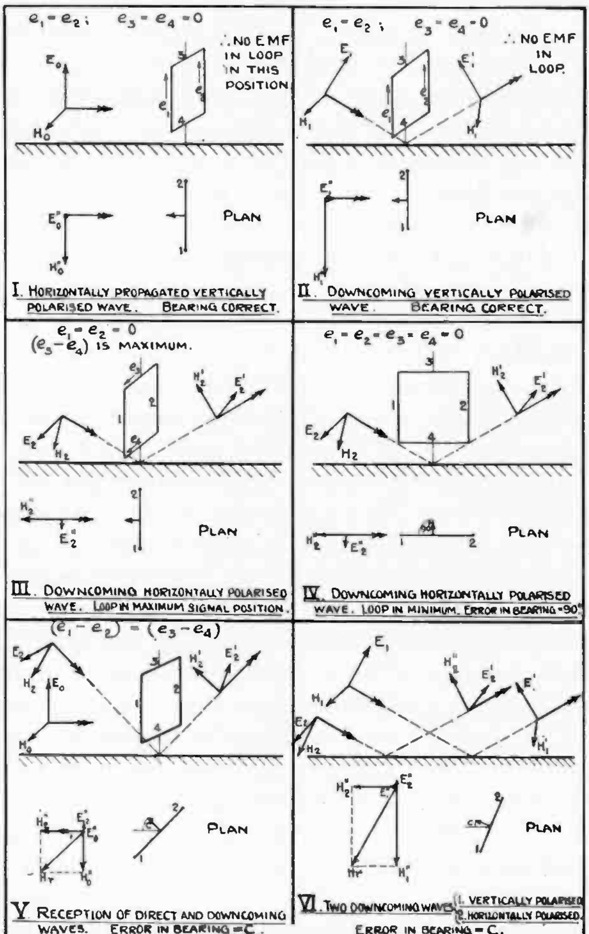

Fig. 15

coil direction-finders are due to the action of the horizontally polarized component of the downcoming waves. The effect of the horizontal component of the electric force in producing an error in observed bearing is illustrated by the series of diagrams forming Fig. 15. It is generally assumed that the downcoming waves have travelled through the upper regions of the earth's atmosphere without deviating laterally from the great-circle plane through the transmitter and receiver. The author believes he is correct in stating that this assumption remains undisputed at the present time, except for wavelengths below about 50 meters. It will be evident, therefore, that any receiving system which is unaffected by a horizontal component of electric force would be free from night errors, even though the vertically polarized downcoming waves might still produce variations in received signal strength. A direction-finding receiving arrangement which fulfils this condition was patented by Adcock[14] in

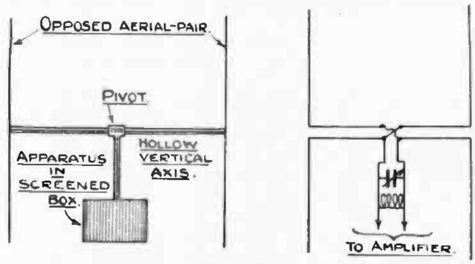

Fig. 16

1919, but this system does not appear to have received practical consideration until Mr. Barfield and the author[74] experimented with it in 1926.

The simplest form of the Adcock aerial system is a pair of spaced vertical aerials arranged to rotate about a central vertical axis, as shown in Fig. 16, thus forming the equivalent of the single closed-coil direction-finder. By making all connections to the centers of the aerials the horizontal members of the system are compensated so that no emf is induced in the system by a horizontal electric force. To obtain increased sensitivity larger aerials set at a greater spacing may be employed, and when the system becomes too large to rotate, two pairs of such aerials may be employed in conjunction with a radiogoniometer exactly as employed with closed loops in the Bellini-Tosi direction-finder. The schematic arrangement of such a system is shown in Fig. 17, while the photograph in Fig. 18 gives a view of the practical arrangement employed in a series of experiments which have been described in detail elsewhere.[74] The type of result obtained is illustrated by the curves given in Fig. 19, which shows the results of simultaneous observations made on an ordinary closed-coil direction-finder and on one of the Adcock type on the transmissions from a British broadcasting station. It will be seen from this diagram that while the closed-coil set during this period of observations was giving very bad night variations, the corresponding errors observed on the Adcock direction-finder were negligible. It is to be concluded from these and similar results obtained on the transmissions from other broadcasting stations that lateral deviation plays a negligible part in producing the large and variable errors which are obtained at night on the present type of closed-coil direction-finding set, and that therefore these errors are almost entirely caused by the arrival of downcoming waves polarized with the electric force horizontal.

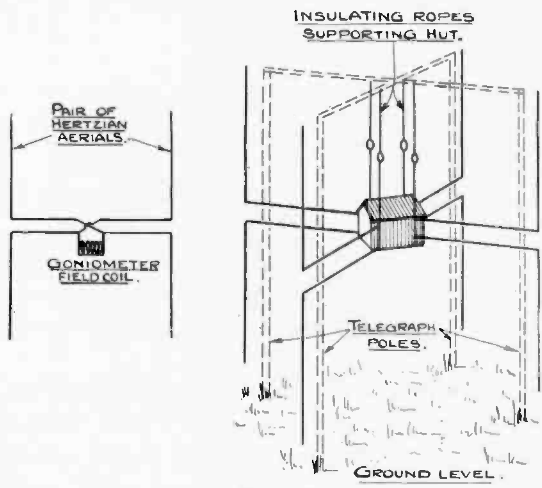

Fig. 17

It will be appreciated that it follows from the above conclusions that such a system may be used as a direction-finder which gives the true great-circle plane of arrival of wireless waves, whatever may be their state of polarization or their angle of incidence at the earth's surface. The system should, therefore, have important applications as an accurate direction-finder under night conditions, or for use in observing on transmissions from aircraft at high angles of elevation, when the ordinary closed loop type of instrument is subject to large errors. Conversely the Adcock aerial system may be used in place of the closed loop at a directional transmitting station for use either as a course-setter or as a bearing indicator, with freedom from the night errors which have already been experienced.[33,44] The practical development of the system both as a transmitter and as a receiver towards the above ends is now being pursued in Great Britain.

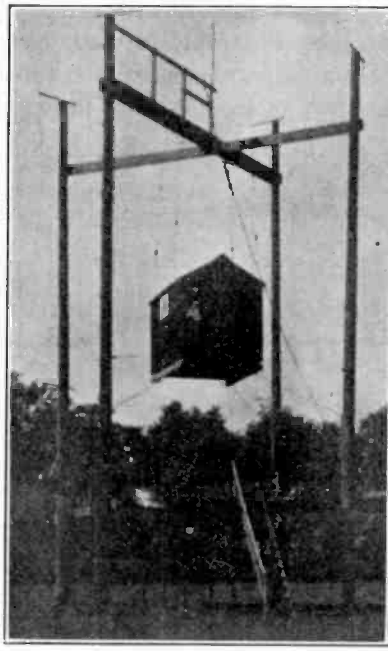

Fig. 18—View of Hut Suspended at the Center of an Adcock Aerial System. The hut contains the radiogoniometer and receiver used in taking bearings free from night errors.

6. Relative Advantages of Direction-Finding by Transmission and Reception for Navigation Purposes

(*a*) *Location of the Direction-Finder*

At the outset it must be admitted frankly that, owing to the more advanced state of its development at the present time, the wireless direction-finder when used in a fixed position on land gives a somewhat superior accuracy to the rotating beacon; for it is not easy to obtain bearings on the rotating beacon to a greater accuracy than two degrees, whereas a good land direction-finding station should give bearings reliable to one degree. This, however, is not the whole story and reference must be made to the conclusions of a controversy of long standing on the matters of the location of the direction-finder, whether on ship or shore, and of the individual upon whom it is most desirable to place the responsibility of observing the bearings. Without giving the full details of this controversy it may be stated that it is very desirable for the navigator to take the wireless bearings personally or have these observations made by somebody under his direct control and supervision. Since the navigator is responsible for the safety of his ship it is unreasonable to expect

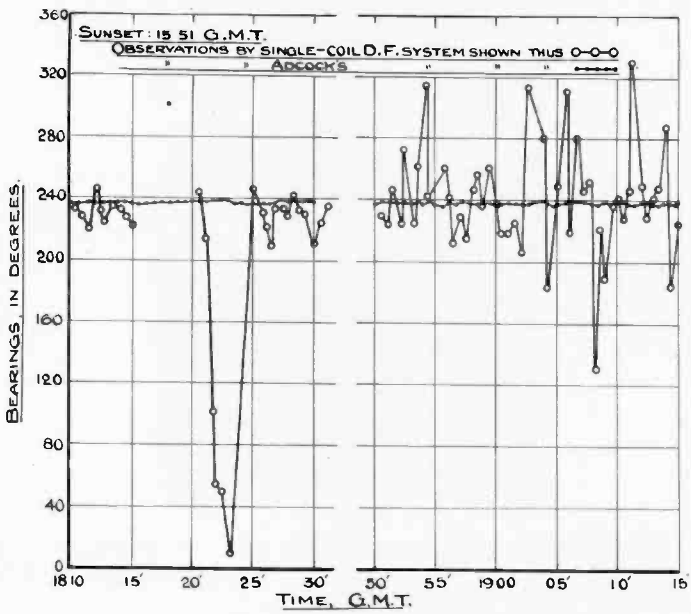

Fig. 19—Observations of Bearings on Bournemouth, December 10, 1925 ($\lambda = 386$ m)

him to rely, particularly in emergencies, upon observations made at a shore direction-finding station by a man quite unknown to him, and of whose skill and reliability he is quite unable to judge. In addition there is the possibility of error in signalling the bearings from shore to the ship, the interference to other wireless traffic in doing so, and the point of some strategic importance that the information as to the ship's bearings or position is broadcast to all wireless stations in the vicinity. It will be evident, therefore, that the most desirable position for the wireless direction-finder is on the ship itself, and this view is confirmed by the fact that during the past few years an increasing number of ships have been fitted with direction-finders whereas the number of shore direction-finding stations has never been large and is decreasing. The true comparison to be made, therefore, is between the rotating beacon transmitter set up on shore and the direction-finder installed on board ship. In the following paragraphs the discussion of this comparison is classified according to the superiority which one system appears to have over the other.

(*b*) *Superiority of the Ship Direction-Finder over the Rotating Beacon*

It was considered at one time that with the installation of the direction-finder on board ship the necessity for special transmissions for wireless bearing purposes would be eliminated. This, however, has been found not to be the case and it is now the practice to erect fixed transmitting stations or beacons[75] for the sole purpose of providing special transmissions for the use of ship direction-finding sets. These beacons are usually located near lighthouses or on light-vessels at points of importance for navigation. The use of the direction-finder is not limited to such beacons, for bearings may be taken upon the transmissions from any land station the position of which is accurately known. It has been found, for example, that some broadcasting stations form very useful fixed beacons operating for many hours of the day when it is desired to take wireless bearings on a ship at sea. The navigator with a direction-finder under his control thus has the opportunity of taking a series of cross-check bearings and so of improving the accuracy of determination of his position.

A further advantage of the ship fitted with the direction-finding set is that the opportunity is provided for observing bearings upon the transmissions from other ships. This may be useful when contact is made with a ship which knows its own position, but it is of greater importance when applied to the location of ships in distress, as has already been demonstrated in several practical cases. Moreover, there is the possibility that the future development of the ship direction-finder will provide a means for reducing or avoiding collisions between ships in foggy weather.

These advantages are not possessed by the rotating beacon system which provides the ships with the opportunities of obtaining bearings only during the operation of such beacons, and in those areas of the world in which these beacons are installed. The navigator with a direction-finding set under his immediate control would probably use it very frequently and would thus soon become aware of the occurrence of any fault or error. With the rotating beacon system he would be dependent upon information from the shore station staff as to any such errors; but against this it may be urged that such a staff would be more expert at dealing with and removing the error than would the average navigator or wireless operator.

(c) *Superiority of the Rotating Beacon over the Ship Direction-Finder*

By way of countering the remarks made in the above section it may be said that the rotating beacon transmitter retains all the advantages which were sacrificed when the direction-finding installation was moved from the shore to the ship. These advantages comprise the fact that the directional part of the system is fixed in position on solid ground and that it can, therefore, be accurately oriented and calibrated at installation, and also that it can be under the continuous supervision of experts. One directional shore station will provide service to an almost unlimited number of ships, whereas each ship direction-finder must be carefully installed and operated by experienced men.

One of the great advantages of the rotating beacon system is that no apparatus beyond a simple wireless receiver and a chronograph is necessary on the ship itself; a direction-finding service is thus provided for ships of all classes from the largest to the smallest. In the case of many small ships it would not be practicable to install a direction-finder with any pretense to accuracy; and to the large ship already fitted with a direction-finding set a rotating beacon would be an additional asset in enabling further bearings to be taken either for check purposes or for position determination. Furthermore, the method of observing bearings is so simple that they can easily be determined by the navigator himself in any portion of the ship without necessarily requiring the assistance of a wireless operator.

It has already been hinted that the accuracy of bearing observation by direction-finder on a ship at sea is less than that obtainable with a similar installation on land. The difference is, in fact, sufficient to make the optimum accuracy of the ship direction-finder comparable with that of the rotating beacon system. The direction-finding bearing is taken relative to the direction of the ship's head, and its accuracy depends upon the steadiness of the ship and also upon the accuracy with which the direction of the ship's head is given by the compass reading at any desired instant. In anything but a calm sea it is difficult to keep the head of a small ship steady to within one or two degrees, and in a rough sea the swing may amount to five degrees or more. Also there is probably a lag between the actual direction of the ship's head and the reading of the compass, whereas no such lag exists on the direction-finder. The bearing obtained from the rotating beacon is entirely free from these limitations and its accuracy is practically the same whether the ship is at sea or in dock. Also since the accuracy of observed bearing has been shown to be largely immune from conditions local to the receiver, no correction or compensation is necessary corresponding to the quadrantal error associated with the ship direction-finder. This error is likely to be serious in the case of many small ships, and there is the added possibility of its alteration with draught and nature of cargo.

The limitation of range of accurate bearings due to night effect has been shown, both theoretically and experimentally, to affect both systems of directional wireless to the same degree. The accuracy of the rotating beacon has also been found to be sensibly the same for both continuous wave and interrupted continuous wave transmission. Considering the possibility of interference of the rotating beacon transmitters with other wireless services, a similar objection may be raised to the fixed beacon transmitter which has been found to be so necessary in conjunction with the ship direction-finder. In neither case, however, is any serious interference likely to be caused since definite and distinct wavelengths have now been allocated to both types of beacon.

A small point just worthy of mention in concluding this section is that rotating beacons erected on the coast would be of some considerable service to aircraft navigators, particularly those making daily flights along the principal air routes.

(d) Conclusions

It will be gathered from the above discussion that the rotating beacon system is considered to have some advantages over the ship's direction-finder in the application of directional wireless to marine navigation. These advantages are, however, probably not sufficiently well defined at present as to make the future policy of those concerned with these matters independent of certain other factors; and in any case it is evident that the economics of the situation must be considered as well as the technical features. The rotating beacon system would at first appear to be an economy in that the whole cost of the directional apparatus is removed to the authority controlling the shore stations; and it is to be presumed that the cost of installing and maintaining the rotating beacons would be met by the levy of a tax upon all ships using the beacons. This might be a great advantage to the shipowners who, judging from their tardiness in equipping their ships with direction-finders, do not appear to find this apparatus very cheap. To the cost of such direction-finders, moreover, is to be added that of the fixed beacons specially built for their use. This cost depends upon local conditions and whether or not the beacon can be installed at an existing lighthouse and maintained by the personnel of the lighthouse. The first rotating beacon for practical working to ships has yet to be built so that details of the cost are at present unknown.

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SOME EXPERIMENTS IN SHORT DISTANCE SHORT-WAVE RADIO TRANSMISSION*

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Summary—*Some experiments in short-wave radio transmission over a distance of 55 miles are described, the results of which are interpreted to indicate the presence of strong "sky" waves, with "ground" waves of negligible amplitude in comparison with the "sky" waves as received. Upon decreasing the transmitter wavelength, at a given time of day, a minimum wavelength was reached below which no communication could be obtained; this wavelength is termed the "cut-off" wavelength. The average value of the cut-off wavelength, for various times of day, is given for several different months. The minimum observed wavelength upon which communication was possible was 28 meters,*

A series of experiments in which an orientable half-wavelength antenna was employed served to indicate definitely an optimum position of the antenna for transmission over the 55-mile distance. The indicated transmission path left the transmitter at an angle of approximately 65 degrees to the horizontal. In long distance communication the position of the antenna was found to have no appreciable effect.

THE work herein described was carried out over a period of two years, over a fixed distance of approximately 55 miles between Round Hill, South Dartmouth, Mass. and Auburndale, Mass. on wavelengths ranging from 25 to 80 meters. In view of the results obtained which are explainable in a rather straight-forward manner on the basis of refraction of the radio waves in the upper atmosphere, the presence of such a refracting medium will be assumed as an hypothesis. It was early found in the course of the experiments that at times no communication could be obtained on the wavelengths, and at the time of day, when under normal conditions very strong signals would be received. This phenomenon is believed to be due to conditions of the refracting layer such that it was impossible for refracted waves to return to the surface of the earth within the fixed distance of 55 miles. The noticeable absence of signals during these periods indicated that the "ground" signals, due to waves

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following the surface of the earth, did not play any appreciable part in contributing to the usual received signal.

A very complete theoretical study of the transmissions paths of short waves, through an electron atmosphere, has been made by Baker and Rice.[1] Their conclusions are here utilized in brief form, in the summary of the following paragraphs. For further interesting and valuable discussions of the problem the reader is referred to the books and papers below.[2]

Fig. 1 is a sketch showing the paths of the various rays radiated by an ideal transmitter having a characteristic as sketched

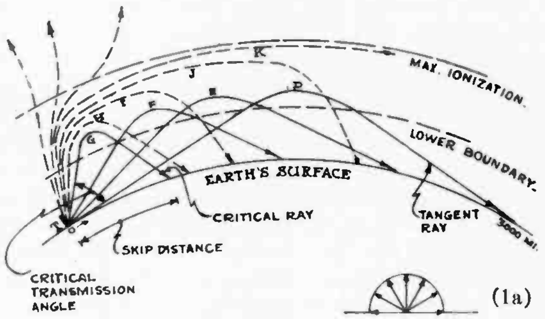

Fig. 1—Sketch Showing the Paths of the Various Rays Radiated by an Ideal Transmitter Having a Characteristic as Sketched in Fig. 1a, as Given by Baker and Rice.

in Fig. 1a, as given by Baker and Rice. The tangent ray, *TD*, has the greatest range of all the rays radiated close to the horizontal. The critical ray, *TG*, traverses the minimum distance along the surface of the earth. Rays leaving the transmitter near the vertical may return to the surface of the earth at great distances from the transmitter, as *TJ*, *TK*. Rays which penetrate to the region of maximum ionization are given curvatures

[1] W. G. Baker and C. W. Rice, "Refraction of Short Waves in the Upper Atmosphere," *Jour.*, A.I.E.E., 45, p. 535–539, June, 1926; also reprints, of a more detailed nature, of paper presented to A.I.E.E. in February, 1926.

[2] A. H. Taylor, "Relations between Height of Kennelly-Heaviside Layer and High Frequency Radio Transmission Phenomena," Proc. I. R. E., 14, 521–540; August, 1926. A. H. Taylor and E. O. Hulburt, "The Propagation of Radio Waves over the Earth," *Phys. Rev.*, 27, February, 1926. Also *QST*, October, 1925. H. W. Nichols and J. C. Schelleng, "Propagation of Electric Waves over the Earth," *Bell Sys. Tech. Jour.*, VI–2, 215–235, April, 1925. P. O. Pederson, "The Propagation of Radio Waves," published by "Danmarks Naturvidenskabelige Samfund," 1927, and sold by G. E. C. Gad, Vimmelskaftet 32, Copenhagen, K. Denmark. (In English.)

departing only slightly from that of the layer itself; the rays may consequently pass around the earth before returning to the surface or may be bent out into space. Rays emitted at angles very near to the vertical pass through the layer and out into space with relatively small changes in direction.

In Fig. 1 an ideal transmitter is assumed at T, i.e., a system which radiates equally well in all directions above the surface of the earth— as sketched in Fig. 1A. Considering now the range of rays emitted at various angles above the horizontal, we find that the tangent ray TD, if unaffected by surface conditions, will return to the surface of the earth at a distance, in round numbers, of 3,000 miles from the transmitter T. This distance is only slightly dependent upon the wavelength and the conditions of the refracting layer, because of the relatively small portion of the path which is traversed within the refracting layer. For increasing angles of transmission, the range is decreased, very rapidly at first and then more and more slowly until the minimum range is reached (TG), at which point the change of range as a function of transmission angle is zero. The path for the minimum range is very critically influenced by the conditions of the refracting layer (height, thickness, value of maximum ionization density and the distribution of ionization), because of the greater penetration and the greater curvature given the ray, and consequently the path varies rapidly with the wavelength. If higher angles of transmission are considered, the range increases as the angle is increased, slowly at first and then more and more rapidly. At the higher angles, the rays might travel around the earth before being given a sufficient curvature to return them to the earth's surface. For angles near the vertical, the rays are bent but little, and pass through the layer and out into space.

The particular point of interest in the summary above is that, with fixed layer conditions, there exists a minimum range for the refracted rays, associated with a definite transmission angle. This minimum range is many times confused with the "skip-distance," i.e., that range over which no signals at all are received. When quite short waves are used, so that the minimum range is of the order of several hundred miles, this confusion is not serious, because of the usually limited range of the ground wave. For short distance operation, however, the ground wave intensity becomes very important in determining the actual skip-distance. The observed skip-distance, in these cases, depends not only on the minimum range of the refracted waves (which defines the outer skip-distance boundary) but also on the maximum range of the ground waves (which defines the inner skip-distance boundary). Any factors tending to decrease the first, or to increase the second, will result in a decreased skip-distance. If the ground waves reach the minimum refracted wave range with an appreciable intensity, then no skip-distance is encountered, as, for example, in short-wave transmission from aircraft. If the surface waves are highly attenuated near the transmitter, then the only recourse for short distance short-wave communication is to utilize relatively high angle rays.

For certain layer conditions, short distance communication will not be possible unless the power of the transmitter is increased to a point where the attenuation of the ground waves is overcome by sheer force to provide a signal of practical intensity. In these experiments the power output of the transmitter was purposely restricted to 50 watts, or less, in order that good reception would be attained only when favorable transmission conditions existed, making the delineation between favorable and unfavorable conditions as marked as possible. In practice there is little difficulty in identifying the "ground" wave and "sky" wave signals as received. The former entirely lack the general characteristics of short-wave transmission, i.e., violent and rapid changes in amplitude (even when the transmitter is carefully controlled as regards frequency and amplitude of the antenna current); the ground wave signals are remarkably steady, reminding one of very long wave signals.

For long range communication, 5,000 miles or more, it is seen from the considerations above that two classes of transmission path are possible. The first employs the rays radiated close to the horizontal at the transmitter, which are effective to distances of approximately 3,000 miles. To cover ranges greater than this it is necessary to invoke the aid of multiple reflections from the earth's surface. The idea is theoretically tenable, but has no great appeal from a practical viewpoint owing to the high absorption encountered by the waves at surface grazing regions, and the scattering effect of surface irregularities. The second class of path is provided by any rays which cover a range greater than 3,000 miles, invoking no multiple reflections. These paths are the high angle paths, indicated by the dashed curves of Fig. 1. The loss of energy due to dispersion of these paths over the earth's surface may in a large measure be overcome by the low attenuation, resulting in signal amplitudes of practical interest.

The experiments of Meissner[3] with a "searchlight" beam transmitter definitely indicate the usefulness of comparatively high angle radiation in effecting communication between Germany and Argentina on a wavelength of 11 meters. Two transmission angles for maximum received signal strength were found within the range of the observations, one at approximately 80 degrees and the other at approximately 37 degrees with the horizontal. It is regrettable that the physical limitations of the reflectors did not permit of swinging the beam to the horizontal, instead of a minimum of 30 degrees. Transmission at high angles

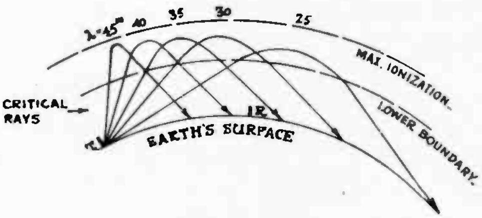

Fig. 2—Paths of the Critical Rays (*TG* of Fig. 1) for Various Wavelengths, Based on the Work of Baker and Rice.

over great distances is further substantiated by the general experiences of amateurs, using low power, and, in the majority of cases, essentially horizontal antennas at such heights above earth that a strong component of radiation is sent out at high angles.

Returning to the specific problem of short-distance communication, where the distance to be covered was sometimes less and sometimes more than the minimum refracted ray range, observations were made to determine the minimum wavelength which would provide reliable reception at various times of day and in various seasons. With given conditions of the refracting layer, the minimum range of transmission will increase as the wavelength is decreased, somewhat as sketched in Fig. 2. For a given distance between transmitter and receiver, *T–R*, a wavelength of 40 meters would produce strong signals, while a wavelength of 35 meters would fail entirely. For some wavelength,

[3] A. Meissner, "Directive Radiation with Horizontal Antennas," Proc. I. R. E., 15, 930–934; November, 1927.

here about 38 meters, the path of the minimum range ray would strike the earth in the immediate vicinity of the receiver. Any slight irregularities of the layer conditions would then cause the foot of the path to sweep back and forth across the receiving point, producing violent "fading" or "fluttering." Such was found to be the case in these tests, the signals swinging from relatively large amplitudes to zero. Under more stable conditions of the layer, the fluttering was not pronounced, and, under such conditions, the wavelength at which communication just failed or was "cut off," could be determined within about one per cent.

Fig. 2 shows the paths of the critical rays (*TG* of Fig. 1) for various wavelengths, based on the work of Baker and Rice. For each wavelength the distance from the transmitter *T* to the point at which the ray returns to the earth's surface is approximately the "skip-distance." For the conditions of the diagram, wave-

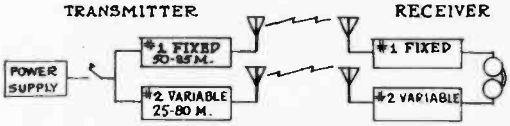

Fig. 3—Arrangement of Duplex Transmitter-Receiver Equipment Used in Making the Observations Described.

lengths longer than about 38 meters will be received at *R*, but wavelengths shorter than this value will not be received.

The equipment was arranged as in Fig. 3. Channel No. 1 was arranged as a communication channel, or "order wire," to be operative on wavelengths which had been found to give reliable communication at the time of day at which the experiments were being conducted. Channel No. 2 was arranged with a special transmitter designed for rapid manual change of wavelength. The transmitters were keyed simultaneously on the same power supply. The receivers were of similar design, consisting of an autodyne detector followed by two stages of audio-frequency amplification. Each receiver connected to one telephone receiver of a "split" headset.[4] If equal signal intensities were obtained on both wavelengths, and if the operator adjusted the autodynes to produce the same beat tone, the signal heard in the headset was remarkably similar to that obtained with a single receiver, except that the signal appeared to change from one ear to the

[4] J. K. Clapp, "Multiplex Short Wave Reception," *QST*, March, 1926.

other, as the fading periods on the two wavelengths were not the same. No definite relationship between the fading periods on any two wavelengths was observed, even when the difference in wavelength was small.[5] Ordinarily the fading period, on the wavelengths covered in this investigation, is so short that the effect is that of an irregular amplitude modulation of the signal

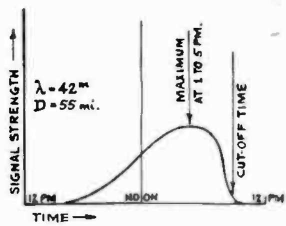

Fig. 4—Illustrating Average Variation in Received Signal Strength, for Short Distance Communication, as a Function of the Time of Day.

as received, made evident to the ear by a roughening of the beat tone without much variation of the average beat tone intensity.

By changing the wavelength of transmitter No. 2 in successive steps, a general idea of the "cut-off" wavelength at a given time of day and under given conditions of the refracting layer could readily be obtained. The received signal was found to vary with

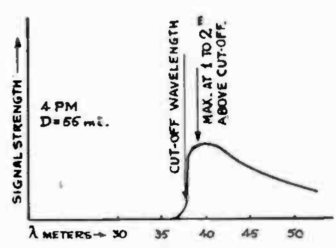

Fig. 5—Illustrating the Variation in Received Signal Strength, for Short Distance Communication, at a Given Time of Day, as a Function of the Wavelength of the Transmitter.

the wavelength as sketched in Fig. 5. When the signal had been reduced to a point where it could just be identified, though far too weak for communication, communication was considered as being "cut-off." Reception varied with the time of day, on a

[5] R. Brown, De L. K. Martin, and R. K. Potter, "Some Studies in Radio Broadcast Transmission," Proc. I. R. E., 14, 57–131; February, 1926.

fixed wavelength, as sketched in Fig. 4. The values shown in Figs. 4 and 5 are for summer conditions. A decided drop in signal strength accompanied any marked increase in wavelength above the cut-off value. It was soon found, in making observations, that the value of the cut-off wavelength was subject to large and rapid fluctuations.[6] As interest was here centered on *average* values, no attempt was made to develop means for making more rapid determinations. The oscillographic method described by Heising could well be adapted to this study, as well as the method of "wobbling" the transmitter frequency.[7]

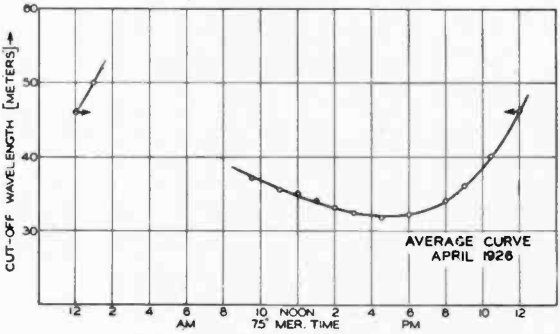

Fig. 6

The results obtained, over the fixed distance of 55 miles, are set forth in Figs. 6 to 11 inclusive. The early summer and midsummer records show a rather flat curve, while the late fall records show a more or less regular steep curve. The cut-off wavelengths are plotted against the time of observation, all times being given in Eastern Standard Time. Signals on wavelengths lying just below the curve were not received, while, in general, good reception was obtained on wavelengths lying just above the curve; that is, on wavelengths just above the cut-off wavelength. Observations were made on three dates in April, 1926, between the hours of 9 A.M. and 1 A.M. of the succeeding day. The curve of Fig. 6 shows the minimum wavelength on which communication was possible in this period to have been 32 meters, occurring at about 5 P.M.

[6] R. A. Heising, "Experiments and Observations Concerning the Ionized Regions of the Atmosphere," Proc. I. R. E., 16, 75–99; January, 1928.

[7] R. A. Heising, J. C. Schelleng, and G. C. Southworth, "Some Measurements of Short Wave Transmission," Proc. I. R. E., 14, 613; October, 1926.

Fig. 7 indicates the results of tests during May, 1926, in which efforts were made to obtain data throughout the twenty-four hours. From 9 A.M. to 1 A.M. definite results were obtained, but from 1 A.M. until 9 A.M., particularly between 5 A.M. and 9 A.M.,

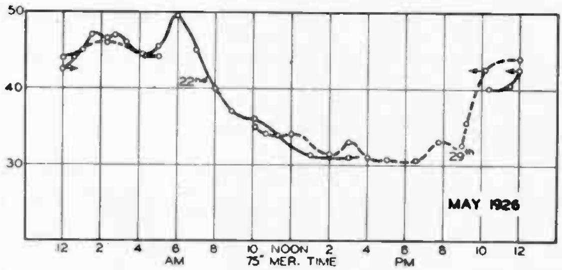

Fig. 7

the results were quite frequently indefinite. In every case the value of the cut-off wavelength rose abruptly just before sunrise, reaching a maximum shortly after sunrise and then gradually diminishing throughout the morning. The minimum wavelength on which satisfactory communication could be obtained during this period was 31 meters, attained at approximately 5 P.M.

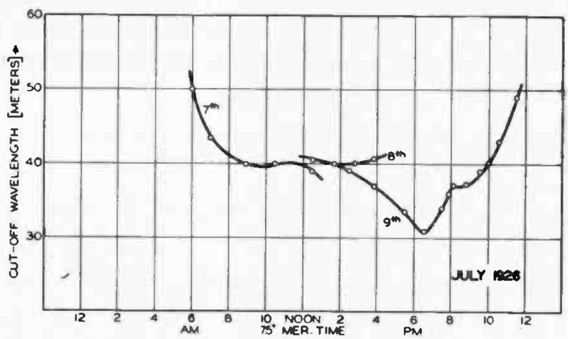

Fig. 8

Fig. 8 shows the results of a three-day test in July, 1926. During this period the signals obtained after midnight did not show any evidence of being due to refracted waves, but appeared to be due solely to the ground wave, as in this interval the signals were characterized by extreme constancy of amplitude. In the interval from 6 A.M. to midnight the results were quite definite, as shown by the curve. The minimum wavelength for communication in this interval was about 32 meters.

At the end of July, 1926, a four-day test was made, after improvements in the methods of handling the tests had made possible more rapid determinations. The four curves of Fig. 9 show the great fluctuations in the value of cut-off wavelength which were encountered in relatively short intervals of time. The

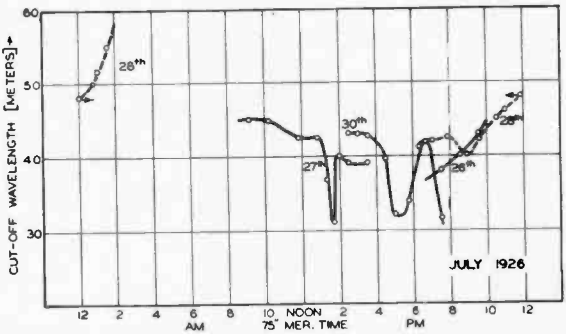

Fig. 9

average cut-off wavelength during these tests was higher than that obtained earlier in the month, but at times wavelengths very near to 30 meters were observed. The erratic nature of these curves is typical of the observations by the more rapid method, but it is surprising what a regular curve is obtained on averaging a large number of such observations.

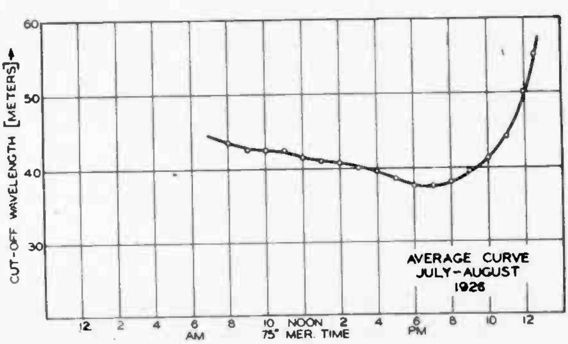

Fig. 10

All of the data for the tests of July and August, 1926, were averaged and the curve of Fig. 10 shows the result. The minimum wavelength of the average curve is 37.5 meters, where under temporary and more favorable conditions wavelengths as short as 31 meters were observed. The results of this averaging are so striking as to suggest strongly that the *average* conditions of the refracting layer undergo a regular variation. From time to time, "bumps" or "hollows," or regions of greater or less density of ionization, drift across the path of transmission, causing the transient irregularities which were observed.

Fig. 11 shows the average of the observations for October, 1926, the minimum wavelength observed being 29 meters at approximately 1 P.M. The curve as a whole has steepened materially, indicating that the number of hours of the day during which satisfactory communication could be obtained was decidedly less than in the preceding months. It would be expected

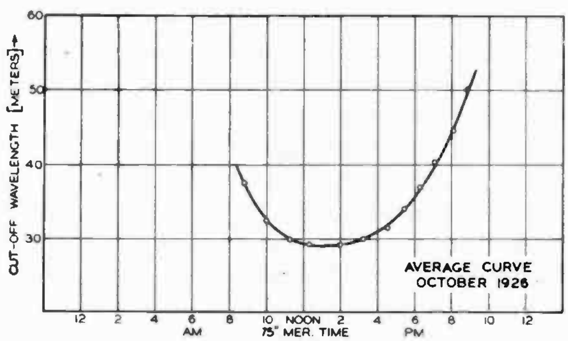

Fig. 11

that the minimum value of cut-off wavelength would increase as winter came on, owing to the reduced density of ionization, or to an increased average height of the refracting layer. The reduction in cut-off wavelength here encountered may be associated with the heavily overcast weather which was encountered during the period of the observations.

In this connection it was repeatedly observed that when large, well-defined clouds drifted across the path of transmission the received signals underwent a definite change in intensity. When the clouds were sufficiently well separated so that distinct observations could be made, it was found that the signal intensity rose when the cloud was in the line of transmission. On days which were heavily overcast, with or without fog at Round Hill (the station there being located within twenty yards of the shore of Buzzard's Bay), the average signal intensity was materially greater than on clear days. When rain was falling over the territory including both transmitter and receiver, the signals fell below the clear weather average.[8]

At times when the cut-off wavelength changed very rapidly, as between 7 and 9:30 P.M. during October, 1926, it was impossible to change wavelength with sufficient rapidity by manual methods. Resort was then had to the use of two transmitters at each point, the wavelengths being "staggered." For example:

Round Hill		Auburndale	
No. 1	35 meters	No. 1	37 meters
No. 2	39 meters	No. 2	41 meters

As the cut-off wavelength rose toward 35 meters, the signals from Round Hill would begin to flutter and then die out. Auburndale then communicated with Round Hill on 37 meters, until the cut-off wavelength rose to that value. Round Hill, on the extinction of their 35-meter signals, would transmit on 39 meters, thereby maintaining communication. If time permitted, Round Hill would increase the wavelength of transmitter No. 1 to some value higher than 41 meters, thus extending the range of the observations. By this means it was possible to obtain the times at which each of the four, or more, wavelengths were cut off. In many instances it was found that the cut-off wavelength rose 10 to 20 meters above its initial value in a period of ten or fifteen minutes. In the early evening the cut-off wavelength often reached the vicinity of 55 meters (above which no sharply defined cut-off effects were observed) from a value of 38 to 42 meters within fifteen minutes. Communication then usually failed entirely, except for faint signals on wavelengths of 80 meters or more, until the following forenoon. When communication failed abruptly in this manner, no instance was observed in which communication could be re-established on the same wavelength during the same evening. It appeared as though the characteristics of the refracting layer altered abruptly and did not return to the average normal until the changes of the ensuing day had taken place.

The above discussion of short distance transmission, including the interpretation on the basis on high angle refracted waves, is based on the theoretical premise of the work of Baker and Rice. In order to obtain an experimental verification of this viewpoint,

[8] "The Effect of Water Vapor in the Atmosphere on the Propagation of Electro-magnetic Waves," *Jahrb. d. Draht. Tel.*, **12**, 184; August, 1927. Also **19**, 58–72; January, 1922.

a series of tests was conducted with an orientable transmitting antenna system.[9] The antenna proper consisted of fifty feet of copper tubing mounted on a light wooden lattice frame, carrying the transmitter at the midpoint. The center of the frame was supported on a universal joint at the top of a fifty-foot telegraph pole, set "in the clear" on the beach at Round Hill. Thus it was possible to place the antenna in any desired direction in space, the center of the antenna system being fifty feet above the surface of the earth.

The first series of tests was made to determine the best position of the antenna for transmission from Round Hill to Auburndale, using a wavelength of 42 meters. Definite results were very difficult to obtain because of fast fading; by graphically recording the received signals for a period of three minutes for each chosen position of the antenna, taking the average value of the record by planimeter, and taking a large number of observations, some indication of the average received signal intensity was obtained. An optimum position of the antenna was clearly indicated. The antenna was contained in a vertical plane passing through the transmitter and receiver, with the end of the antenna nearest to the receiver depressed some 25 deg. below the horizontal, as indicated in Fig. 12. Application of antenna theory to this configuration indicates that the antenna radiates with greatest intensity at an angle of about 65 deg. above the horizontal, in the direction of the receiver, and that the image of the antenna does not contribute materially to this radiation. The optimum position of the antenna indicates that the effective transmission path left the transmitter at an angle of 65 deg. to the horizontal, bearing out the idea of high angle transmission.

Consideration of the antenna and its image would lead one to expect fairly good transmission if the antenna were horizontal and at right angles to the line between stations; this was found to be true. If the antenna were placed in the line of the transmission path, then the only received signal would be due to the image, which would of course depend largely upon the character of the earth. With highly comducting earth, good signals should be obtained, while with highly absorbing earth the signals would be weak. In a few observations moderately good signals were obtained; in a very large number the signals were quite weak and

[9] G. W. Pickard, "The Polarization of Radio Waves," PROC. I. R. E., 14, 205–212; April, 1926, and references given therein.

in three instances no signals at all could be obtained. The experimental evidence is far from complete, but it indicates a condition of very imperfect reflection from the earth in the vicinity of the transmitter. The results of tests in which the angle of inclination of the antenna was varied, while the antenna remained in the plane containing the transmitter and receiver, are given in Fig. 12.

The theoretical radiation characteristics of antennas in "principal" positions, i.e., horizontal or vertical, over perfectly

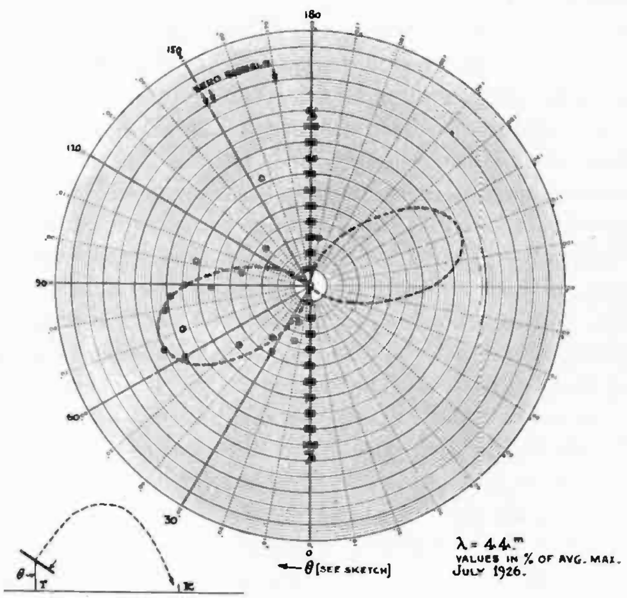

Fig. 12

conducting earth, have been considered by various investigators.[10] The problem of the antenna over an imperfect earth has been attacked also.[11] The problem of an inclined antenna offers many difficulties, even if perfect earth conditions are assumed. In this

[10] G. W. Pierce, "Electric Waves and Oscillations." S. Ballantine, "On the Radiation Resistance of a Simple Vertical Antenna at Wavelengths below the Fundamental," Proc. I. R. E., 12, 823; December, 1924. S. Ballantine, "On the Optimum Transmitting Wavelength for a Vertical Antenna over Perfect Earth," Proc. I. R. E., 12, 833; December, 1924. S. A. Levin and C. J. Young, "Field Distribution and Radiation Resistance of a Straight Vertical Unloaded Antenna Operating at One of its Harmonics," Proc. I. R. E., 14, 675; October, 1926.

[11] L. Bouthillon, "Influence de la nature du sol sur l'emission et la reception radio-electriques," *L'Onde Electrique*, 6, No. 71; November, 1927.

case the earth surface was composed of fine sand, which was highly piezo-electric,[12] showing strong resonances at frequencies from as high as 15,000 kc to less than 3,000 kc, that is, over a range of frequency considerably greater than that employed in the experimental work. One is then confronted with the vexatious though interesting problem of trying to account for the effect of the dancing sands under the atenna in attempting to calculate the radiation characteristics.

When using this antenna system in long range communication, it was found that the position of the antenna had no marked effect, though no careful measurements could be carried out. Apparently the random polarization of the waves at the receiver, due to the characteristics of the medium of propagation, completely wiped out all effects due to the position of the antenna itself.[13] These longer range tests were carried out mainly with amateurs in England and Belgium.

In conclusion the author wishes to express his appreciation of the able assistance and active cooperation of Mr. Walter D. Siddall and Mr. Gordon G. Macintosh in carrying out the experiments.

[12] I am indebted to Dr. G. W. Pierce for the suggestion that the piezo-electric character of the sand might be an important influence.

[13] Baker and Rice, loc. cit.

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WIRELESS TELEGRAPHY AND MAGNETIC STORMS*

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Summary—*A recent theory of auroras and magnetic storms attributes these phenomena to the action of a flash of ultraviolet light from the sun. The flash causes an unusual ionization in the Kennelly-Heaviside layer. Therefore, it is only daylight wireless circuits which are, or may be, disturbed at the commencement of the magnetic storm, the night circuits remaining normal until dawn when they may be disturbed; the disturbance in the daytime circuits may persist after night-fall. This very simple theory is found to be borne out in a detailed discussion of the data of the short-wave (15 to 40 meters) circuits of the United States Navy during the magnetic storms of May 28, July 7, October 18, and October 24, 1928.*

IT is an accepted belief, based on a long accumulation of evidence, that terrestrial magnetic storms are caused by unusual bursts of radiation of some sort from a disturbed region of the sun. The assumption that the solar disturbance is a flash of ultraviolet light has been shown in a recent paper[1] to explain practically all the complicated magnetic effects observed during a magnetic storm. In a simple case the flash was assumed to blaze out at full intensity for some minutes and then to die away in a few hours or days; it might, of course, flare out again irregularly or intermittently. The flash was such as would come from a hot spot 1/10,000 of the solar disk in size and at a temperature of 30,000 degrees K; the radiation from the hot spot would be largely in the far ultraviolet region of wavelengths which ionize the atmospheric gases. Calculations showed that this radiation, barely perceptible at sea level because it is almost entirely absorbed in the upper reaches of the atmosphere, would heat up the atmosphere at levels above 50 km causing it to expand, and would increase the ionization in the high atmosphere very greatly. The effect of the flash was therefore to increase the ion and electron densities in the Kennelly-Heaviside layer and to raise the entire layer upward about 100 km. This agreed well enough with the measure-

* Dewey decimal classification: R113.5. Original manuscript received by the Institute, December 28, 1928. Published by the permission of the Navy Department, Washington, D.C.

[1] H. B. Maris and E. O. Hulburt, "A Theory of Auroras and Magnetic Storms," *Phys. Rev.*, March, 1929.

ments of Dahl and Gebhardt[2] who found an increase in the apparent height reached by 70-m waves in the daytime of about 70 km during the magnetic storm of August 19, 1927, and with the recent measurements of Hafstad and Tuve,[3] who observed an increase in the apparent daytime height of the layer of 100 km during the magnetic storms of October 7 and of October 18, 1928.

The atmosphere on the daylight side of the earth is influenced directly by the flash, that on the night side is not affected directly but indirectly, as the day side is turned by the rotation of the earth and carries with it into the shadow the influence it received while in the sunshine. Therefore, only daytime wireless communication may be disturbed during the commencement of the magnetic storm, the night communication remaining normal. If the flash continues, with perhaps lessening intensity, the night communication will, or may, experience disturbance at dawn. If the communication channel extends from night into day, or vice versa, the effects may be complicated. Since the flash heats the atmosphere and thereby raises the Kennelly-Heaviside layer in the sunlit areas, long-wave daylight transmission may be improved, or probably will not be weakened, during the magnetic storm, because the waves are propagated with fewer earth and layer reflections than normally. At night, however, due to the diffusion of the unusual amount of ionization into lower strata where the gas molecules are more dense, the absorption of the long waves is increased and the transmission falls below the normal nighttime values. These conclusions are in general accord with the facts brought out by Austen,[4] Espenschied, Anderson and Bailey,[5] Pickard,[6] Anderson,[7] and others for waves from 5000 to 20,000 m.

In general, long waves are not so sensitive as the short waves to movements and changes in the upper atmosphere, because of their length and their relatively less penetration into the ionized regions. Therefore, the very superficial description just given of the effects of the storm in the high atmosphere,

[2] O. Dahl and L. A. Gebhardt, Proc. I. R. E., **16**, 290; March, 1928.
[3] Hafstad and Tuve, *Terr. Mag. and Atmos. Elec.*, **34**, March, 1929.
[4] L. W. Austin, Proc. I. R. E., **15**, 825; October, 1927.
[5] L. Espenschied, C. N. Anderson, and A. Bailey, Proc. I. R. E., **14**, 7; January, 1926.
[6] G. W. Pickard, Proc. I. R. E., **15**, 749; September, 1927.
[7] C. N. Anderson, Proc. I. R. E., **16**, 297; March, 1928.

which has perhaps sufficed for a rough explanation of the behavior of the long waves during the storm, is hardly sufficient for the case of the short waves. A more careful examination is necessary, especially as data are now available in considerable detail of the short-wave storm characteristics. The conditions in the atmosphere arising from the solar ultraviolet flash are in the main complicated. If, as a result of the heavy ionization caused by the storm, the lower surface of the ionized layer is sharply defined, the short waves may be reflected without great penetration and their transmission will be good; but if the lower surface is not well marked, or if it is agitated, etc., the transmission may be greatly disturbed. And which of the conditions obtains in any particular case depends upon the rates of diffusion of the ions and electrons, the winds in the high atmosphere, the character of the solar flash, e.g., whether it is short and intense, or mild and long, or irregular, etc., etc. Actually the various possibilities are met with, as brought out in the detailed discussion of four magnetic storms given in the following paragraphs, there being cases in which the short-wave full daylight transmission was greatly disturbed at the commencement of the storm, and other cases in which it was disturbed to a less extent. But, it must be emphasized again, no case was encountered in which the full night-time communication was troubled perceptibly at the commencement of the storm. Since the atmosphere is heated and expanded at the beginning of the storm in those regions where the sun is more or less overhead, as from ten to four o'clock local solar time, winds in the high atmosphere will blow from the heated regions and produce turbulence and swirls of the ions and electrons on the borders of those regions. Short wireless waves passing into this turbulence will be scattered, or absorbed, or poorly reflected, as the case may be, and poor transmission will result. When night falls over the daylight areas, the turbulence may slowly diminish and the transmission may improve in the early morning hours, and then with the dawn may continue to improve or may fall off again, depending upon the activity of the flash. Thus, in part, the solar disturbance, which causes the magnetic storm, accentuates and widens the usual sunset and sunrise vagaries in the wireless transmission.

In Figs. 1, 2, 3, and 4 are given data for the four magnetic storms of May 28, July 7, October 18, and October 24, 1928.

respectively. The wireless information was obtained from the log books of the Radio Division of this Laboratory, and the magnetic data from the Coast and Geodetic Survey Observatory at Cheltenham, Maryland, U. S. A. The abscissas of the figures are the Eastern Standard times of the various days. The ordinates give the wireless communication as expressed qualitatively by the words "good", "poor", and "bad". "Good" means the normal signal intensity obtained with the usual day and night routine wavelength bands which were 14 to 25 and 25 to 40 meters, respectively; "poor" means signals below normal due to fading and low intensity, and "bad" means signals very much below normal, or absent altogether. Curves 1 of the figures refer to the short-wave communication from Washington, D. C., U.S.A., to Europe, along the Atlantic sea-board and to South America. Curves 2 refer to the Washington-San Francisco short-wave circuit.

Curves 3 of the figures give the variations in H, the horizontal component of the magnetic field of the earth; these curves are free-hand sketches from the magnetograph records of the Cheltenham Observatory. On a quiet day the H curves are smooth with diurnal undulations of a regular type. A ragged H curve with a sharp initial rise, a fairly rapid decrease to negative values and a slow period of recovery, is the characteristic type of storm curve. These characteristics are world-wide, being the same, apart from local variations peculiar to the station, for all the magnetic stations of the earth; the storm commences simultaneously, within a minute at all the stations. According to the theory of auroras and magnetic storms[1] the initial rise and fall to zero of the H curve is due to a pulse of current flowing from west to east around the earth in the conducting region of the atmosphere. The pulse of current is caused by the increased ionization in the Kennelly-Heaviside layer when the ultraviolet flash flares up to full intensity. The decrease of H to negative values is attributed to the induced currents in the earth, and the slow recovery of H to the dying away of the currents as well as to the fading out of the flash. Irregularities which occur during the recovery period probably indicate recurrences of the flash, although the induced current reactions may also play a part.

The four storms illustrate four quite different types of conditions; the effects on wireless communication, however, were in each case in general accord with the theoretical views which have been outlined. On May 27 the magnetic disturbance began gently at about 10 A.M., as shown in Fig. 1, increased to a moderate intensity on May 28 and died away the next day.

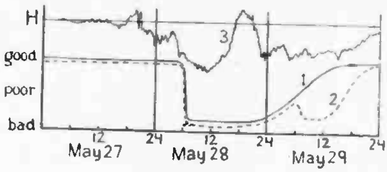

Fig. 1

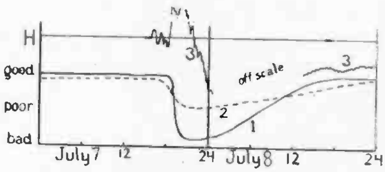

Fig. 2

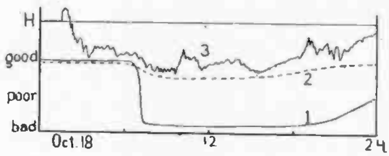

Fig. 3

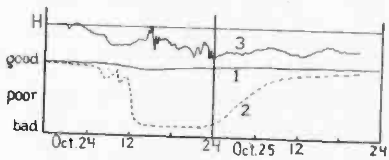

Fig. 4

In the above figures the abscissas are Eastern Standard Time. Curve 1 gives the short-wave communication on the Washington circuits to Europe and South America and along the Atlantic seaboard; curve 2 refers to the Washington-San Francisco circuit. "Good" means the normal signal strength. Curve 3 gives H, the variations in the horizontal component of the earth's magnetic field, as sketched from the magnetograph records of the Cheltenham Observatory, Maryland, U.S.A.

Wireless showed no evidences of trouble on the 27th, but at about 6 A.M. of the 28th the wireless channels both to the east and the west became inoperative. During the day of May 28 wireless was poor, and then began to recover in the night. The recovery on the Atlantic circuits continued through the dawn of May 29 and was complete by noon. The San Francisco communication, however, became poor again at sunrise of May 29 and did not return to normal until that night. Just why the San Francisco circuit experienced more trouble on May 29 than the Atlantic circuits is not clear. Perhaps local winds in high atmosphere, irregularities in the ionization, or many other factors neglected in the present simple theory were the cause. It should also be mentioned that the wireless data indicated in a number of cases a non-reciprocity of signalling, that is, signals were received at one station from a second, but the second station did not receive the signals from the first. However, the data were not sufficiently complete, nor is the theory sufficiently detailed, to permit the discussion of these complexities. They will require further investigation.

On July 7 at 4:30 P.M. a short severe magnetic storm set in and continued until about noon on July 8, as shown in Fig. 2. Communication from Washington both east and west dropped sharply to low values at about 7 P.M., and recovered slowly during the night and the following day. The Pacific circuits Honolulu to Cavite, which lay nearly directly under the influence of the storm flash, apparently were not disturbed on July 7 (actually July 8 at Cavite, which is on the other side of the international date line), but at 8 A.M., Honolulu local solar time, of July 8 short-wave communication faded to low values for ten hours.

The storm of October 18, Fig. 3, began at 2:27 A.M., with a fairly pronounced magnetic disturbance; the Washington circuits to the east and west showed no indications until the dawn. During the daylight hours of the 18th the Atlantic communication was poor or zero; the San Francisco circuit, although somewhat troubled, remained in operation.

A storm of moderate intensity, Fig. 4, began slowly in the morning hours of October 24 with a small increase at about 2 P.M. The Washington-San Francisco circuit had periods of low signal strength from 9 A.M. to 12, and in the afternoon communication became poor. The Atlantic circuits were little disturbed. Meanwhile the Pacific circuits, which were in the dark when the storm began on the 24th, experienced low signal strength and fading during the daylight hours of this period.

In addition to the facts which have been mentioned, the wireless log books indicated clearly that fading and poor signal strength were the general rule on days of magnetic character 1 or greater; 1 means moderate, 2 strong magnetic disturbance, etc. In 1927, a year of maximum disturbance, there were 83 days of character 1 or greater; wireless therefore might have encountered difficulties due to solar activity on more than one fifth of the days of the year. Three or four years from now the solar activity will be at the minimum of its eleven-year cycle and one may expect a less number, perhaps only 10 or 20, of magnetically disturbed days during the year. The magnetic observations may properly be regarded as the weather stations for the wireless traffic and the magnetic storm charts as the wireless weather maps.

In conclusion it is a pleasure to express our thanks to the Coast and Geodetic survey for their courtesy in giving us promptly and fully the magnetic data of their observations.

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RECENT DEVELOPMENTS IN SUPERHETERODYNE RECEIVERS*

By

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Summary—*Major electrical elements of a modern superheterodyne receiver-tuned radio-frequency amplifier, intermediate frequency amplifier detector and audio-frequency amplifier—are briefly discussed in light of recent developments. A practical automatic volume control is described. Curves illustrating the major performance characteristics of the receiver are shown.*

Introduction

IN the past four years broadcasting conditions have changed so greatly that receivers which were giving satisfactory service at the beginning of that period are now obsolete. The steady increase in the number of broadcasting stations and the advent of the super-power stations have imposed exacting selectivity requirements on modern receiving sets. The congested condition of our cities with their numerous apartment buildings and the resultant lack of antenna facilities have likewise created the demand for receivers having sufficient sensitivity to permit the use of either a small indoor or outdoor antenna. The marked improvement in the quality of radio programs and their transmission and the development of the moving coil type of loudspeaker have made the fidelity of present day receivers a consideration of major importance. The superheterodyne receiver is particularly adapted to meet these modern broadcasting conditions. It is the purpose of this paper to discuss some recent developments in this type of receiver.

General

The conventional tuned radio-frequency receiver has two main electrical elements, namely, the tuned radio-frequency amplifier and the detector and audio-frequency amplifier. The modern superheterodyne receiver has both these elements and, in addition, an intermediate frequency amplifier with associated

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frequency converting oscillator and detector. The high amplification and great selectivity of this intermediate frequency amplifier largely account for the remarkable performance of the superheterodyne receiver.

The ease of obtaining high amplification and selectivity in an intermediate frequency amplifier is chiefly due to the low frequency used and to the fact that the characteristics of such an amplifier are independent of the broadcast frequency to which the set is tuned. At these lower frequencies by the use of coupled circuits it is possible to obtain the so-called band-pass filter selectivity characteristics.

Improved radio-frequency circuits and the use of a higher intermediate frequency have contributed a considerable re-

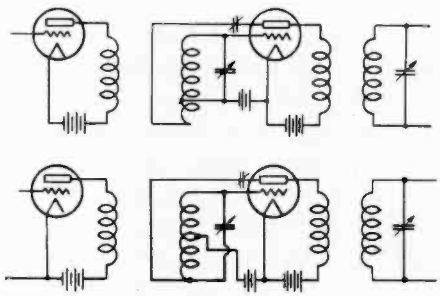

Fig. 1

duction in hiss and extra responses common to previous superheterodyne receivers.

The adjacent channel selectivity and the fidelity of broadcast receivers using a given number of tuned circuits are so related that it is impossible to increase either of these characteristics beyond certain limits without a corresponding sacrifice in the other.

A radio receiving set may be designed using four tuned circuits which will have a better adjacent channel selectivity than an eight tuned circuit receiver which is designed for good fidelity. The four tuned circuit set will be lacking in fidelity due to the attenuation of the side bands, and will also have less selectivity for stations separated by 30 kc or more. If the four tuned circuit set is made to equal the fidelity of the eight tuned circuit set, it will be inferior in selectivity in every way.

The use of broader radio-frequency and intermediate frequency circuits in connection with a negatively biased detector capable of high voltage outputs and a single stage of audio-frequency amplification has contributed a major improvement in the fidelity of the modern superheterodyne receiver.

The incorporation of a practical automatic volume control has eliminated the necessity of repeated adjustment of the volume control both when tuning from distant to local stations or vica versa, and when receiving stations whose field strength is varying periodically.

Radio-Frequency Amplifier

The selectivity of a well designed superheterodyne receiver for eliminating local stations is chiefly determined by the selec-

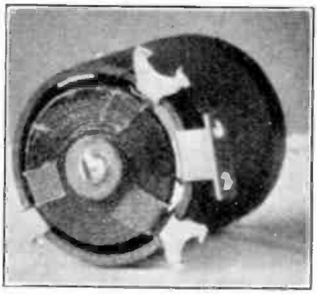

Fig. 2

tivity characteristics of the intermediate frequency amplifier. There are, however, a few exceptions; for example, if no radio-frequency selectivity is employed, two signals of equal strength differing in frequency by twice the intermediate frequency will be received with equal intensity with the heterodyne oscillator tuned midway between them. In addition to this objectionable response, harmonics of the oscillator heterodyning undesired signals are likely to cause interference. An input circuit tuned to the signal it is desired to receive reduces the possibility of interference to some extent, but in the vicinity of powerful broadcasting stations more than one tuned circuit is necessary.

The usual type of tuned radio-frequency transformer consisting of a few turns in the plate circuit of the amplifier tube coupled to the tuned secondary gives a selectivity characteristic which is much sharper at the low-frequency end of the broadcast range than at the high. In fact, it is usually so sharp that two or three stages of this type of amplification results in considerable reduction of the high modulation frequencies. A transformer of this type designed for good selectivity at the high-frequency end of the range will usually be lacking in amplification at the low-frequency end of the range.

A new radio-frequency system has been developed which overcomes most of the objections to the type just described. It provides much more uniform selectivity and amplification without resorting to some mechanical means of varying the coupling with frequency. The only difference between the new transformer and the old is in the type of primary used. Where the primary for the old type of radio-frequency transformer was

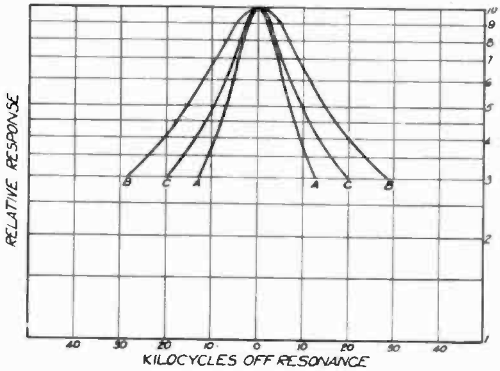

Fig. 3

wound with a small number of turns and was resonant to a frequency above the high-frequency end of the broadcast range, the improved transformer has a large number of turns on the primary, making it resonant to a frequency below the low-frequency end of the range. The old primary increased the effective secondary resistance at the higher frequencies where it was normally too great for good selectivity. The new primary increases the effective secondary resistance at the low-frequency end of the range where it is normally too low for high fidelity.

Since the primary is resonant at a frequency below the broadcast range, the amplification is increased at the low frequencies and reduced somewhat at the high, making it uniform over the range.

In order to realize the normal amplification of high inductance primary transformers, some means must be used to compensate for the effect of the grid to plate capacity. This is due to the primary being tuned to a lower frequency than the secondary, thus giving the plate circuit capacitive reactance. The voltage fed back through the tube capacity is therefore of such a phase as to oppose the applied grid voltage and will reduce this voltage to a fraction of its normal value. Either of the methods shown in Fig. 1 may be used to overcome this effect. If the feed-back capacity is made too large, it is possible to make the circuit oscillate.

Fig. 2 shows one form of a transformer of the high inductance primary type. Curves *A*, *B*, and *C*, Fig. 3, are resonance curves taken at 600 kc showing the effect of the two types of primaries

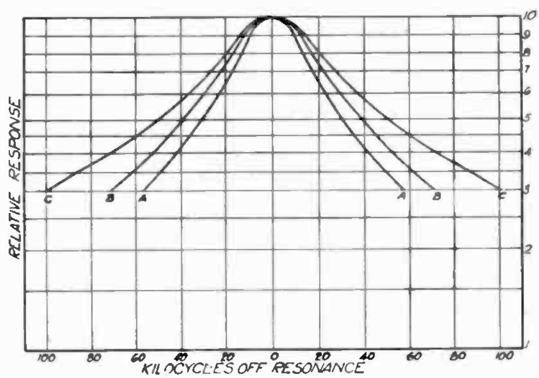

Fig. 4

on the tuned secondary. Curve *A* is the resonance curve of the secondary alone. Curve *B* shows this secondary coupled to a high inductance primary, and Curve *C* shows the same secondary coupled to a low inductance primary. Curves *A*, *B*, and *C*, Fig. 4, are similar curves taken at 1400 kc. Fig. 5 shows the amplification curve for a complete stage of radio-frequency amplification using a high inductance primary transformer and a UY-227 tube.

Intermediate-Frequency Amplifier

In past superheterodyne receivers the intermediate frequency has usually been in the neighborhood of 40 or 50 kc. This choice resulted from the ease of obtaining a stable amplifier for a frequency in this region having the necessary amplification and the desired selectivity characteristics. Now, however, another important factor must be considered in the choice of an intermediate frequency.

From Fig. 6, showing the selectivity of the two tuned radio-frequency circuits, it is noted that the higher the intermediate

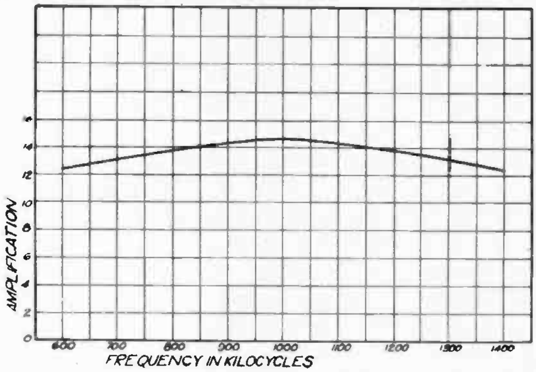

Fig. 5

frequency used the less the possibility of encountering interference from stations separated by twice the intermediate frequency. From the curve it will be seen that this interference for a 40-kc amplifier would be 350 times that for a 400-kc amplifier and 60 times that for a 200-kc amplifier.

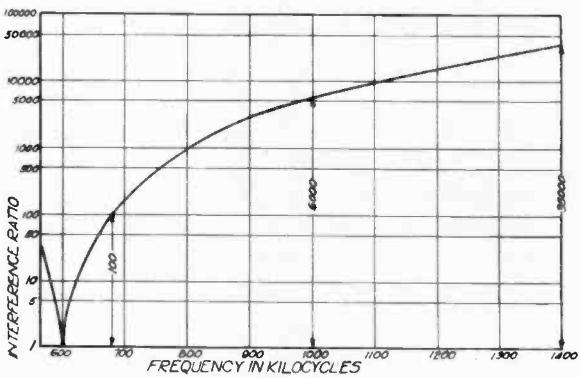

Fig. 6

An intermediate frequency of 180 kc was finally chosen as the best compromise between amplification, stability, selectivity, and undesired responses.

With an intermediate frequency of 180 kc and the oscillator tuned to a higher frequency than the radio-frequency circuits, it will be seen that broadcasting stations separated by twice the intermediate frequency will not produce interference at frequencies above 1140 kc. The selectivity of the radio-frequency system at the high frequencies is therefore not as important in this receiver as at the low frequencies.

Both the primary and the secondary of the three transformers used in the 180-kc amplifier are tuned, and the two windings are so coupled as to give a broad top resonance characteristic. Curve *A*, Fig. 7, is for a single stage of the inter-

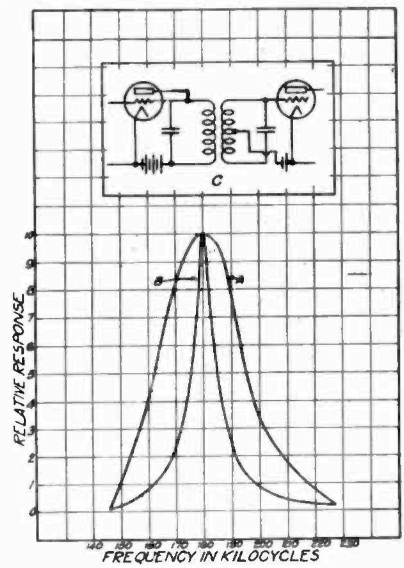

Fig. 7

mediate-frequency amplifier as shown in circuit *C*, having the proper magnetic coupling between the primary and secondary Curve *B* shows the combined characteristic of the primary and secondary used as separate tuned circuits with vacuum-tube coupling between them. Such a characteristic would be obtained if these individual circuits were used separately in a cascade amplifier. These two curves indicate the improvement that can be obtained by the use of coupled circuits, provided the losses in the individual circuits can be kept reasonably low.

The overall resonance curve for the intermediate-frequency amplifier is shown in Fig. 8. The approximately ideal band-pass filter characteristics of this amplifier should be noted, the band width at 50 per cent peak amplitude being 16 kc while at 1 per cent peak amplitude it is only 40 kc.

The three transformers are each mounted in individual metal containers which serve both to protect the transformer and shield it electrically. The primary is tuned by a compact fixed condenser, and the secondary by a small adjustable condenser which permits accurate alignment of the three transformers.

The balancing, primary, and secondary tuning condensers are mounted on a small piece of bakelite to which are also riveted

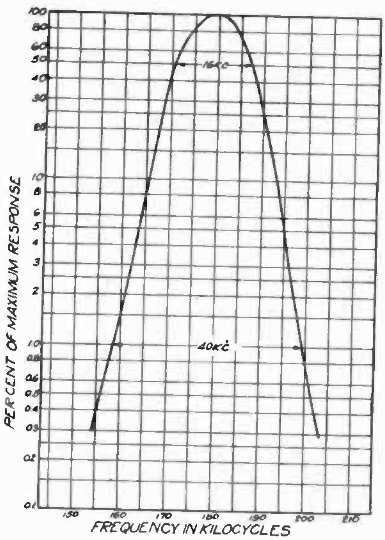

Fig. 8

the two brackets for supporting the transformer windings. Fig. 9 illustrates the manner in which these condensers, the transformer windings, and the terminals are mounted. A transformer completely assembled ready to mount on the chassis is shown in Fig. 10.

Audio-Frequency System

The audio-frequency detector in radio receiving sets is responsible for some distortion and contributes to such disturbances as microphonic howl and a.c. hum.

These objectionable features are considerably reduced, and other performance advantages are gained by employing a plate circuit detector and by using but one audio stage.

The relative merits of the conventional audio system consisting of a grid circuit detector and two audio stages as compared with a combined radio and audio system employing a radio-

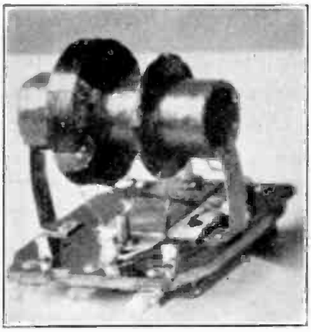

Fig. 9

frequency stage, plate circuit detector, and one audio stage are as follows:

Changing from a grid circuit to a plate circuit detector in a given receiver results in a sacrifice in sensitivity. This reduction in sensitivity can be overcome by increasing the radio-frequency

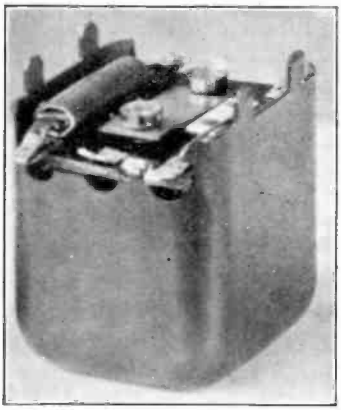

Fig. 10

amplification and reducing the audio-frequency amplification. In general, it can be said that substituting a radio-frequency stage of equal amplification for an audio stage will result in no loss of sensitivity from substituting a negatively biased detector for a grid leak and condenser detector.

With improved audio response, particularly at low frequencies, when two audio stages are used, it has become increasingly difficult to avoid a.c. hum from the power supply, and audio howls due to the microphonic action of tubes. The blasting and breaking up of the sound output when tuning through a local station is ordinarily due to overloading the output tube. This disturbance can be reduced if the circuits are so designed as to allow the detector and output tube to overload at the same time.

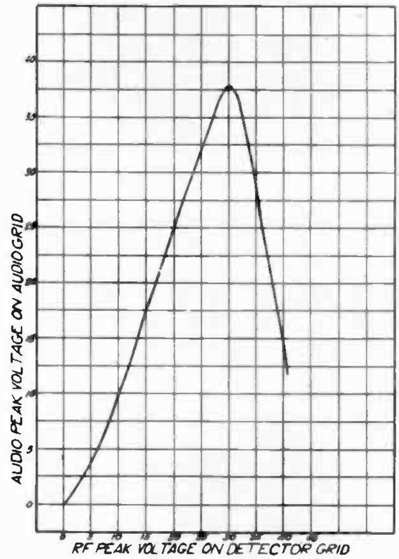

Fig. 11

The time lag distortion associated with detectors employing grid leak and condenser combinations is not present when plate circuit detection is used.

The curve in Fig. 11 shows the relation between the peak voltage on the grid of a UY-227 tube functioning as a negatively biased detector and the peak audio voltage on the grid of the audio amplifier tube. The plate potential on the UY-227 tube is 180 volts and the bias 25 volts. The carrier is modulated 15 per cent at 100 cycles. The reduction in output for an input in excess of 30 volts is due to the grid current load on the tuned circuit, through which the voltage is applied to the detector grid.

Automatic Volume Control

A receiving set equipped with a practical automatic volume control has several distinct advantages over the set which lacks this equipment.

One of the chief advantages is the ability to change the tuning of the receiver without making any change in the volume control setting. Once the volume control has been set for the desired sound output, either distant or local stations may be tuned in without any further volume control adjustment. If the distant station provides sufficient field strength (depending

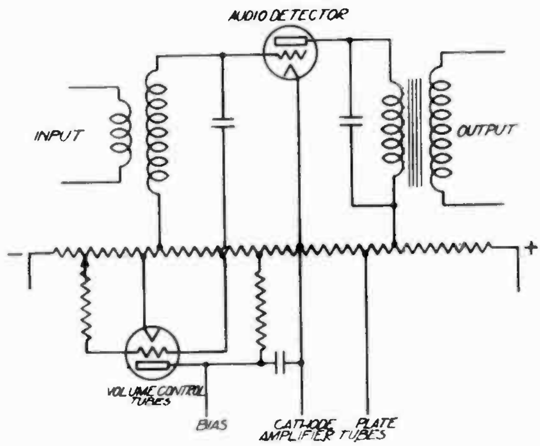

Fig. 12

on the maximum sensitivity of the receiver) it will produce practically the same sound output as the local station. It is assumed that the per cent modulation used by both stations is nearly the same.

The ability of an automatic volume control to limit the sound output to any desired value is of particular importance in light of the present trend towards the use of output tubes capable of handling considerable power.

While automatic volume controls have sometimes been called fading eliminators, this term is, of course, erroneous. An effective automatic volume control, however, does automatically adjust the sensitivity of the receiver while the field strength from a station is varying so as to maintain a constant output

There are numerous occasions when a powerful distant station has sufficient field strength at any time during an evening to give a satisfactory loudspeaker signal, but the field strength varies through such a wide range and so frequently that the program cannot be received satisfactorily without continuous adjustment of the volume control. Under such conditions an automatic volume control will function satisfactorily. The only indication that the user will have that the signal is fading will be an increase in the ground noise when the signal drops to such

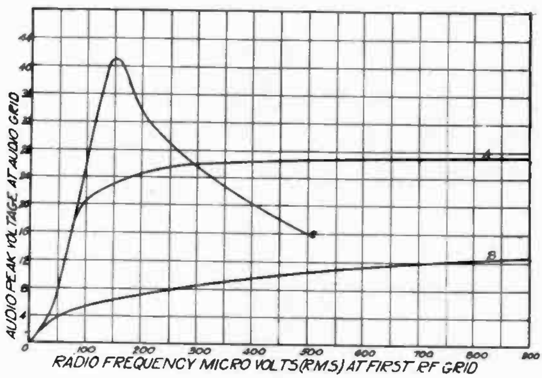

Fig. 13

a value that nearly the maximum sensitivity of the receiver is required to produce the desired sound output.

There are some types of fading that are accompanied by a distortion of the audio modulation, and in such cases an automatic volume control will be of little value as far as compensation for this type of fading is concerned.

The chief objections to past automatic volume control systems have been the number of adjustments required and the use of separate voltage supplies for certain parts of the circuit. To obtain sufficient control some systems also require additional amplification either for the a.c. voltage on the detector grid or for the bias voltage before it is impressed on the amplifier grids. This latter objection is overcome by the use of but one stage of audio amplification and the corresponding increase in the grid swing on the detector tube. Fig. 12 shows a schematic diagram for an arrangement which overcomes the other objections. The grid of the volume control tube is connected in parallel through a coupling condenser to the grid of the second detector. The voltage drop across a resistor in the plate circuit of this tube is used as additional negative bias on the amplifier tubes and thus reduces the sensitivity of the receiver. The values of this plate circuit resistor and its shunting capacity are so chosen as to give the combination a time constant sufficiently low to prevent the smoothing out of the lower modulation frequencies and still high enough to prevent its action from being sluggish.

The bias on the volume control tube is normally adjusted to the point where, when no signal is being received, the tube

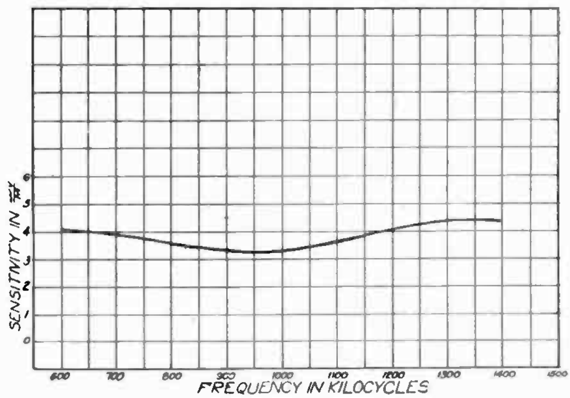

Fig. 14

draws no current. Then when the grid swing on the second detector exceeds a certain value, the effective bias on the control tube is reduced and its plate current increased. This increase in plate current causes a corresponding increase in the bias voltage applied to the radio-frequency and intermediate frequency amplifier tubes with a resultant reduction in the sensitivity of the receiver, thus tending to maintain a uniform grid swing on the second detector. By means of a manual control the negative bias on the volume control tube can be increased permitting a larger grid swing on the detector tube before the automatic volume control tube takes effect. In this manner any desired audio output can be obtained. The variation of the bias on the volume control tube as the manual adjustment for the output level also compensates for the manufacturing variations in cutoff of the tubes as automatic volume control tubes. Curves *A* and *B* in Fig. 13 show the effectiveness of the automatic volume control for two output levels. Curve *C* shows the variation in output without the automatic volume control.

The use of an automatic volume control in a radio receiver presents some problems which are not encountered when this equipment is not used. Due to the automatic volume control maintaining constant audio output, it is difficult to tune the receiver accurately unless some resonance indicating device is provided. A meter in the plate circuit of either the control tube or the tubes controlled provides a satisfactory resonance indicator.

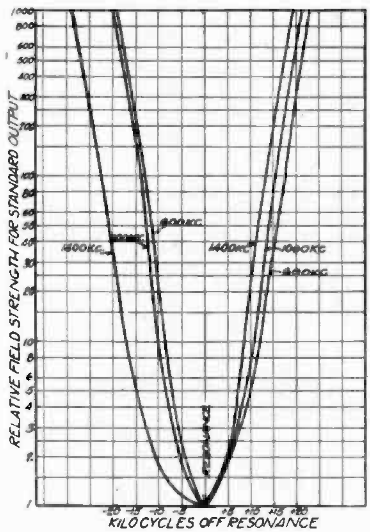

Fig. 15

In localities where there is considerable interference due to power line leakage, etc., the noise encountered when tuning between stations with a set equipped with automatic volume control is objectionable unless a sensitivity control is provided. This is due to the fact that when no signal is being received the receiver is automatically adjusted for maximum sensitivity, and the time constant of the automatic volume control circuit is such that it does not limit the sharp impulses of such interference. The sensitivity control may be a voltage divider which varies the normal bias on the amplifier tubes, or in receivers where an untuned input circuit is employed a voltage divider may be used to vary the signal potential on the grid of the input tube.

By means of the sensitivity control, the maximum sensitivity of the receiver can be reduced to such a value that the noise encountered in tuning between stations is not objectionable. This sensitivity control will in no way destroy the effectiveness of the automatic volume control.

Overall Performance

The major electrical elements of a modern superheterodyne receiver have been briefly discussed. The performance char-

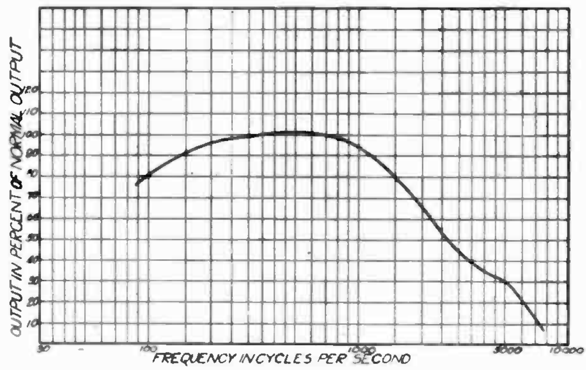

Fig. 16

acteristics of a complete receiver embodying these elements are as follows:

Fig. 14 is the sensitivity curve of a receiver consisting of two radio-frequency stages, heterodyne detector and oscillator, two intermediate-frequency stages, high output detector, and single audio stage. The receiver employs UY-227 tubes throughout except for the power output tube.

The three curves in Fig. 15 show the selectivity of the receiver at three frequencies in the broadcast range. The fidelity characteristic of the complete receiver is shown in Fig. 16.

The curves show the high uniform degree of selectivity obtained by the use of the eight tuned circuits while still retaining unusual fidelity characteristics.

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AN EXTENSION OF THE METHOD OF MEASURING INDUCTANCES AND CAPACITIES*

By
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Summary—*The substitution method commonly employed for measuring small capacities is shown to be a special case of a more general principle. As other special cases of this principle methods are presented for simultaneously measuring inductance and capacity when joined in series and when joined in parallel. The cases discussed indicate the method of application of the general principle to any type of measuring or measured circuit.*

THE method commonly employed for measuring the capacity of condensers, in which the unknown condenser is connected in parallel with a calibrated condenser in a resonant circuit, is a special case of the more general method described in this paper. The several special cases of the more general method are of interest in that they furnish simple and convenient ways in which to measure circuit elements when

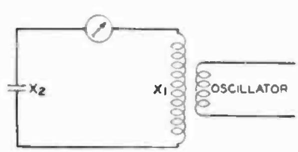

Fig. 1

connected together in circuit. The general principle of the substitution method can be explained by means of Figs. 1 and 2. A series circuit including a current indicator (e.g., a wavemeter) is coupled loosely to an oscillator. Resonance is obtained by adjusting x_2 so that

$$x_2 = x_1 \tag{1}$$

The coupling between x_1 and the oscillator is assumed to be so loose that the reaction between the circuits is negligible. The unknown reactance x_3 is then connected in parallel with x_2, and the latter is then readjusted so that resonance is again obtained. Then

$$\frac{x_3 x_2'}{x_3 + x_2'} = x_1 \tag{2}$$

* Dewey decimal classification: R230. Original manuscript received by the Institute, November 19, 1928.

Equating (1) and (2), and solving for the unknown x_3:

$$x_3 = \frac{x_2' x_2}{x_2' - x_2} \tag{3}$$

This is the general condition for all such measurements, and from it the particular cases can be derived. The wavemeter is the most convenient instrument to use in many of these measurements, so that we may put

$$x_1 = j\omega L_1, \quad x_2 = -\frac{j}{\omega C_2}, \quad x_2' = -\frac{j}{\omega C_2'} \tag{4}$$

and (3) becomes

$$x_3 = \frac{j}{\omega(C_2' - C_2)} \tag{5}$$

Case 1. If x_3 is a pure capacitive reactance, then equation (5) becomes

$$C_3 = C_2 - C_2' \tag{6}$$

Case 2. If x_3 is a pure inductive reactance, it becomes

$$L_3 = \frac{1}{\omega^2(C_2' - C_2)} \tag{7}$$

Case 3. If x_3 consists of an inductance in series with a capacity, as for instance an antenna circuit, then $x_3 = j(\omega L_3 - 1/\omega C_3)$ and (5) reduces to

$$L_3 = \frac{C_3 + (C_2' - C_2)}{\omega^2 C_3 (C_2' - C_2)} \tag{8a}$$

or,

$$C_3 = \frac{(C_2' - C_2)}{\omega^2 L_3 (C_2' - C_2) - 1} \tag{8b}$$

In order to obtain the values of L_3 and C_3 it is necessary to make two measurements at different frequencies. Let these frequencies be f_1 and f_2, and the corresponding values of $(C_2' - C_2)$ be $\underline{C}'$ and $\underline{C}''$. Then (8a) may be written

$$L_3 = \frac{\underline{C}' + C_3}{\omega_1^2 \underline{C}' C_3} = \frac{\underline{C}'' + C_3}{\omega_2^2 \underline{C}'' C_3}$$

and solving for C_3:

$$C_3 = \frac{(\omega_1^2 - \omega_2^2)\underline{C}'\underline{C}''}{\omega_2^2 \underline{C}'' - \omega_1^2 \underline{C}'} = \frac{1 - \left(\frac{f_2}{f_1}\right)^2}{\left(\frac{f_2}{f_1}\right)^2 \frac{1}{\underline{C}'} - \frac{1}{\underline{C}''}} \tag{9}$$

Similarly, starting with (8b) and solving for L_3:

$$L_3 = \frac{\underline{C}'-\underline{C}''}{\underline{C}'\underline{C}''(\omega_2^2-\omega_1^2)} = \frac{1}{4\pi^2(f_2^2-f_1^2)\left(\dfrac{\underline{C}'\underline{C}''}{\underline{C}'-\underline{C}''}\right)} \tag{10}$$

The quantities $\underline{C}'$ and $\underline{C}''$ may be termed *apparent* capacities. For example, in determining the constants of an antenna, it is regarded as a simple capacity, and its apparent values at two different frequencies are measured as in Case 1. These values,

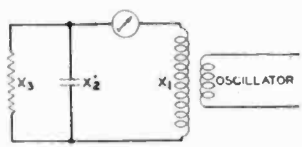

Fig. 2

substituted in (9) and (10), yield the true capacity and inductance. In applying the method to circuits containing coils which have appreciable capacity, the two frequencies should not differ very widely, as the apparent inductance of the coil changes with frequency.

Case 4. If x_3 is an inductance paralleled by a capacity, then

$$x_3 = j\,\frac{\omega L_3}{1-\omega^2 L_3 C_3}$$

Following the same procedure as in Case 3, we obtain:

$$C_3 = \frac{\omega_1^2\underline{C}'-\omega_2^2\underline{C}''}{\omega_2^2-\omega_1^2} = \frac{\underline{C}'-\left(\dfrac{f_2}{f_1}\right)^2\underline{C}''}{\left(\dfrac{f_2}{f_1}\right)^2-1} \tag{11}$$

$$L_3 = \frac{\omega_2^2-\omega_1^2}{\omega_1^2\omega_2^2(\underline{C}'-\underline{C}'')} = \frac{f_2^2-f_1^2}{4\pi^2 f_1^2 f_2^2(\underline{C}'-\underline{C}'')} \tag{12}$$

Discussion

R. R. Batcher[1]: It seems to the writer that several precautions are necessary in applying the measurement methods outlined in this paper. It has been his experience that the procedure taken up in Case 3 and the

[1] Decatur Manufacturing Co., Inc., Brooklyn, N. Y.

use of formulas (9) and (10) might lead to erroneous results in some cases. This is due to the nature of the circuit resulting when x_3 is replaced by a series arrangement of inductance and capacitance. Such a circuit is resonant to two frequencies, one greater than the natural resonance frequency of the L_3C_3 path and the other less than this frequency. This condition has been examined[2] and used in several cases by the writer and a number of formulas were developed to cover the several variations of conditions found in practice. The following is illustrative of the circuit relations:

$$\frac{f_{(x_1x_2x_3)}}{f_{x_3}}=\sqrt{\frac{L_1C_2+L_3C_3+L_1C_3\pm\sqrt{(L_1C_2+L_3C_3+L_1C_3)^2-4L_1L_3C_2C_3}}{2L_3C_3}}.$$

This is the ratio of the frequency of $x_3x_1x_2$ paths to the resonant frequency of x_3.

It is the condition that permits this circuit to be tuned to a wavelength shorter than the natural of x_3 that makes the circuit so useful. If x_3 is an antenna system lower waves can be tuned to than can be obtained with a condenser in series with the antenna circuit.

Used in a measurement circuit it is evident that the measurement frequencies must be selected with care, as it will be impossible to obtain a satisfactory adjustment at a frequency near that at which the x_3 path becomes resonant. It can be shown that it is necessary to consider the value of x_1 (that is L_1) in any computations. In some cases it may be desirable to determine the ratio of

$$\frac{\text{Resonant frequency of } x_1x_2x_3}{\text{Resonant frequency of } x_1x_2}$$

instead of that given by the above formula. In this case the values obtained for either the low or the higher frequency must be multiplied by the factor

$$\sqrt{\frac{L_3C_3}{L_1C_2}}$$

which is equivalent to changing the denominator to $2L_1C_2$. It is possible to convert this formula to a more convenient form for use in measuring work.

In Case 4 in the above paper a condition may be found where the resonant frequency of x_3 may be near or equal to the oscillator frequency. In this case there will be little or no change in the tuning of the x_1x_2 circuit after the addition of x_3. It seems that other peculiar conditions might be encountered if the two measuring frequencies happened to be on opposite sides of the frequency of x_3.

Quite aside from the above comments it seems that the accuracy of the above method is determined by the ratio of f_2/f_1. However, mention is made that the two frequencies should not differ very much. If the distributed capacity of the wavemeter pickup coil is measured and the value added to that of the condenser and the precaution taken to use as large a value of C_2 and as small a value of pick up inductance the error is

[2] "Prepared Radio Measurements," pages 89 to 91; and *Wireless Age*, p. 39, April, 1919.

somewhat lessened and it might be possible to use a larger frequency ratio. Since we are mainly concerned with the difference between two readings of C_2 the effect wavemeter coil capacity which is effectively in parallel with the condenser may not introduce as great an error in results as might be found with the use of two measuring frequencies differing but little. The effect of the distributed capacity of the coil under measurement is rather hard to predict, however.

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APPARENT EQUALITY OF LOUDSPEAKER OUTPUT AT VARIOUS FREQUENCIES*

By
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Summary—*A type of alternation phonometer has been developed which permits rapid switching of power at two frequencies to the same loudspeaker without the distracting effect of the transients that would result from ordinary types of commutation. This result is obtained by the use of rotating condensers to provide variable capacitative reactance in the input circuit of the power amplifier that operates the speaker. The power consumed by the loudspeaker is measured with a specially constructed wattmeter of the electrodynamometer type and the output of the loudspeaker is measured by means of the torques produced on a Rayleigh disc. With the aid of the alternation phonometer and an additional capacitative reactance, the observer is able to adjust the power input to the loudspeaker until two tones of different frequencies appear to have the same intensity. The purpose of the research was to develop a method for the comparison of loudspeaker efficiency at various frequencies that could be used in ordinary laboratories with limited equipment.*

Previous Work

THAT the sensitivity of the human ear is a function of the frequency of the tone has long been assumed, and quantitative results on this sensitivity for *minimum audition* have been obtained by Fletcher and Wegel.[1] They employed a telephone receiver clamped over the ear of the observer as a sound generator. For tones of greater intensity, Dayton C. Miller[2] employed a set of organ pipes which when driven under certain standard conditions of air pressure gave tones which in the opinion of the builder (an expert pipe organ man) gave tones of equal apparent intensity.

B. A. Kingsbury[3] compared tones of different pitch for the sake of determining the actual pressure on the ear drum for equal apparent intensity at various pitches. He employed a single receiver clamped over the ear after the manner of Fletcher and Wegel. The observer varied the intensity of one tone by means

* Dewey decimal classification: R376.3. Original manuscript received by the Institute, November 20, 1928. Presented before meeting of the Buffalo section of the Institute, January 17, 1929.

[1] Fletcher and Wegel, "Frequency Sensitivity of Normal Ears" *Proc.* Nat. Acad. Sci. 8, 5, 1922.

[2] Dayton C. Miller, "The Science of Musical Sounds," Macmillan Co.

[3] B. A. Kingsbury, "A Direct Comparison of the Loudness of Pure Tones," *Phys. Rev.*, 29, 588; April, 1927.

of an attenuator, and he shifted his attention from one tone to the other by manually operating a double pole double throw switch so that he listened first to one tone and then to the other.

Previously, Donald MacKenzie[4] had pointed out certain defects in this method of alternating the tones due to the "decay of sensation" on the part of the observer. He therefore devised an instrument called an "alternation phonometer," which bears some relation to the flicker photometer of optics. Power from two oscillators was alternately impressed on a sound generator by means of a polarized telegraph relay driven from another relay at controllable speeds. The speed found to be most satisfactory was approximately 12 per second in the frequency region 100 to 4000. That is, each source was turned on and off 12 times per second. Only about 0.002 second elapsed between the opening of one contact and the closing of the other. A ther-

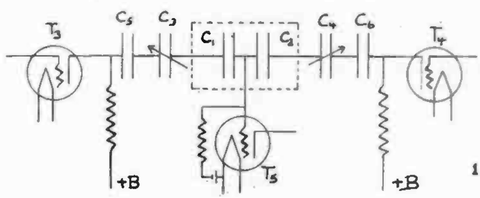

Fig. 1—The Variable Reactance Alternator with Associated Apparatus.

mophone held tightly to the ear was used as the sound generator for part of this work, and an electro-magnetic receiver similarly placed was used for the part involving intensities above the capacity of the thermophone.

Purpose and General Method

The present paper is an account of work done by the authors in attempting to apply the general principle of the alternation phonometer to a method for the determination of the apparent efficiencies of loudspeakers at various frequencies. The general method was to adjust one oscillator to give a steady tone at an arbitrarily chosen intensity. The observer then adjusted the intensity of the other tone until he obtained apparent equality. The two tones were rapidly alternated by a new type of alternation phonometer. The electrical power input to the loudspeaker was then determined for each tone by means of a specially con-

[4] Donald MacKenzie, "The Relative Sensitivity of the Ear," *Phys. Rev.*, 20, No. 4; October, 1922.

structed electrodynamometer calibrated at each frequency used. The actual sound intensity at the position of the observer's head was determined from Rayleigh disc measurements.

The Alternation Phonometer

In the place of MacKenzie's relay, the authors attempted to use a rotating commutator, but found that with the amplification employed between the commutator and the loudspeaker, the transients introduced by the sudden starting and stopping

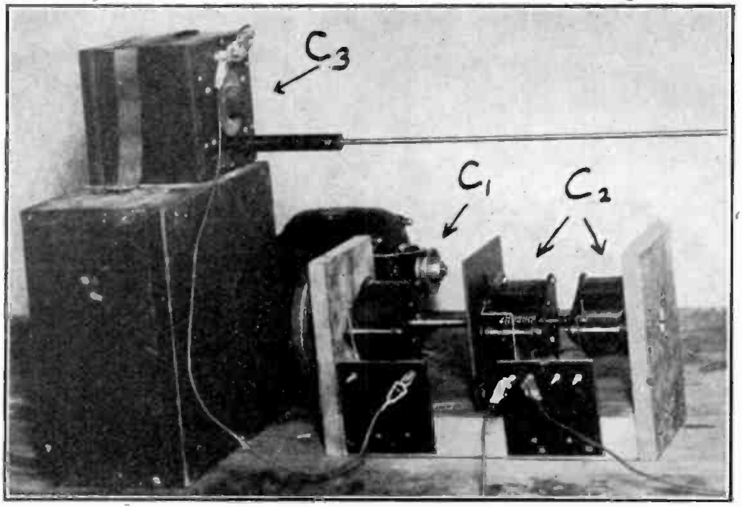

Fig. 2—The Variable Reactance Alternation Phonometer.

of the power from the oscillators were fatiguing to the observer and seriously interfered with his ability to compare the intensities of the tones. An arrangement of variable capacitative impedance in the input of the amplifier was then tried, and it proved to be much more satisfactory.

In the diagram of Fig. 1, C_1 and C_2 are variable air condensers of 0.0005 μf maximum capacity. They are mounted with their rotors on a common shaft so that one condenser is at minimum capacity when the other is at maximum value. Fig. 2 shows two condensers for C_2. These are electrically insulated and are arranged so that they may be used either independently or in series or in parallel. It was found necessary to use only one of them independently in the work reported in this paper. The shaft on which the rotors are mounted has a pulley on one end and is belt driven by a variable speed d.c. motor. The speeds most commonly used gave 8 or 9 alternations per second. That is, each tone was heard that number of times per second.

Intensity Control

In the diagram of Fig. 1, C_4 is a variable condenser which enables the operator to make an arbitrary setting for the maximum value of the intensity of the tone to be used as a basis for comparison. C_3 is used to vary the intensity of the tone

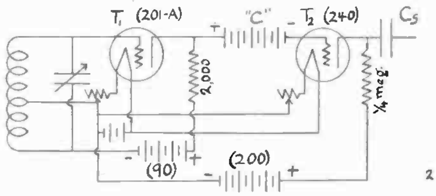

Fig. 3—Oscillator with Conductively Coupled Amplifier.

being compared. It is operated by a long shaft running into the sound compartment so that the observer may readily operate it. C_5 and C_6 were large condensers (4 μf each) used merely to keep the plate potentials off the control condensers C_3 and C_4. T_3 and T_4 were amplifiying tubes which were in turn fed by oscillators.

Oscillators and Amplifiers

The oscillators were of the Hartley type. Air core coils were employed and tuning was accomplished by means of step variable condensers. Each oscillator was conductively coupled to a one-stage amplifier. The arrangement of one of these oscillator-amplifier combinations is shown in Fig. 3.

The controlled output from the rotating condensers C_1 and C_2 was fed into a resistance coupled amplifier of conventional design. The first tube of this amplifier is shown in Fig. 1 and the entire arrangement in Fig. 4. The amplifier is built into a brass-lined box with brass partitions between the separate stages.

Separate filament batteries are used for each oscillator and for the resistance coupled amplifier. But the circuits are so arranged that although separate B and C batteries are used also, the negative sides of all the B batteries used on the amplifiers are electrically connected. This is of course necessary for the operation of the variable reactance in the grid circuit of the amplifier input.

Loudspeaker

The loudspeaker used in these experiments was an exponential horn driven by a unit of the Baldwin type. The horn was octagonal in cross section and was built of bass wood. The length

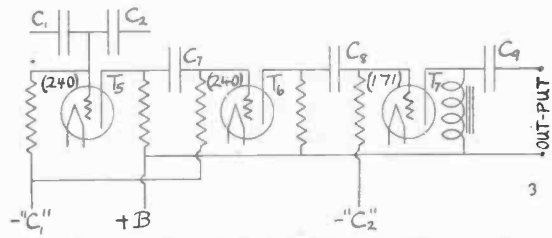

Fig. 4—Resistance Coupled Amplifier. The coupling condensers are 1 μf each. The filaments are in parallel with a common rheostat. Both grid and plate resistances are ¼ megohm each.

along the axis was 8 ft. The open end had a cross section of 400 sq. in. and the small end a cross section of approximately 0.3 sq. in. The equation for the shape of the horn is therefore given by

$$A = \epsilon^{(0.075x - 1.181)}$$

where A is the area of cross section in square inches, x is the distance in inches measured along the axis from the smaller end, and ϵ is the base of the natural system of logarithms.

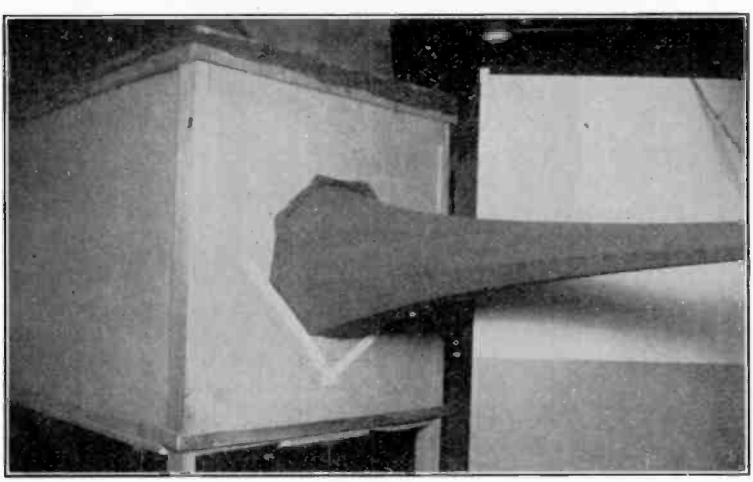

Fig. 5—The Loudspeaker and the Sound Compartment.

Sound Compartment

The mouth of the loudspeaker opened into the end of a 4-ft. x 4-ft. x 8-ft. compartment as shown in Fig. 5. The box was built of ½ in. celotex mounted as shown on a 2-in.x 4-in. lumber frame. It was lined on the inside with 2 layers of ½-in. hair felt. On the under side of the box, at the end opposite the loudspeaker, a little of the celotex was cut away, and the hair felt folded back to permit the observer to stand upright on the floor of the laboratory with his head approximately along the mid-axis of the compartment and near its rear end wall. The long shaft from the volume control condenser, C_3, entered the compartment near this end, so that the observer could easily adjust the tone intensity.

Rayleigh Disc Measurements

When Rayleigh disc measurements were to be made the hair felt was closed and the celotex replaced. The Rayleigh disc used in these experiments was a piece of mica 8.75 cm in diameter

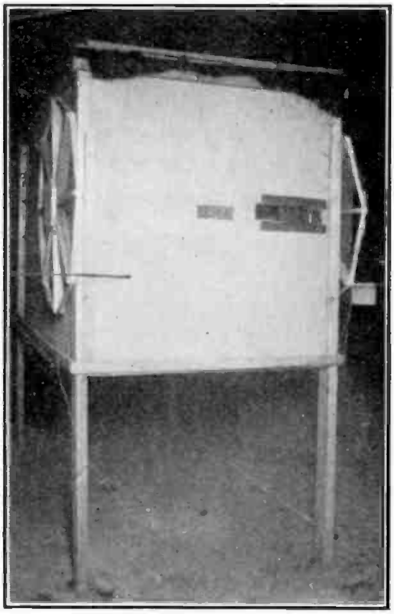

Fig. 6—Rear End of the Sound Compartment Showing the Window for Making Observations and the Octagonal Coils for Establishing the Restoring Field to the Magnet.

suspended from one edge by a thread of unspun silk. On the mica was mounted a small galvanometer mirror which received and reflected light through a narrow glass window in the rear end of the box. (See Fig. 6.) Since the zero position for the disc was 45 deg. to the axis of the box, it will be seen that this window was not directly behind the disc, but rather near one edge of the end wall.

The disc also carried a tiny magnet (1.49 cm in length and 0.1389 gram weight) mounted at 45 deg. to the plane of the disc. With the major axis of the sound compartment running north and south, the disc was then in its zero position (45 deg. to the axis of the compartment) when the small magnet was parallel to the earth's magnetic field (H_e).

Essentially a Rayleigh disc depends for its operation on the fact that when an object finds itself in a field of uniform flow it tends to set itself with its greatest dimension cross-wise to the direction of flow. A quantitative development[5] for the case of a round thin disc located in a field of alternating flow where the alternations are simple harmonic gives

$$\text{Torque} = 8/3\pi^2 a^2 n^2 \rho C^3 \sin 2\theta$$

where

- a is the amplitude of the vibration
- n the frequency
- ρ the density of the medium
- C the radius of the disc
- θ the angle between the normal to the disc and the direction of flow.

Now since the mean square velocity in simple harmonic motion is given by $2\pi^2 a^2 n^2$, and since the energy in a sound wave is proportional to the mean square velocity of the vibrating particles it follows that the torque on the Rayleigh disc is proportional to the intensity of the sound at the point considered. Obviously this torque is a maximum when the angle θ equals 45 deg.

The sound waves striking the disc tended to rotate it and the attached magnet. As the magnet moved out of the earth's magnetic field, the magnetic couple due to that field tended to restrict the motion. A second magnetic field, H, at right angles to the earth's field was then established by sending a measured current through the coils shown in Fig. 6. The couple due to this field also tended to return the magnet (and hence the disc) to its original position. Since the couple due to the earth's field is equal to zero when the magnet is in its original position the final magnetic couple, G, is given by

[5] Winklemann, *Handbuch der Physik.*, II. p. 238.

$$G = H\ M$$

where H is the field due to the current in the coils and M is the magnetic moment of the magnet. But this couple must just balance the torque on the disc due to the sound waves. Hence, since H is proportional to the current in the coils, this current will be directly proportional to the intensity of the sound. Since relative loudspeaker efficiencies were the chief concern in this work, these torques are here expressed in terms of this current in milliamperes.

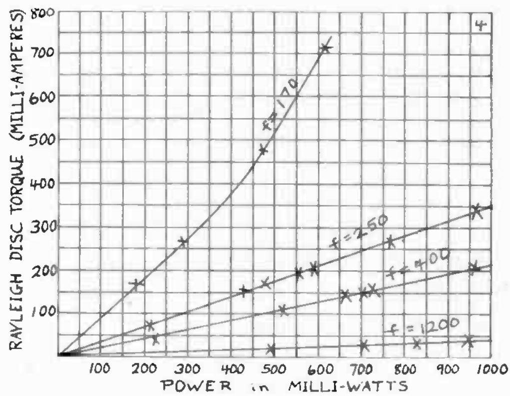

Fig. 7—Sound Intensity Compared to Power Input to the Loudspeaker at Various Frequencies.

To determine zero position for the disc, light sent through the window and back from the mirror mentioned in a preceding paragraph was focused at the source and received on a direct vision screen.

Since the operation of the Rayleigh disc requires considerable care, all the sound intensity measurements were made at one time and the data at each frequency plotted against electrical input to the loudspeaker. Fig. 7 shows the calibration curves for the various frequencies used. With the aid of these curves the sound intensity could be determined for each setting of an observer by simply reading the electrical power input.

Wattmeter

For the purpose of measuring the power input to the loudspeaker a wattmeter of the electrodynamometer type was constructed. The dynamometer with the front of the case removed may be seen in Fig. 8, and a wiring diagram showing internal and external connections of the instrument is shown in Fig. 9. It will be seen that the instrument functions as a simple indicating wattmeter.

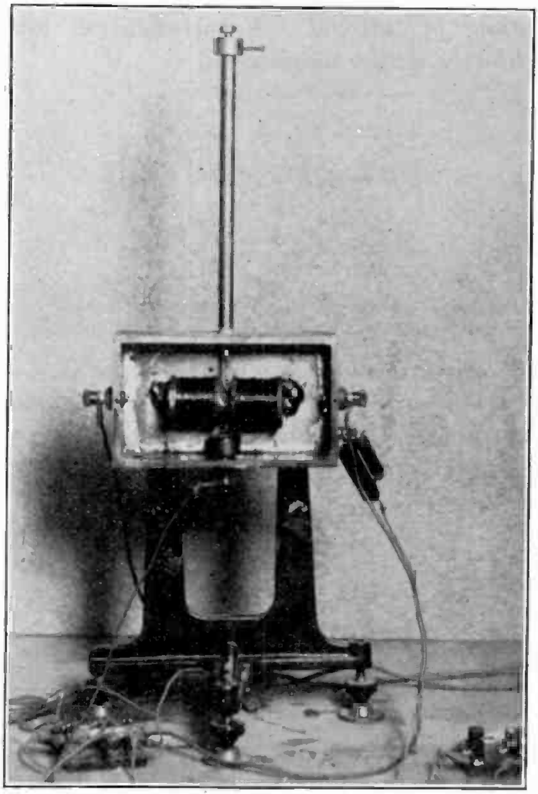

Fig. 8—The Electro-Dynamometer with the Front of the Brass Case Removed.

The moving coil of the wattmeter consists of 2,100 turns of No. 40 enameled cupron wire wrapped on a fiber form of about 2.0 cm diameter. A resistance of 50,000 ohms is in series with this coil. The coil resistance is 3740 ohms giving a total of 53,740 ohms for the potential circuit of the dynamometer. The stationary coil is divided into two parts with the movable coil between them as shown in the photograph. The stationary coil is made of 1,200 turns of No. 28 enameled copper wire. Its resistance is 37 ohms.

The movable coil has a standard galvanometer suspension of phosphor bronze ribbon above and a coil of phosphor bronze ribbon beneath itself. This coil makes contact through a small copper container which carries oil. Two wire prongs extend downward from the moving coil into this oil and serve to damp the oscillations of the coil. A galvanometer mirror is also mounted directly on the moving coil.

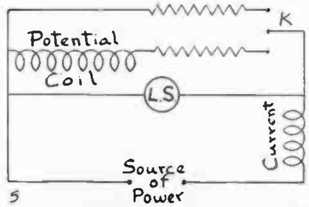

Fig. 9—Schematic Diagram of the Wattmeter Showing Connections to the Source of Power and to the Loudspeaker.

To avoid any errors that might arise from lack of shielding, frequency variation, energy used by the dynamometer itself, etc., the instrument was calibrated in place at every frequency and throughout the range of power used. Fig. 10 shows the

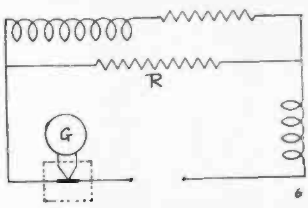

Fig. 10—Schematic Diagram for the Calibration of the Wattmeter.

arrangement used for calibrating. Power was supplied at the various frequencies to a pure resistance. The current was measured by means of a Western Electric thermocouple calibrated with direct current and a milliameter.

The deflections of the wattmeter are read by means of a telescope and scale placed at a distance of 200 cm. Fig. 11 shows a calibration curve for 25 cycles, 250 cycles, and 1,200 cycles. Table I shows the necessary data for the use of the dynamometer at all the frequencies employed.

TABLE I

Sensitivity of Wattmeter

Frequency	Milliwatts per cm.
25	67.0
170	68.5
250	70.4
400	73.0
1,200	77.3

While the alternation phonometer was operating and an observer was adjusting the intensity of one of the tones the switch K shown in Fig. 9 was turned so as to cut the potential coil out of the circuit and put a conductor of approximately equal resistance in its place. As soon as the observer decided on his adjustment, the rotating condensers were stopped with either C_1 or C_2 in its maximum position. Energy to the other condenser was cut off by removing the plate potential from the oscillator-amplifier feeding it. The potential coil of the dynamometer was then placed in the circuit by means of switch K

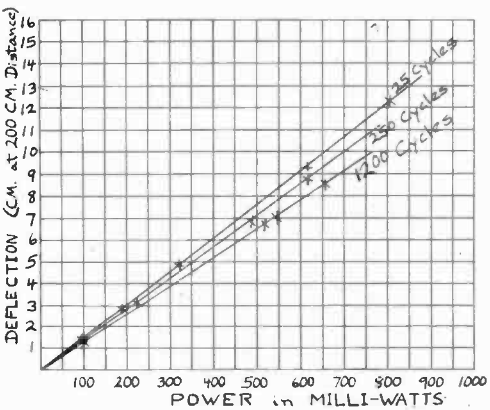

Fig. 11—Calibration Curves for the Wattmeter at Various Frequencies.

and the deflection of the dynamometer determined. The condensers were then rotated through 180 deg. and the power input to the loudspeaker from the other source determined in a similar manner. The frequency of the variable source was then altered and the process repeated. It was of course necessary to keep the intensity of the tone used as a basis for comparison as nearly constant as possible.

Experimental Results

Fig. 12 shows a single set of observations of sound intensity versus frequency for equal apparent intensity of tones using a frequency of 400 at an electrical input of 755 milliwatts as a base. This data is represented by the crosses. The circles show the average of 3 sets of data taking a frequency of 1,200 at an electrical input of 1055 milliwatts as a base. The squares are the average of 2 sets of data using a frequency of 250 at 332 milliwatts as a base. The solid line shows the average of 4 sets of data using each tone once as a base. The conformity of the curves for all the observations shown in this figure to the same general shape is an indication of the accuracy of judging equal apparent intensities with the aid of the alternation phonometer described even at rather high loudspeaker intensities.

In Fig. 13 we have a record of the same observations as in the solid curve of Fig. 12 except that here we have plotted power input against frequency. This figure is of course not of general interest, since it applies only to the loudspeaker used in these tests.

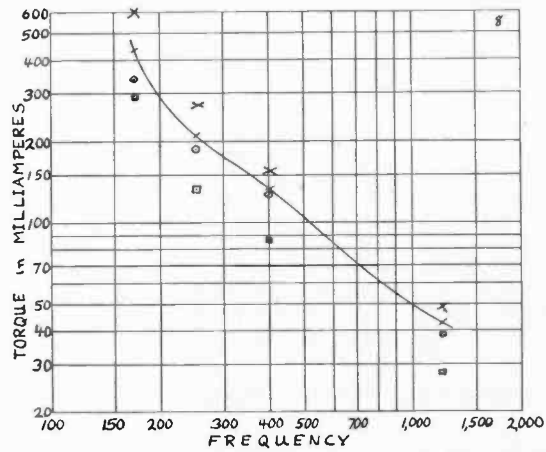

Fig. 12—Observations of Sound Intensity Versus Frequency for Equal Apparent Intensity. (See text for explanation of marks.)

These curves (Fig. 12) show, as was to be expected from the work of previous investigators, that the ear sensitivity falls off for the lower tones. On the other hand, we see by plotting the ratio of Rayleigh disc torques to electrical input against frequency for equal intensity (data for the observations shown in the solid curve of Fig. 12) that the loudspeaker used is more efficient in our lower range than in the upper. (See Fig. 14.) A similar curve plotted for equal actual intensities would show this characteristic still more.

Except for a frequency of 170, Fig. 7 indicates that the efficiency of this loudspeaker does not vary with intensity at a given frequency in the region covered by this graph.

Sources of Error and Limitations of the Device

The alternation phonometer did not prove as satisfactory as a manual switching of sources when both tones were at approximately the same frequency, due largely to beat notes.

The plates of condensers C_1 and C_2 were semicircular. It will be readily seen that three questionable things occur with commutation by means of these condensers. First, at no time is

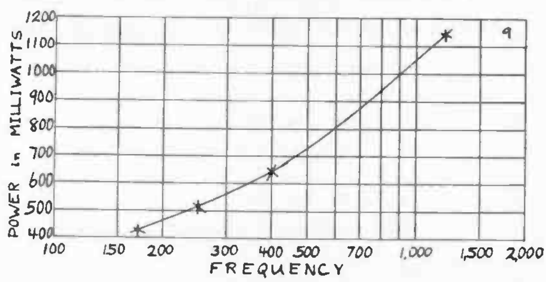

Fig. 13—Power Input Versus Frequency for Equal Apparent Intensity

the capacity of either condenser zero, and consequently at all times both tones are present to some extent. Second, the intensity of either tone approaches a maximum and at once starts to recede. It does not stay at constant intensity even approximately for any large percentage of the time. Third, twice during every cycle of the alternator both tones are present simultaneously at the same intensity. Whether or not any or all of these items are seriously objectionable is difficult to say. The second item could probably be rectified by using condenser plates of different shape.

It is probable that the absolute values of sound energy as could be determined from the Rayleigh disc torques might be in error, in the first place, due to another torque from radiation pressure. The possibility of error from this cause can be obviated by repeating the measurements with the disc rotated through 90 deg. and the two sets of data averaged.[6] It was not thought necessary to take this precaution for the purposes of this experiment.

There is also the possibility of error due to reflections of sound waves from the walls of the compartment. Essentially this phenomenon may be thought of as sound waves approaching

[6] S. L. Quimby, "On the Experimental Determination of the Viscosity of Vibrating Solids," *Phys. Rev.*, 25, 558, 1925.

the disc from various directions. The result of such reflections may be either to increase or decrease the torque on the disc. Judging from the data of Watson,[7] it seems unlikely that much more than 25 per cent of the incident energy could be reflected. From the general nature of the Rayleigh disc calibration curves for various frequencies shown in Fig. 7 it would seem that no very prominent standing wave patterns existed in the sound compartment. Had they existed, the disc would of necessity have found itself in different parts of the pattern for different

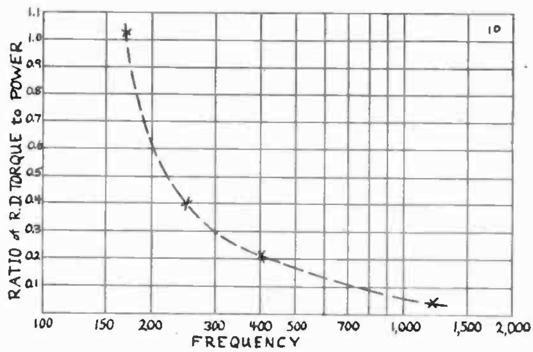

Fig. 14—Apparent Relative Efficiency of Loudspeaker.

frequencies. These curves do not indicate such an effect. It would seem that the value of the torques on the Rayleigh disc are at least dependable for relative values of intensity. We hope, however, to improve this feature for further measurements.

The principal source of error is probably traceable to the use of too small a power tube to feed the loudspeaker. This matter will also be taken care of in future measurements.

Utility of the Alternation Phonometer

In some respects this paper is in the nature of a preliminary report. However, its publication at this time seems warranted by the expectation that it describes a method applicable to loudspeaker measurements in laboratories with limited facilities for such measurements.

In many cases of practical work with loudspeakers the matter of relative efficiency at various frequencies is of more importance than actual efficiency of the speaker. It is therefore hoped that the work here described may suggest the possibility of making

[7] F. R. Watson, *Phys. Rev.*, 7, 125, 1916.

analyses of loudspeakers over a considerable frequency range in commercial work. For such work the Rayleigh disc could be omitted and only the wattmeter and the alternation phonometer used. For rough work the sound compartment could be omitted, but for more nearly reproducible results it will be found quite necessary.

Acknowledgment

The authors are indebted to Mr. L. C. F. Horle, of the Federal Radio Corporation, for advice and suggestions during the progress of this work.

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FACSIMILE PICTURE TRANSMISSION*

By
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(Research Laboratory, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Penna.)

Summary—*A facsimile picture transmitting system is described. The chief object of the design of this system was to produce a simple, rugged apparatus for practical usage, which would not require the attention of a skilled operator. The system does not require a special preparation of the original, and the receiver records the copy directly on the photographic paper.*

The usually delicate problem of photo-cell current amplification has been simplified to such an extent that only three stages of resistance coupled amplification suffice between the photo-cell and modulator of the broadcasting station. This was made possible through the design of a very efficient optical system, which supplies to the photo-cell quite enough light reflected from the picture even though only a small incandescent lamp for illumination is used.

The synchronizing and framing have also been simplified to such a degree that they do not require any special channels or special amplifiers.

Automatic starting devices obviate the use of any complicated scheme of signal dispatch for starting the apparatus. In spite of the simplicity of operation, it is capable of transmitting a 5 in. by 8 in. picture either in black and white or in half-tone in 48 seconds, or a message at the rate of 630 words per minute over short distances.

The resulting picture prints are of a quality quite satisfactory for newspaper reproduction and clear facsimile of messages may be made from typewritten originals.

Optical System

All the existing methods of electrical picture transmission can be divided into two classes: one which requires special preparation of the original before it can be transmitted, and the other which can transmit the original directly.

The first one includes the electrical contact method, now almost abandoned, which requires the preparation of the original in such a form that the dark and light of the picture give variable electrical resistance when explored by a traveling contact.

In another form of transmitter of the same class, as in the Belin system, which is still in commercial use in France, the picture is embossed with a special ink so that it may be reproduced by a microphone in the same way as an electrical pick-up reproduces phonograph records.

The method which requires the preparation of a transparent picture either in negative or in positive form belongs also to

* Dewey decimal classification: R582. Original manuscript received by the Institute, November 24, 1928. Presented before New York meeting of the Institute, January 2, 1929.

the same class.[1] In this case the picture is explored by a sharply defined pencil of light which passes through it and activates a photo-cell placed behind it. The variation in optical density produces a corresponding variation in absorption of the light, and therefore the photo-cell delivers an electric current varying according to the picture.

The present requirement of high-speed transmission, however, rules out all these methods due to the time necessary for preparation of specially treated originals. In this case only one solution remains, and this is the scanning of the original by a pencil of light and the utilization of the light reflected from its surface. The amount of reflected light is directly dependent on the density of the picture or lettering. The specular reflection

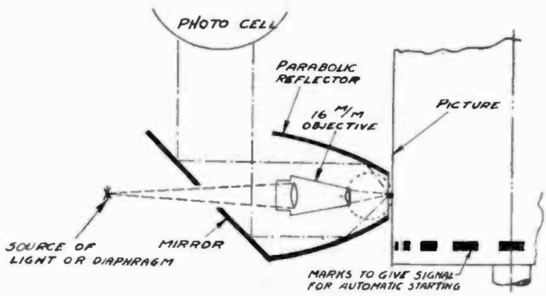

Fig. 1—Optical System of the Picture Machine.

from the surface of the paper is negligible and equal at all points on the paper, and therefore does not interfere with the reflecting scanning method. However, difficulties arise in the optical part of the problem due to the small amount of light reflected. This necessitates the utmost care in the design of a very efficient optical system.

Here again are two possible solutions of the problem. One is the illumination of the original by strong diffused or concentrated light and cutting off from the illuminated area a small, sharply defined spot. The light from this spot is directed into a photo-cell. In this case the optical efficiency is determined first by the ratio of the size of the scanning spot to that of the total illuminated area, and by the light-gathering power of the optical lens. In general, in spite of all the precautions, the over-all optical efficiency of this method is quite low.

[1] This method is still in general use and, a few years ago, was the only optical method employed.

The second method, which is used in this transmitter, is inverse to the first one. In this case the size of the scanning spot is adjusted to the required dimension and the reflected light is collected. Fig. 1 gives an idea of the arrangement. The source

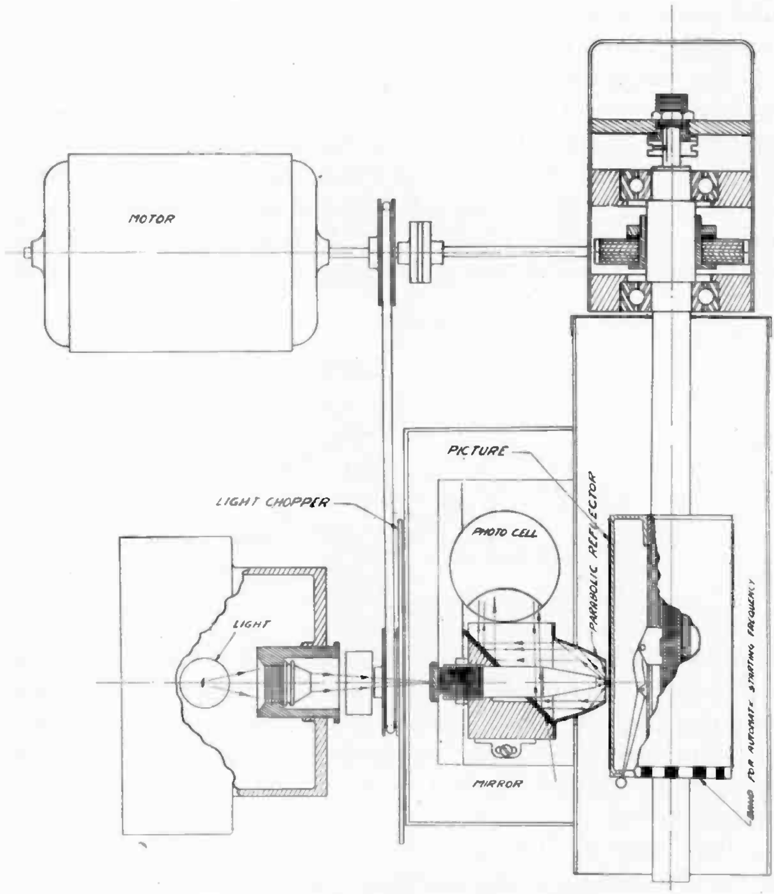

Fig. 2—Facsimile Picture Transmitter.

of light is focused first on a diaphragm to make the size of the spot independent of the size of the source. The image of the diaphragm, with necessary reduction, is focused on the surface of the picture. The reflected light is gathered by means of the parabolic reflector, the focus of which coincides with the illuminating point. Part of the reflector is cut away in order to pass the light, and the remaining part is brought into close proximity to the surface of the picture. In this case almost all the reflected light is collected and projected as a more or less parallel beam by the reflector. A plane mirror with a small hole for passage of the illuminating spot intercepts the reflected light at 45 degrees and diverts it to the photo-cell. The optical path of the whole system is quite short and the construction is flexible for adaption to almost all kinds of scanning systems. The over-all optical

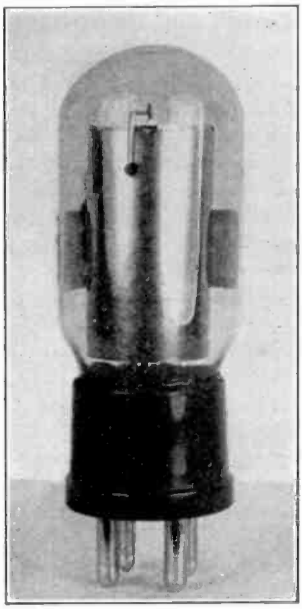

Fig. 3—Glow Tube.

efficiency is many times greater than the best possible solution by the first method.

Scanning Arrangement

In the present article only the intermittent type transmitter, i.e., the type in which it is necessary to stop the machine after every picture for reloading, is described. Although this type is not very suitable for commercial purposes, it has many advantages for experimental work and also for all kinds of communication where traffic requirements are not very high.

In this type, the picture to be sent is in the shape of a 5 in. by 8 in. rectangle and is wrapped around a cylinder which is placed on the shaft as shown in Fig. 2. The shaft is hollow and has a screw inside which can be locked either to the shaft or to the support. The cylinder has a locking nut, which, by means of a lever, can be raised or lowered, locking the cylinder with the shaft and screw. While the screw is connected to the shaft, the cylinder rotates with it, but remains stationary in longitudinal direction. When the picture is ready for transmission, the screw is released from the shaft and locked to the support by means of an electromagnetic clutch. This makes the screw stationary in respect to the rotating nut and the cylinder begins to advance,

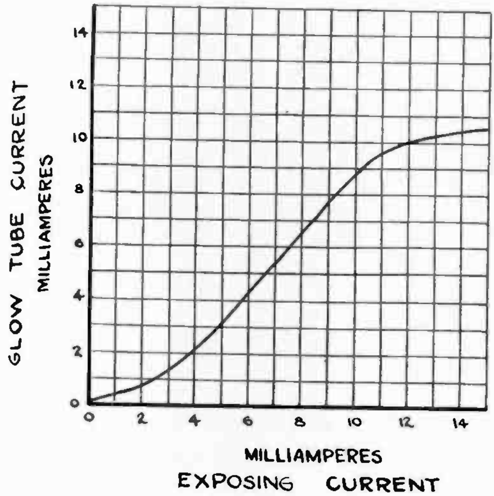

Fig. 4—Fidelity Curve.

exposing gradually the whole surface to the scanning spot. The speed of scanning is 56 in. per second, while that of the cylinder feed is 1/64 in. per revolution, so that 52.5 sq. in. of the picture are covered per minute. Allowing, as usual, 12 words per sq. in., the rate of transmission amounts to 630 words per minute. The 1/64 in. picture feed was found very satisfactory for typewritten messages and for most other pictures.

Care, of course, is taken to move the cylinder with uniform speed in order to avoid distortion of the picture.

Mechanically, the receiver is identical with the transmitter. A standard bromide photographic paper 5 in. by 8 in. size is wrapped around the cylinder and the recording is done by means of a glow discharge tube. Fig. 3 shows the type of glow tube used for this purpose. It was developed by Mr. Knowles in the

Westinghouse Laboratory and uses helium glow for recording. The glow is restricted to the required size by a mask built into the tube. A discharge of approximately 15 milliamperes at 400 volts is sufficient at the present speed to produce very satisfactory blackening on the bromide paper.

Fig. 4 shows the fidelity curve for the whole transmitting process. Along the axis of abscissas is plotted the current through the glow tube. The bromide paper is exposed to this glow at working speed and is developed in the usual manner. The "density chart" prepared in this manner is put into the trans-

Fig. 5—Photo Cell.

mitter, and the output of the amplifier is plotted along the axis of ordinates. The curve, therefore, represents the true relation between the densities of the original and of the reproduced copy.

This relation shows good proportionality from 2 to 12 milliamperes, which ratio usually is maintained for transmission of half tone pictures. For white and black manuscripts it is preferable to sacrifice the proportionality and work further along the characteristic curve in order to produce sharper contrast.

For a highly efficient commercial transmitter, the intermittent type is not suitable, due to loss of time required for reloading. Another machine of continuous type has been developed for this purpose. Although the principle and even the optical system remains the same, the relative motion of the paper with respect to the scanning light is changed, and this in turn changes the whole appearance of the apparatus. The reflected light is conveyed by plane mirrors along the axis into a photo-cell, which remains stationary.

Photo Cell

Fig. 5 shows a photo-cell used in the picture transmitter. It is of magnesium-caesium type, filled with argon. It consists of two electrodes, one on the inner surface of the glass bulb and another in the shape of a ring in the center of the bulb. A window is provided in the coating for admittance of the light. The coating is photo-sensitive; i.e., it emits electrons at a rate

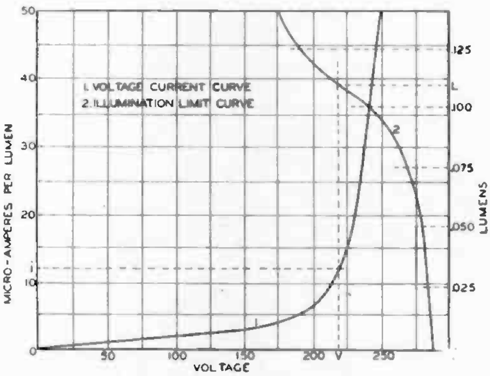

Fig. 6—Characteristics of Gas-Filled Photo-Electric Cell.

proportional to the quantity of light absorbed by the coating. These electrons flow to the anode under the accelerating potential of an outside battery. During this passage they collide with the molecules of the argon, and since their velocity-voltage is higher than the ionizing potential of the argon, ionization occurs. Thus the output of the cell is increased many times without destroying the proportionality between the quantity of light absorbed by the photo-cell and the output of the cell. Fig. 6 shows the relation between the voltage applied to the cell and its output calculated in microamperes per lumen. The second curve on the same figure gives an idea of the safe operation of the cell for various voltages and degrees of illumination.

Amplifier

Since the photo-cell, under operating conditions, supplies a current of the order of 1/20 of a microampere for the white portion of the picture, a strong amplification is necessary before the output of the cell can be used for radio transmission.

The requirements for the amplifier are quite severe. It should not distort the signals and should not have a tendency to oscillate, which results in distortion of the picture.

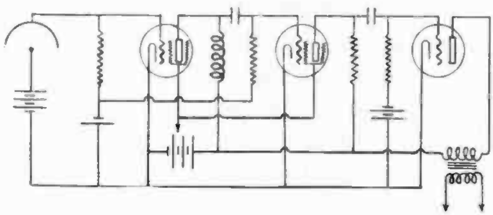

Fig. 7—Photo-Cell Amplifier.

In actual cases we used screen-grid tubes and the circuit as shown in Fig. 7. Voltage output of the third tube is about 40 volts, which is quite sufficient to operate the modulator of the broadcasting station through a line of considerable length. Fig. 8 shows an oscillograph actually received from the picture signals.

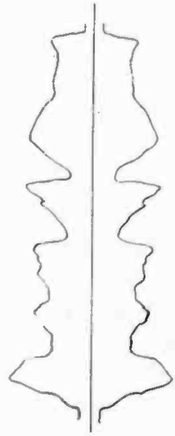

Fig. 8—Envelope of Signal Current.

Receiver and Amplifier

For the reception of the picture signals, the radio set may be a standard receiver. The amplification, in the case of weak signals, is preferably at radio frequency in so far as possible, in order to reduce distortion. Transformer-coupled audio-frequency amplification, however, gives very good results if the gain is fairly uniform between 2000 and 4000 cycles. To date, a standard R.C.A. short-wave receiver has been used for all work. This employs a stage of radio-frequency amplification with a screen-grid tube, detector, and two audio stages.

Control of Glow Tube

For the control of the glow tube which exposes the photographic paper, a vacuum tube is used. The glow tube is connected in series with the plate voltage for the vacuum tube. Fluctuations in voltage upon the grid due to the picture signal produce corresponding variations in the glow tube current. If the signal as it comes from the audio amplifier were applied

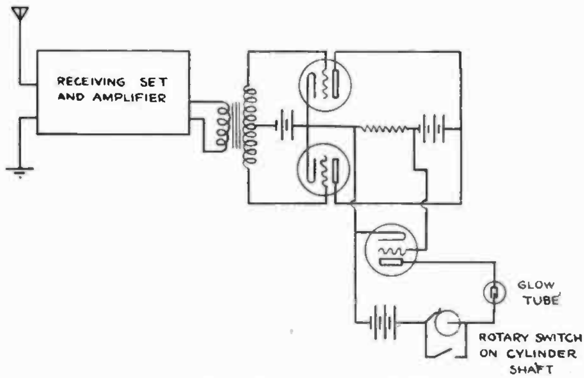

Fig. 9—Glow Tube Control Circuit.

directly to the grid of the control tube, a negative picture would result. That this is true can be verified by following the steps in the transmission of the picture. When the light is reflected from a white area in the original picture, a relatively large amount reaches the photo-cell. The corresponding photo-cell current is amplified, producing a loud signal. At the receiving end this signal would increase the average plate current of a tube working on the lower bend of the characteristic curve. Such an increase would augment the light from the glow tube, darkening the photographic paper instead of making it lighter.

Unless the picture is to be recorded upon a film, and subsequent prints are to be made, it is necessary to reverse the process. This reversal might take place at the transmitter, but is undesirable for pictures which are largely white, as printing, for example. Bursts of static would be recorded as black spots on the white background. On the other hand, if the reversal occurs at the receiver, these disturbances tend only to make the white whiter. Hence, reversal at the receiver is used.

The circuit employed for the control of the glow tube is shown in Fig. 9. Voltage from the receiving set is applied to the push-pull detector, using UX-112 tubes. These are so biased as to give practically zero plate current in the absence of signal. Any voltage supplied causes, on either the positive or negative half of the cycle, a voltage drop across the plate resistor. This

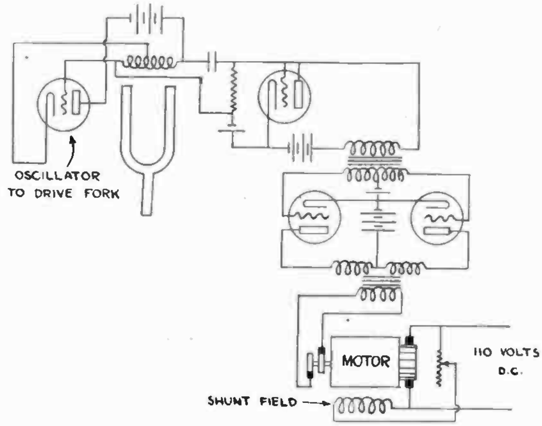

Fig. 10—Synchronizing System.

voltage drop is impressed on the grid of the control tube, decreasing the glow tube current in the case of a strong picture signal.

Synchronizing

The problem of synchronizing transmitter and receiver is of great importance, particularly for high speed transmission. The plan of broadcasting a standard frequency by a series of stations scattered throughout the world is one of considerable merit, but has not yet been adopted. The use of voltage from interconnected power lines has been proposed, but is impractical in the general case, since the phase relations between ends of the system are too variable to permit high speed transmission. It is necessary, then, to do one of three things: (1) provide independent, accurate sources of frequency for transmitter and receiver, or (2) send a synchronizing signal continuously to the receiver, or (3) correct periodically a less accurate source of frequency at the receiver by an impulse from the transmitter. The third method is the one used.

The source of frequency at both transmitter and receiver is a 70-cycle tuning fork in a constant temperature box. These forks are so adjusted that there is but one beat between them in 20 seconds or more; this condition is relatively easy to maintain. The fork at the receiving machine is then corrected every revolution of the picture cylinder (every seventh of a second) by an impulse of about one-half cycle duration. This impulse is transmitted over the same channel as the picture, but on the margin of the paper to avoid interference with picture signals.

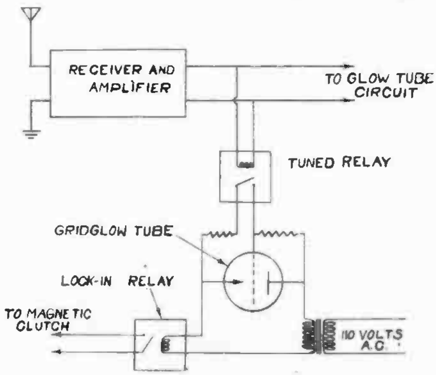

Fig. 11—Automatic Starting Arrangement.

Having obtained the standard frequency, the next step is to use it most advantageously in the control of the motors. To amplify a small amount of energy to such a degree that it could supply the full load of the machine would be wasteful. It is common practice at the present time to use two motors on the same shaft—one to furnish most of the torque, and one to keep the speed constant. In the present arrangement, the two machines are combined into one, similar to a rotary converter. Voltage from the tuning fork is amplified, using two UX-250 tubes in the final stage. The power from these tubes is applied to the motor slip rings, while most of the energy comes from the direct-current source. Fig. 10 shows the schematic diagram of the synchronizing circuit.

Framing of Picture

It is not enough that the cylinders on both transmitter and receiver rotate at exactly the same speed; the picture must be framed as well. In other words, the first edge of the picture being sent should be under the spot of light at the transmitter at the same instant that the first edge of the photographic paper is being exposed by the glow tube at the receiver.

The framing is accomplished by the following method. The picture to be transmitted is held on the cylinder by a longitudinal

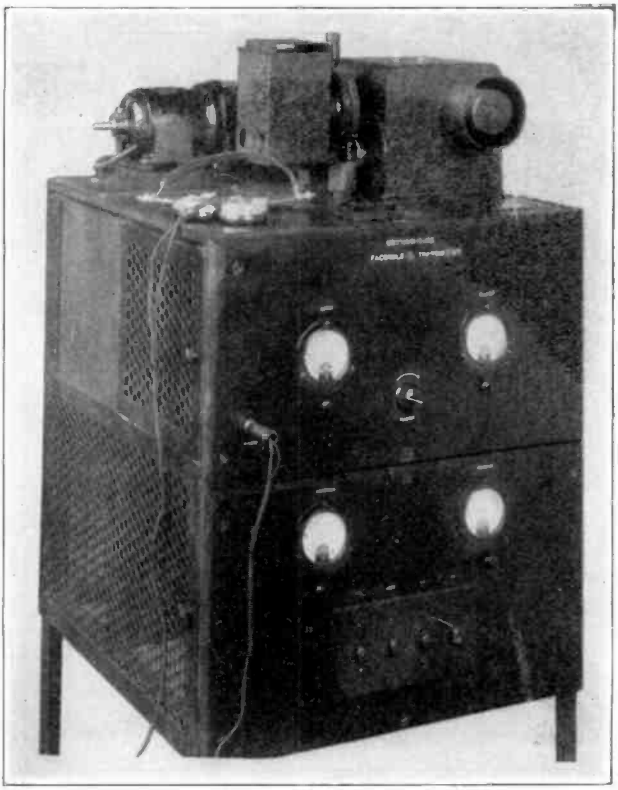

Fig. 12

black band; at the end of the cylinder first transmitted is a narrow white ring. As the light spot explores this ring, a continuous signal is transmitted except for the interval when the black band is absorbing most of the light. The glow tube at the receiver flashes once for each time the black band occurs, or seven times per second. At the end of the shaft upon which the receiving cylinder rotates is an interrupter which breaks the glow tube current for a time equal to that required for the transmission of the band. If the interruption takes place at the same time the flash normally occurs, the light from the glow tube appears steady, and framing is known to be correct. If the flashes are seen, however, it is necessary to correct the relative position of the glow tube with respect to the position of the cylinder at a given instant. This is done by a process equivalent to rotating the frame of the motor.

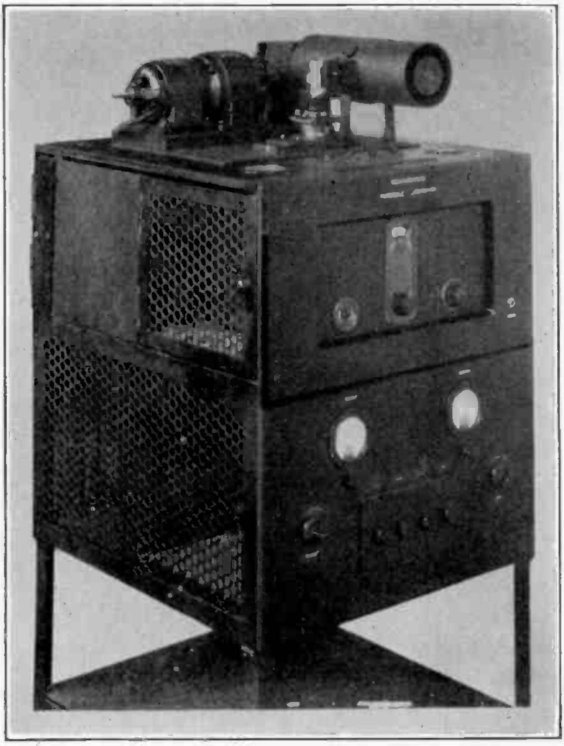

Fig. 13

The framing process described above is carried out for each picture transmitted by the intermittent machine, since the framing is lost when the motors are stopped. In the continuous machine the motors run constantly, hence framing is required only at the beginning of transmission.

Starting of the Receiver

When synchronizing and framing is accomplished the picture starts to pass under the transmitter's scanning spot. The starting of the receiving cylinder is accomplished automatically. The principle of operation of this starter is as follows: On the front end of the transmitting cylinder a band of black and white spots is engraved. This can be seen on Fig. 1. When the picture is started, this band comes first under the scanning spot. As a result, the corresponding frequency is produced by the transmitter and reproduced by the receiving amplifier. This frequency operates a small tuned relay, Fig. 11, which in turn starts a grid glow tube.[2] The current passing through the grid glow tube operates a lock-in relay which completes the circuit

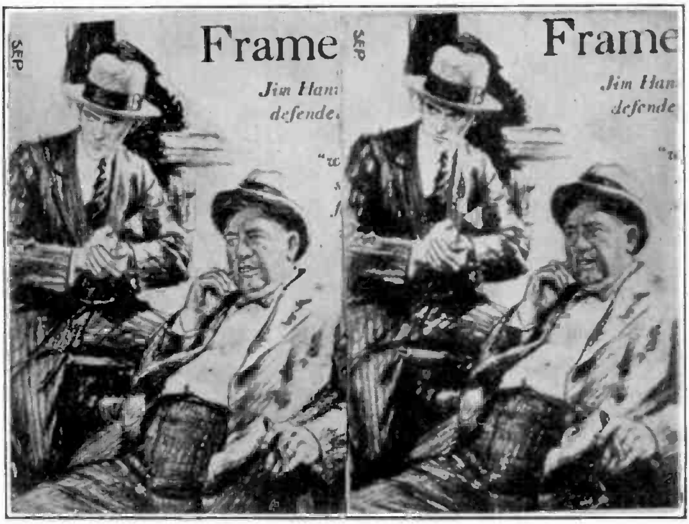

Fig. 14

to the magnetic clutch; this starts the receiving cylinder. The starter does not require any additional equipment at the transmitter, nor at the broadcasting station.

Assembled Machines and Results Obtained

Figs. 12 and 13 show the finished appearance of the intermittent type of transmitter and receiver, respectively. Both machines are self-contained, including all the amplifiers, rectifiers, and tuning forks. In size, the cabinets are two ft. square by four ft. high. The transmitter could be installed at any convenient place connected with the broadcasting station by

[2] See description of grid glow tube by Knowles, *Elec. Jour.*, April, 1928.

means of a telephone line. The receiver should be placed either in a dark room or adjacent to a small developing booth. With the exception of the darkening of the end of the receiving machine for handling the bromide paper, no other precautions are required in the illumination of rooms where both machines are located. In Fig. 14 are shown side by side an original picture and the facsimile transmitted over a short telephone line and a few miles of radio channel.

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NOTES ON GRID-CIRCUIT DETECTION*

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Summary—*A dynamic method of finding $\partial^2 i_g/\partial e_g^2$ or $\partial k_g/\partial e_g$, the main term in grid-circuit rectification, is given. This method is based upon formulas given by Chaffee and Browning*[1] *and consists in calculating $\partial k_g/\partial e_g$ from the change of d.c. when a known a.c. input voltage is applied to the grid. The values of $\partial k_g/\partial e_g$ found by the dynamic method are compared with the values found by the usual method. The effect of frequency, internal grid resistance, and external resistance on the detection voltage introduced in the plate circuit are also considered. An experimentally determined curve is given showing the detector frequency distortion of a commercial set for a 2-megohm grid leak and for a ½-megohm grid leak.*

THE subject of detection has been covered from the theoretical side in two excellent articles. The article by Chaffee and Browning[1] gave a comprehensive theoretical treatment of detection together with a bridge method of experimentally determining the detection coefficient. The article by Llewellyn[2] covered the general theory of vacuum-tube operation. The theory in the above article was complete and the equations were applied in some detail to grid-leak detectors. An article by Smith[3] gave a good physical picture of grid rectification as far as the grid circuit itself was concerned.

The main difficulty in using the theoretical analysis as given by the first two mentioned articles is in determining the second derivatives of the currents with respect to the voltages over the range of input voltages applied to the detector. To determine these derivatives it is necessary to plot the conductance curve from the static characteristic curve, then plot another curve from the conductance curve. There is also the uncertainty of whether the dynamic value will correspond with the static value found graphically. If the values of the second derivatives

* Dewey decimal classification: R134. Original manuscript received by the Institute, November 14, 1928.

[1] E. L. Chaffee and G. H. Browning, "A Theoretical and Experimental Investigation of Detection for Small Signals," Proc. I. R. E., 15, 113; February, 1927.

[2] F. B. Llewellyn, "Operation of Thermionic Vacuum Tube Circuits," *Bell System Tech. Jour.* 5, 433; July, 1926.

[3] Lloyd P. Smith, "Theory of Detection in a High Vacuum Thermionic Tube," Proc. I. R. E., 14, 649; October, 1926.

could be found by some simple means for the desired value of input voltage the usefulness of the theory would be increased.

The theory itself could be checked and the range over which the theory holds could also be found. Different types of tubes could be compared easily as the main terms in both plate and grid rectification are the second derivatives of the currents with respect to the voltages.

It is the purpose of this article to show that the value of the second derivative of the grid current with respect to the grid voltage, the main term in grid rectification, may be found by the change in direct current in the grid circuit with any de-

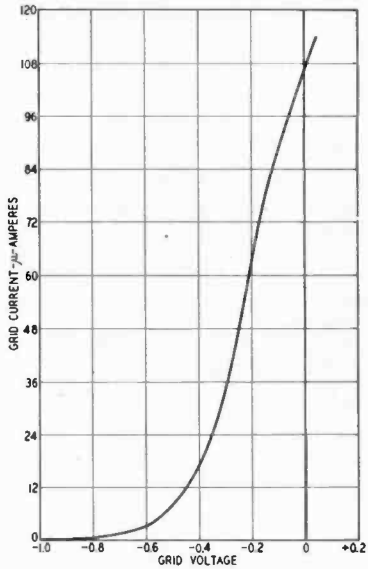

Fig. 1—Grid-Current Grid-Voltage Characteristics; Typical C-327 Tube.
Eb—45 v.
Ef—2.5 v.

sired value of input voltage. The results are also a check on the theory. In another article the author[4] shows how the value of the second derivative of the plate current with respect to the grid voltage, the main term in bias detection, may be found when the input voltage is fairly large.

A sensitive direct-current meter with a full scale reading of about five microamperes is required. Good accuracy may

[4] J. R. Nelson, "Detection with the Four Element Tube," Proc. I. R. E., 16, 822; June, 1928.

be obtained by balancing out the direct current if it is more than three or four microamperes. There is no difficulty in using a meter of this type in the grid circuit, but it is difficult to keep the plate current constant enough to use it in the plate circuit of a three-element tube. Chaffee and Browning[5] give the following formulas for the increment of direct current.

$$\overline{\Delta^2 I_g} = \frac{\overline{\Delta^2 E_g}}{r_g} + \frac{1}{4}(\Delta E_g)^2 \quad \frac{\partial K_g}{\partial e_g} \tag{1}$$

Where

$\overline{\Delta^2 I_g}$ = The increment of direct current
$\overline{\Delta^2 E_g}$ = The increment of steady voltage
$\underline{\Delta E_g}$ = The maximum value of input voltage
r_g = Grid resistance
K_g = Grid conductance
$\overline{R}$ = Resistance to a steady current

$$\overline{\Delta^2 E_g} = -\overline{R}\Delta^2 I_g \tag{2}$$

$$\overline{\Delta^2 I_g} \times (r_g \overline{R}) = \frac{r_g}{4}\frac{\partial K_g}{\partial e_g}\underline{(\Delta E_g)}^2 \tag{3}$$

$$\overline{\Delta^2 I_g} = \frac{r_g}{r_g + \overline{R}}\ \frac{1}{4}\underline{(\Delta E_g)}^2 \frac{\partial K_g}{\partial e_g} \tag{4}$$

$$\frac{\partial K_g}{\partial e_g} = \frac{4\overline{\Delta^2 I_g}}{\underline{(\Delta E_g)}^2}\ \frac{r_g + \overline{R}}{r_g}. \tag{5}$$

If the d.c. resistance is small compared to r_g Eq. (5) reduces to

$$\frac{\partial K_g}{\partial e_g} = 4\frac{\overline{\Delta^2 I_g}}{\underline{(\Delta^2 E_g)}^2}. \tag{6}$$

Fig. 1 shows the grid-current grid-voltage characteristic of a typical C-327 tube with $Eb = 45$ volts and $Ef = 2.5$ volts. The curve is steeper than the curves obtained with other types of tubes such as the CX-301 A, CX-340, etc. The tangents are difficult to obtain accurately, but it was felt that if the theory could be checked using this type of tube the method of determining $\partial K_g/\partial e_g$ by the change in direct current could be applied to other types of tubes without the necessity of checking the values graphically.

[5] Loc. cit., page 129.

Fig. 2 shows the grid conductance, $\partial i_g/\partial e_g$ of the typical C-327 tube, plotted against the grid voltage over the range which is of most interest. This curve was obtained from Fig. 1 by finding the tangent $\Delta i_g/\Delta e_g$ at the different values of grid voltages, then plotting the values of tangents against the grid voltages. Fig. 3A shows $\partial K_g/\partial e_g$ or $\partial^2 i_g/\partial e_g^2$ plotted against the grid voltage. This curve was determined from Fig. 2 by finding the values of $\Delta K_g/\Delta e_g$ at the different grid voltages.

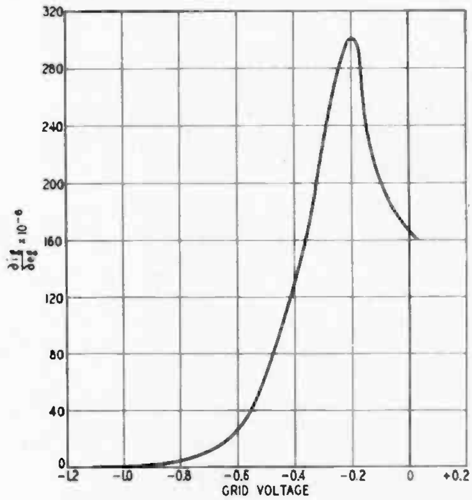

Fig. 2—Grid Conductance, $\partial i_g/\partial e_g$, of Typical C-327 Tube.
Eb—45 v.
Ef—2.5 v.

This is the usual method of determining the value of $\partial K_g/\partial e_g$ or $\partial^2 i_g/\partial e_g^2$. If the values of $\partial K_g/\partial e_g$ found from the change of direct current as explained below check the values of $\partial K_g/\partial e_g$ found from the static characteristic as explained above, the assumptions made in developing the theory are justified.

Fig. 4 shows the circuit used to determine the values of $\partial K_g/\partial e_g$ at different operating voltages. Alternating current from the source flows through the meter A_2 and the resistance R. The value of R was less than 10 ohms so that the input voltage is equal to the product of the reading of A_2 and R. No load is shown in the plate of the C-327, but if desired the normal load may be placed in the plate circuit. The a. c. source may be either radio frequency or audio frequency, as the theory is independent of the frequency of ΔE_g. If a specific case is being investigated by placing a load in the plate circuit the input voltage should be radio frequency so as to take into account the input impedance of the detector at radio frequency.

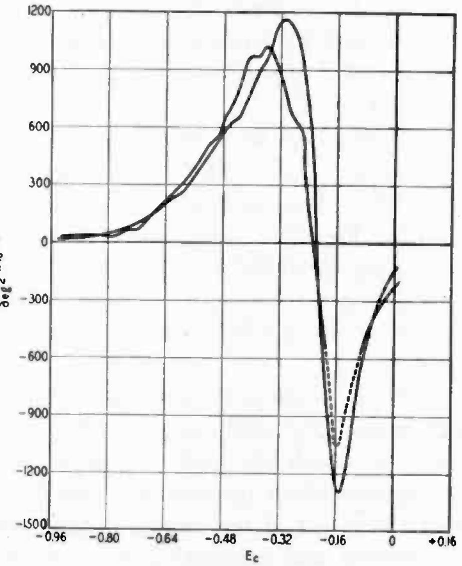

Fig. 3—Variation of Grid Conductance, $\partial K_g/\partial e_g$, of Typical C-327 Tube.
Eb—45 v.
Ef—2.5 v.

The meter A_1 had a resistance of about 5000 ohms so that it was necessary to use Eq. (5). The value of r_g was determined from Fig. 2. The meter A_1 was shorted for a.c. with a large con-

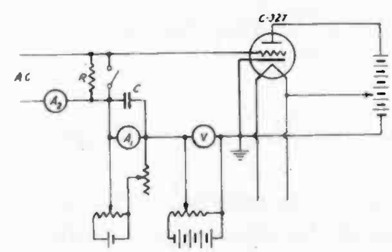

Fig. 4

denser so that it was not necessary to correct for ΔE_g. After the grid current was above five microamperes it was balanced out. The resistance of the balancing out circuit was high, so that it was not necessary to correct the increment of d.c. as read on A_1.

The d.c. was balanced out of A_1 and R was shorted out. The peak volume of a.c. across R was kept constant at 0.035 volt. The short circuiting switch around R was then opened, and the increment of d.c. was read on A_1. This was repeated for different values of E_c.

The values of $\partial^2 i_g/\partial e_g^2$ were then calculated from Eq. (5) for the different values of E_c. The values thus found are shown plotted in Fig. 3B. The agreement is good considering the difficulty of finding Fig. 3B. The peaks are separated less than the total grid swing, $2\times 0.035=0.07$ volt. The dotted portion of B is estimated, as no accurate voltage between -0.1 and -0.2 of a volt could be determined with the one-volt thermo-voltmeter used.

The curves of Fig. 3 do not show where the point of maximum detector sensitivity will occur. They show only the value of voltage to which the grid should be biased to obtain the maximum current when the external grid circuit is shorted. In determining the point of maximum voltage on the grid the values of the internal and external grid impedances as well as the value of $\partial K_g/\partial e_g$ have to be taken into account.

Chaffee and Browning[6] give the following equation for the voltage introduced in the plate circuit.

$$(\text{Det. E})_l=\frac{r_p}{4}\left[-\frac{R_1}{\sqrt{R_1^2C_1^2w^2+1+R_1K_g(2+R_1K_g)}}g_m\frac{\partial K_g}{\partial e_g}+\frac{\partial g_m}{\partial e_g}\right]B\sqrt{2}m(\Delta E_0)^2 \tag{7}$$

where

(Det. E)$_l$ is the audio-frequency voltage introduced in the plate circuit.

R_1 is the value of the external grid resistor.

C_1 is the value of the external grid condenser.

Eq. (7) neglects the effect of the input conductance not due to the electron flow and the input capacity of the tube at

[6] Loc. cit., page 142. Note: If the part due to bias rectification is neglected the same equation may be obtained from Eq. (43), page 448 of the article by F. B. Llewellyn, "Operation of Thermionic Vacuum Tube Circuits," *Bell System Tech. Jour.* 5, No. 3; July, 1926.

audio frequencies. If it is desired to take the above factors into account the article of Ballantine[7] may be consulted.

The voltage introduced in the plate circuit given by (7) may be used as μe_g in the usual amplifier equations, and the value of the voltage across the external plate impedance found as soon as its value is known.

The usual method of using a heater type of tube such as the C-327 for grid-circuit detection is to return the grid to the

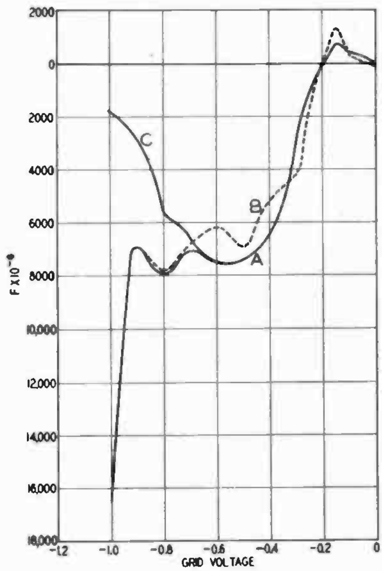

Fig. 5

$$F=\left[-\frac{R_1}{\sqrt{R_1{}^2\omega^2C_1{}^2+1+R_1K_g(2+R_1K_g)}}g_m\frac{\partial K_g}{\partial e_g}+\frac{\partial g_m}{\partial e_g}\right.$$

$C_1=250$ $\mu\mu$f.

A—Dynamic Value of *F* Zero Frequency
B—Static Value of *F* Zero Frequency
C—Dynamic Value of *F* 3000 cycles

cathode which is at zero potential. The grid may be returned to any other part of the *B* or *C* supply. It might be of advantage in this type of tube to return the grid to some point of the *B* supply which is at a small positive potential above the cathode. A larger value of grid leak could then be used to pass through some desirable operating point than if the grid is returned to

[7] Stuart Ballantine, "Detection by Grid Rectification," Proc. I. R. E., 16, 593; May, 1928.

the cathode. In this investigation it was decided to return the grid to the cathode and try various values of R_1.

Fig. 5A and 5B shows the part of (7) in parenthesis plotted for different values of R_1 returned to the cathode. The curves were plotted by finding from Fig. 1 the required values of R_1 to pass through, zero and different values of E_c. The value of K_g was then found from Fig. 2. A and B were plotted for zero frequency. The presence of the grid condenser causes frequency distortion. Fig. 5C shows curve A when the audio frequency is 3000 cycles and C is $250 \mu\mu$f. There is quite serious frequency distortion if R_1 is chosen so that it intersects I_g in Fig. 1 at more than 0.7 volt negative.

The mutual conductance for this tube is shown in Fig. 6 and the values of $\partial g_m/\partial e_g$, the main term in plate rectification, are shown plotted in Fig. 7A and 7B. Their effect in changing (Det. E)$_l$ is small over most of the range. The agreement is

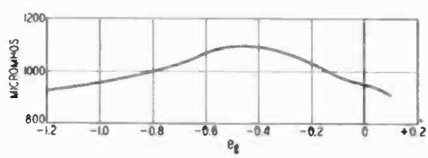

Fig. 6—Mutual Conductance, g_m, of Typical C-327 Tube.
Eb—45 v.
Ef—2.5 v.

not very good between the static and dynamic values. The plate current would change several microamperes making it difficult to obtain the true change in direct current when a signal was applied to the grid.

The dropping off of the mutual conductance as shown by Fig. 6 occurs at a small negative potential. In the usual type of tube the mutual conductance curve straightens out at about 2.5 volts positive, or near the potential of the filament center.

The frequency distortion of this tube used in a popular radio set was checked experimentally for two values of grid leaks 2.0 megohms, the grid leak furnished with the set, and 0.5-megohm grid leak. The set uses a push-pull stage for the last audio stage. The frequency distortion was determined experimentally by the method shown by Ballantine.[7] Briefly this consists of determining the audio amplification from the grid of the detector to the grid of the last tube with the plate load or speaker in place. The input is then placed in series with the grid leak with the low side grounded. Because of the shape of the mutual conductance curve it was found to be necessary to modify Ballantine's method slightly. Instead of shorting the grid leak R to determine the audio amplification it was bypassed with a large condenser. This keeps the same bias on the tube for both measurements. This is important if the mutual conductance changes much from the operating

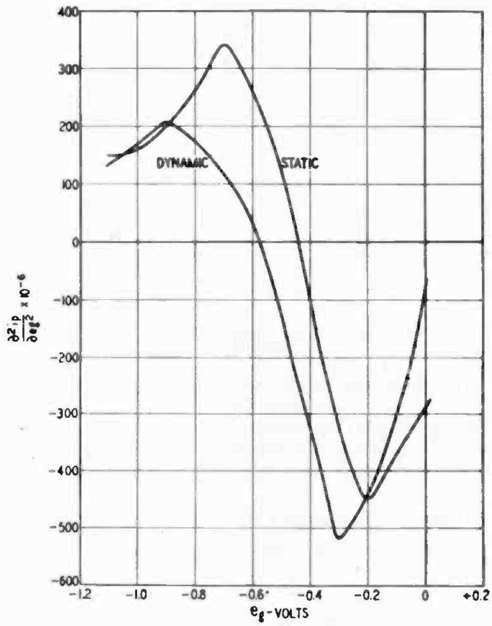

Fig. 7—Variation of Mutual Conductance, $\partial g_m/\partial e_g$, of Typical C-327 Tube.
Eb—45 v.
Ef—2.5 v.
A—Static Value
B—Dynamic Value

point to zero bias. After the two curves were determined experimentally the factor to bring them together at a low frequency, in this case 60 cycles, was determined. The values of the curve determined by the input being in series with the grid leak were then multiplied by this factor. The difference between the values at the higher frequency represents the loss caused by frequency distortion of the detector.

Curve A of Fig. 8 shows the audio amplification from the grid of the detector up to the grid of one tube of the push-pull stage determined as shown above. Fig. 8B shows the curve obtained by placing the input in series with the grid leak after the two curves are brought together at 60 cycles. The grid leak used in this case is the 2.0-megohm grid leak furnished with the set. Fig. 8C shows the same curve after a $\frac{1}{2}$-megohm grid leak was substituted for the 2.0-megohm grid leak. The loss in amplification due to the frequency distortion of the detector is somewhat greater than that shown by C and B of Fig. 5 at 3000

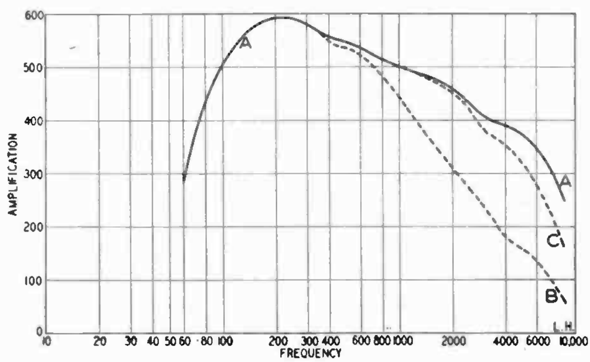

Fig. 8—Audio Amplification and Detector Frequency Distortion of a Commercial Set.
A—Amplification grid of detector to grid second audio tube.
B—Detector frequency distortion with 2.0-megohm grid leak.
C—Detector frequency distortion with 0.5-megohm grid leak.

cycles. This difference is caused by the input capacity of the tube at audio frequencies, which was neglected in calculating B of Fig. 5.

The method of determining the values of $\partial K_g/\partial e_g$ at different grid voltages by the change in direct current offers a simple and accurate means of evaluating this factor. The results bear out the theory for small input voltages. No attempt was made to find the range of input voltages over which the theory would hold.

The value of grid leak should be chosen to fit the type of tube used and the values of d.c. voltages used on it. A and C of Fig. 5 show graphically the range of grid voltage over which the detector will be most sensitive as far as grid detection is concerned, considering both low and high frequency. For example, according to these curves the detector sensitivity would be about the same from -0.4 to -0.7 volt; above -0.7 volt detector frequency distortion becomes serious.

There is another factor to consider also. The conductance at -0.4 volt is 130×10^{-6} mhos and at -0.7 volt it is about 10×10^{-6} mhos. The value of -0.7 volt would be preferable to use as the selectivity of the circuit preceding the detector would be very poor with 130×10^{-6} mhos shunted across it. The value of grid leak to use may be found from the static characteristic of Fig. 1 as soon as the operating point is found from Fig. 5.

The experimentally determined curves of Fig. 8 bear out the theoretical considerations that the grid leak should be chosen to match the tube characteristics. The grid leak should be as high a value as possible considering only the radio-frequency tuned circuit preceding the detector. The value of the grid leak should be as low as possible considering frequency distortion of the detector. Some value in between will be the best compromise. In the tube analyzed a value of resistance that would bias the tube at about -0.7 volt would be the best to use.

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THE RADIATION RESISTANCE OF BEAM ANTENNAS*

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Summary—*In this paper a new method proposed by Brillouin for the calculation of radiation resistance is applied to several types of beam antennas. New formulas are deduced and some interesting results are obtained showing the distribution of the radiated power among the different wires of beam antennas and giving the numerical value of the radiation resistance in various cases (synphase antenna, antiphase antenna, Marconi three-stage antenna). The radiation resistance in the presence of a perfect conducting plane is also considered. A table of values of the components of radiation resistance is added to the paper for practical use.*

There are two methods of computing the power radiated by an antenna. In the first we calculate the Poynting-vector for each point of space and integrate the normal energy flow through any surface enclosing the antenna. This method might be called the Poynting-vector method, and has been used in the well known works of G. W. Pierce,[1] B. van der Pol,[2] S. Ballantine,[3] M. A. Bontsch-Bruewitsch,[4] and S. Levin and C. Young.[5] It may be noticed that we cannot by this method obtain the contributions to the radiated power of different parts of the antenna, which it is sometimes desirable to know when dealing with some practical cases.

The other method is based upon the study of the emfs induced in the antenna by the currents in the wires of which the antenna is constructed. Let AB (Fig. 1) be a wire in which flows a current of frequency f and assume that the distributions of the current and of the charges in the wire are known. We may then calculate the electric force in each point M of the space. It depends upon the combined action at this point of all elements of the wire. In particular we may take the point M_0 to lie in the surface of the wire itself and calculate the emf due to the electromagnetic field of the wire. If we assume the action at a distance of the current to be instantaneous, this emf would

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[1] G. W. Pierce, *Proc.* Amer. Acad. 52, 192, 1916.
[2] Balth. van der Pol, Jr., *Proc.* Phys. Soc. of London, 13, 217, 1917.
[3] Stuart Ballantine, Proc. I. R. E., 12, 823, 1924; 15, 245, 1927.
[4] M. A. Bontsch-Bruewitsch, *Annalen der Physik*, 81, 425, 1926.
[5] S. A. Levin and C. J. Young, Proc. I. R. E., 14, 675, 1926.

be a purely reactive one and we may speak of it as arising from the capacity or the inductance of the wire. If the wire is of a length comparable with that of the electromagnetic wave we must take into account the propagation velocity of the field. Then at a moment t there will act in the point M the current and the charge which have existed at the element dx_1 at the earlier moment $\left(t-\frac{r_1}{c}\right)$, r_1 being the distance of the point from dx_1, and c the light-velocity. Similarly for the element dx_2 we must use the values of current and charge existing at the earlier moment $\left(t-\frac{r_2}{c}\right)$. Under these conditions the calculated emf (or, strictly speaking, the corresponding potential drop) will have a watt component which may be called the radiation emf.

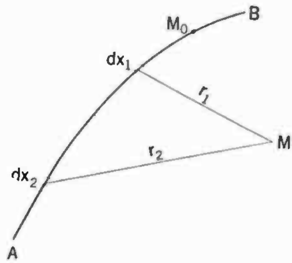

Fig. 1

The product of this emf and the current in an element of the wire gives the radiation from the element. We may find by integration the expenditure of power for radiation in the whole antenna or in its different parts.

We shall call this method the induced emf method. It was proposed by Brillouin[6] and applied by Kliatzkin[7] in the analysis of the radiation of a vertical earthed wire. It is based upon the electromagnetic field equations in the form employing the retarded potentials of Lorentz.[8]

This paper deals with the radiation resistance of antennas, composed of parallel half-wave vibrators.

[6] *Radioélectricité*, April, 1922.
[7] *Telegrafia i telefonia bez provodov* (TITBP) 1(40), 33, 1927.
[8] Lorentz, "The Theory of Electrons," 2 ed., Chap. 1, paragraphs 13 and 14.

1. Outline of the Method. Radiation EMF. We have first to solve the following problem: a single wire with a known distribution of current being specified, a formula is to be found for the component of electric force parallel to the wire at any point of space.

This may be derived from the expression given by Lorentz:

$$E = -\frac{1}{c}\frac{\partial A}{\partial t} - \operatorname{grad}\phi\,; \tag{1}$$

where

$$\phi = \frac{1}{4\pi}\int \frac{1}{r}[\rho]dv \tag{2}$$

is a scalar potential at the given point due to the fixed charges distributed in the space and

$$A = \frac{1}{4\pi c}\int \frac{1}{r}[\rho v]dv \tag{3}$$

is a vector potential due to the charges, moving with the velocity v.

Applying this to the case of a very thin straight wire and passing from the Lorentz units to the absolute system of units we obtain

$$\phi = \frac{1}{\epsilon}\int_0^l \frac{|\sigma|_{t-r/c}}{r}dx \tag{4}$$

$$A = \mu c\int_0^l \frac{|i|_{t-r/c}}{r}dx \tag{5}$$

where σ is the charge per unit length, i is the current in the element dx of the wire, l is the length of the wire, and r is the distance of the given point from dx. The values of charge and current must be taken at the time $\left(t-\dfrac{r}{c}\right)$.

Let the origin of coordinates lie at the one end of the wire and let the OX axis lie along the wire (Fig. 2). The component of the electric force parallel to the wire will then be at the point M (∂, ξ) as follows:

$$E=-\frac{1}{c}\frac{\partial A}{\partial t}-\frac{d\phi}{d\xi}=-\int_0^l \frac{\mu}{r}\frac{\partial i_{(t-r/c)}}{\partial t}dx-\frac{\partial}{\partial \xi}\int_0^l \frac{\sigma_{(t-r/c)}}{\epsilon r}dx \quad (6)$$

If the angular frequency is ω then $i=I_x \sin \omega t$ and

$$\frac{\partial i(t-r/c)}{\partial t}=\omega I_x \cos \omega\left(t-\frac{r}{c}\right) \quad (7)$$

$$\sigma_{(t-r/c)}=-\int \frac{\partial i(t-r/c)}{\partial x}dt=\frac{1}{\omega}\frac{\partial I_x}{\partial x}\cos \omega\left(t-\frac{r}{c}\right) \quad (8)$$

from the equation $-\frac{\partial \sigma}{\partial t}=\frac{\partial i}{\partial x}$ giving the relationship between the

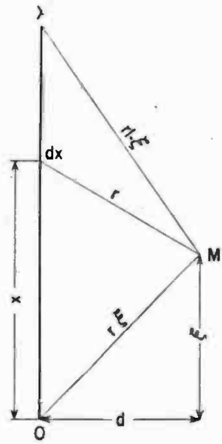

Fig. 2

current and the charge along the wire.

The instantaneous value of electric force will be as follows

$$e_d=-\mu c\left[m^2\int_0^l \frac{\cos (\omega t-mr)}{mr}I_x dx + \frac{\partial}{\partial \xi}\int_0^l \frac{\cos (\omega t-mr)}{mr}\frac{\partial I_x}{\partial x}dx\right] \quad (9)$$

where $m=\frac{\omega}{c}=\frac{2\pi}{\lambda}$ and $r=\sqrt{d^2+(x-\xi)^2}$.

Assume that the current is distributed sinusoidally along the wire and is zero at the origin of coordinates. Thus

$$I_x = I_0 \sin mx \tag{10}$$

where I_0 is the amplitude of the current at the loop.

The expression for e_d will then be

$$e_d = -\mu c\left[m^2 \int_0^l \frac{\cos(\omega t - mr)}{mr} I_0 \sin mx dx + m\frac{\partial}{\partial \xi}\int_0^l \frac{\cos(\omega t - mr)}{mr} I_0 \cos mx\, dx\right] \tag{11}$$

After integration we obtain:

$$e_d = \mu c I_0\left[\frac{\cos(\omega t - m r_{l-\xi})}{r_{l-\xi}} \cos ml - \frac{\cos(\omega t - m r_\xi)}{r_\xi}\right] \tag{12}$$

where $r_{l-\xi} = \sqrt{d^2 + (l-\xi)^2}$ and $r_\xi = \sqrt{d^2 + \xi^2}$.

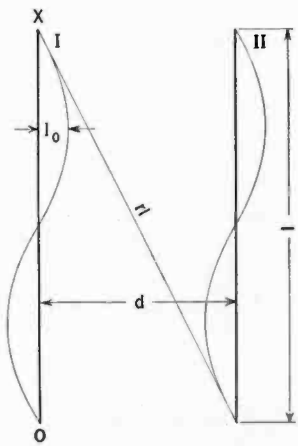

Fig. 3

In the particular case in which the point M lies on the wire itself, $d = 0$ and we shall have:

$$e_0 = \mu c I_0\left[\frac{\cos(\omega t - ml + m\xi)}{l - \xi} \cos ml - \frac{\cos(\omega t - m\xi)}{\xi}\right]. \tag{13}$$

2. Case of Two Parallel Wires. We shall now study the problem of the radiation of power from a system formed by two parallel wires. For this purpose we may assume some conditions which simplify the solution. We shall consider (Fig. 3) equal wires whose lengths are multiples of the half-wavelength. The wires are not displaced in height, that is, their ends must lie on the straight line perpendicular to the direction of the wires. The distribution, the phase and the values of current we assume to be identical in both wires.

Under these conditions the tangential component of E at any point along either wire comprises two parts, the first produced in each one by its own current and a second produced by the current in the other wire: i.e., $e=e_0+e_d$. This electric force produces an emf in the wire, and the power needed to suppress it will be the radiation power. For the element dx of the wire this power will be

$$dP_\Sigma = -EI_x \cos\phi dx \tag{14}$$

where E and I_x are the effective values of the electric force and current and ϕ is the phase angle.

The total power for one wire having the length l will be

$$\begin{aligned} P_\Sigma = -\int_0^l EI_x \cos\phi dx = -\int_0^l E_0 I_x \cos\phi_0 dx \\ -\int_0^l E_d I_x \cos\phi_d dx = P_0 + P_d. \end{aligned} \tag{15}$$

We shall first calculate P_d. Let the full expression of E and I_x be written. To obtain the power in watts we must take the current in amperes and E_d, E_0 in volts. Then

$$I_x = I_0 \sin mx \tag{16}$$

where I_0 is the effective value of the current at the loop in amperes.

E_d is also the rms value and from the formula (12) we obtain two components of it

$$E' = 30I_0 \frac{\cos ml}{r_{l-x}} \quad \text{and} \quad E'' = 30I_0 \frac{1}{r_x} \tag{17}$$

Each of these components has a different phase angle ϕ_1 and ϕ_2. Let us find them.

From the expression (12) we have

$$e_d' = E_d' \cos(\omega t - mr_{l-x}) = E_d' \sin\left(\omega t - mr_{l-x} + \frac{\pi}{2}\right). \tag{18}$$

The current in the wire is $i_x = I_x \sin \omega t$

Therefore $\phi_1 = mr_{l-x} - \frac{\pi}{2}$ and

$$\cos \phi_1 = \cos\left(mr_{l-x} - \frac{\pi}{2}\right) = \sin mr_{l-x} \qquad (19)$$

Similarly

$$\cos \phi_2 = \sin mr_x.$$

Thus we obtain for P_d

$$P_d = -30 I_0^2 \int_0^l \left(\frac{\sin mr_{l-x}}{r_{l-x}} \cos ml - \frac{\sin mr_x}{r_x}\right) \sin mx\, dx \qquad (20)$$

By integrating we obtain the following expression for the radiated power *when the length of the wire is a multiple of the half-wavelength.*

$$P_d = 30 I_0^2 \left[2 Ci\, md - Ci\, m(\sqrt{d^2+l^2}+l) - Ci\, m(\sqrt{d^2+l^2}-l)\right] = 30 I_0^2 M_d \quad (21)$$

Here $Ci(x)$ denotes the integral cosine, d is the distance between the wires, l is the length of the wire.

P_d is merely one of the components of radiation power, depending upon the current in the other wire. The second component P_0 we may obtain as limit of P_d when the distance between the wires approaches O.

$$P_0 = \lim |P_d| = 30 I_0^2 (E + \log 2ml - Ci 2ml) = 30 I_0^2 M_0 \quad (22)$$

where $E = 0.577 \cdots$ is the Eulers constant.

The whole radiation power in one wire will be

$$P = P_0 + P_d \qquad (23)$$

and the radiation power of the system of two wires

$$P_\Sigma = 2P = 2P_0 + 2P_d \qquad (24)$$

Dividing the expressions (21) and (22) by I_0^2 gives the so-called "radiation resistance." Obviously we may speak of this quantity only when the currents in both wires are equal.

3. Application to Beam Antennas. Synphase System. We shall now apply these results to the computation of the radiation resistance for some types of beam antennas. We shall consider first the so-called synphase antenna, composed of single parallel vibrators (Fig. 4). The vibrators are situated along a straight line at a distance of a half-wavelength from each other. Their currents are equal and in phase. In this case the beam has a direction perpendicular to the line of the wires.

The power radiated by any individual antenna wire is composed of the power due to its own current and that due to the electric force induced in it by other vibrators. We shall denote

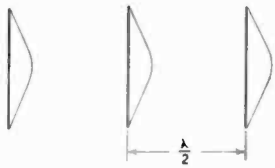

Fig. 4

by P_d the power corresponding to induction by a vibrator at a distance d; in the case of the antenna considered d will be a multiple of a half-wavelength. As stated above in (21),

$$P_d = 30 I_0^2 M_d$$

As the currents in all wires are equal the component of radiation resistance due to another wire will be

$$R_d = 30 M_d.$$

The values of these components are given in Table A (line 1) for distances d which are multiples of the half-wavelength.[9]

Using this table let us now compute the radiation resistance for the antenna composed of three vibrators.

For each of the extreme wires we shall have:

$$R_1 = R_3 = R_0 + R_{\lambda/2} + R_\lambda = 73.3 - 12.4 + 4.1 = 65.0\ \Omega$$

and for the middle wire:

$$R_2 = R_0 + 2R_{\lambda/2} = 73.3 - 2 \times 12.4 = 48.5\ \Omega.$$

The radiation resistance of the whole antenna will be:

$$R_3 = 3R_0 + 4R_{\lambda/2} + 2R_\lambda = 178.5\ \Omega.$$

[9] For these calculations I employed the integral-function curves especially plotted by Mr. E. D. Milovidoff of the staff of the Nijni-Novgorod Radiolaboratory. Interpolation from commonly used tables (Jahnke u. Emde) is rather misleading.

For the four-wire antenna we obtain by analogous calculations:

$$R_2 = 4R_0 + 6R_{\lambda/2} + 4R_\lambda + 2R_{3\lambda/2}$$

and generally for an antenna composed of n wires:

$$R_n = nR_0 + 2(n-1)R_{\lambda/2} + 2(n-2)R_{2\lambda/2} + \cdots + 2R_{(n-1)\lambda/2} \quad (25)$$

Table I contains values of the radiation resistance (a) for each vibrator, (b) for the whole antenna, and (c) the mean value for one vibrator. It might be noticed that when increasing the number of vibrators the last quantity is very rapidly approaching the limit (near 56 ohms), which was obtained for the case of an infinitely great number of vibrators by using the "Poynting vector method" of radiation resistance calculation.[10]

TABLE I

Values of radiation resistance in ohms for synphase beam antenna. n = number of wires; R_n = resistance of nth wire; R = total resistance. R_m = average resistance per wire.

n	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R	R_m
2	60.9	60.9	—	—	—	—	—	121.8	60.9
3	65.0	48.5	65.0	—	—	—	—	178.5	59.5
4	63.2	52.6	52.6	63.2	—	—	—	231.8	58.0
5	64.4	50.9	56.7	50.9	64.4	—	—	287.3	57.4
6	63.6	52.0	55.0	55.0	52.0	63.6	—	341.4	56.9
7	64.0	51.2	56.1	53.2	56.1	51.2	64.0	395.6	56.5

4. Continuation. Antiphase Beam Antenna. We shall now pass on to the antiphase antenna (Fig. 5) which radiates a beam directed in the plane of antenna. It differs from the synphase

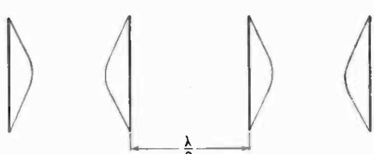

Fig. 5

antenna only in the fact that the currents in the adjacent wires have a phase difference of 180 deg. All the radiation resistance components having d equal to an odd number times the half-wavelength must therefore be multiplied by -1. The other components are the same as before because vibrators spaced by an integral number of wavelengths are in phase.

[10] M. A. Bontsch-Bruewitsch, l. c., p. 434.

The radiation resistance for this antenna is expressed by the following general formula:

$$R_n = nR_0 - 2(n-1)R_{\lambda/2} + 2(n-2)R_\lambda - \cdots + 2R_{(n-1)\lambda/2} \quad (26)$$

where the quantities R_d may be taken from Table A (line 1). The results of calculations for the antiphase antenna are given in Table II.

From Tables I and II we may see that the radiation resistance is different for the various wires in the antenna and this difference is unequal for the two types of antennas. As the number of vibrators is increased the difference diminishes.

TABLE II

Value of radiation resistance in ohms for antiphase beam antenna (for explanation see legend of Table I).

n	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R	R_m
2	85.7	85.7	—	—	—	—	—	171.4	85.7
3	89.8	98.1	89.8	—	—	—	—	277.6	92.5
4	91.5	102.2	102.2	91.5	—	—	—	387.2	96.8
5	92.7	103.9	106.2	103.9	92.7	—	—	499.2	99.8
6	93.4	105.1	108.0	108.0	105.1	93.4	—	612.8	102.1
7	93.9	105.8	109.1	109.7	109.1	105.8	93.9	727.2	103.9

5. Parallel Wires Displaced in Height. As a next step in the development of this method, the radiation resistance of parallel vibrators displaced in height may be calculated, (Fig. 6). The investigation of this case will enable us to study the radiation resistance in the presence of a perfectly conducting plane and to calculate the radiation resistance of multistage antennas.

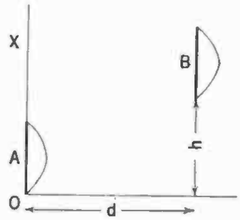

Fig. 6

We will deduce a formula for the radiation power due to the emf induced in the vibrator B by another vibrator A. The wire B is placed a distance d and elevated on a height h with respect to A. We shall denote this power by $P(d, h)$ and the corresponding radiation resistance component by $R(d, h)$.

The electric force near B due to the first vibrator is defined by (12).

The law of current distribution in the wire B is as follows:

$$I_x = I_0 \sin m(x-h) \tag{27}$$

Proceeding exactly as in Sect. 2 we shall obtain for the radiation power due to the induction the following expression:

$$P(d, h) = 30 I_0^2 \int_h^{h+\lambda/2} \left(\frac{\sin m r_{l-x}}{r_{l-x}} + \frac{\sin m r_x}{r_x} \right) \sin m(x-h) dx. \tag{28}$$

The integration gives for the corresponding radiation resistance component a rather complicated expression, as follows:

$$\begin{aligned} R(d, h) = &- 15 \sin mh \cdot \left[S\left(d, h - \frac{\lambda}{2}\right) - 2S(d, h) \right. \\ &\left. + S\left(d, h + \frac{\lambda}{2}\right) \right] \\ &- 15 \cos mh \cdot \left[C\left(d, h - \frac{\lambda}{2}\right) - 2C(d, h) \right. \\ &\left. + C\left(d, h + \frac{\lambda}{2}\right) \right] \end{aligned} \tag{29}$$

where $S(x, y)$ and $C(x, y)$ are the functions:

$$\begin{aligned} S(x, y) &= Si\, m(\sqrt{x^2+y^2}+y) - Si\, m(\sqrt{x^2+y^2}-y) \\ C(x, y) &= Ci\, m(\sqrt{x^2+y^2}+y) + Ci\, m(\sqrt{x^2+y^2}-y). \end{aligned} \tag{30}$$

Fig. 7

This formula is the most general one for the case of two parallel vibrators. The expression (21), obtained for the vibrators placed at the same height, is a particular case of it for $h = 0$. For the other particular case, when $d = 0$ (Fig. 7) we find:

$$
\begin{aligned}
R(0,\, h) = & -15 \sin mh \left[Si\, 2m\left(h - \frac{\lambda}{2} \right) - 2Si\, 2mh \right. \\
& \left. + Si\, 2m\left(h + \frac{\lambda}{2} \right) \right] \\
& -15 \cos mh \left[\log \frac{h^2}{h^2 - \frac{\lambda^2}{4}} + Ci\, 2m\left(h - \frac{\lambda}{2} \right) \right. \\
& \left. - 2Ci\, 2mh + Ci\, 2m\left(h + \frac{\lambda}{2} \right) \right]
\end{aligned} \tag{31}
$$

which is in agreement with the analogous formula obtained by M. A. Bontsch-Bruewitsch.

Having any given complex antenna system comprised of n synphase parallel vibrators we can by means of expressions (29) calculate the radiation resistance for every one of them. This resistance will be:

$$
R_\Sigma = R(0,\ 0) + R(d_1\, h_1) + R(d_2,\ h_2) + \cdots + R(d_{n-1},\ h_{n-1}) \tag{32}
$$

where h and d denote the height difference and the distance between the first vibrator and each other one; $R(O,O) = 73.3\Omega$.

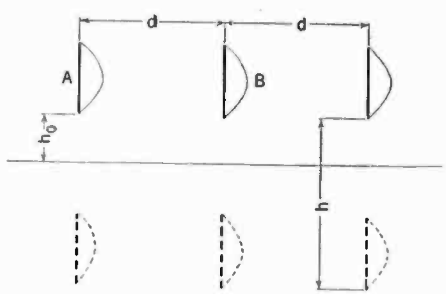

Fig. 8

6. Antenna Over Perfectly Conducting Plane. The expression (29) may also be used for the calculation of the radiation resistance of an antenna erected over a perfectly conducting plane by application of the simple image theory. We shall treat the case of an antenna of which the vibrators are placed at the same height over the plane and at equal distances d from each other.

Let h_0 be the height of antenna over the conducting plane (Fig. 8). Introducing the correction due to the images we shall obtain:

For each of the extreme wires:

$$R_{\Sigma A} = 73.3 + R(0,h) + R(d,0) + R(d,h) + R(2d,0) + R(2d,h) + \cdots + R[(n-1)d,0] + R[(n-1)d,h] \quad (33)$$

where $h = 2h_0 + \dfrac{\lambda}{2}$.

For each wire second from the edge

$$R_{\Sigma B} = 73.3 + R(0,h) + 2[R(d,0) + R(d,h)] + \cdots + R[(n-2)d,0] + R[(n-2)d,h]. \quad (34)$$

If the radiation resistance of the whole antenna is to be found we can use a formula analogous to the formula (25)

$$R_\Sigma = nR_0 + 2(n-1)R_1 + 2(n-2)R_2 + \cdots + 2R_{n-1} \quad (35)$$

where $$R_k = R\left(\frac{k\lambda}{2},\ 0\right) + R\left(\frac{k\lambda}{2},\ 2h_0 + \frac{\lambda}{2}\right).$$

The calculations were carried through by the author for a synphase 7-wire antenna elevated 0, $\dfrac{\lambda}{8}$, $\dfrac{\lambda}{4}$, $\dfrac{3\lambda}{8}$, and $\dfrac{\lambda}{2}$ over the plane. The results are shown in Table III. We may notice that with increasing height the total radiation resistance rapidly

TABLE III

h_0	$r_1 = r_7$	$r_2 = r_6$	$r_3 = r_5$	r_4	R	r_m
0	84.7	58.2	74.7	62.0	497.3	71.0
$\frac{\lambda}{8}$	65.0	41.8	59.8	43.7	376.8	53.8
$\frac{\lambda}{4}$	62.8	44.7	58.8	42.2	374.8	53.5
$\frac{3\lambda}{8}$	65.8	50.5	59.0	51.2	401.8	57.4
$\frac{\lambda}{2}$	66.4	51.2	55.5	54.4	400.6	57.2
∞	64.0	51.2	56.1	53.2	395.6	56.5

approaches the value obtained for free space, but the energy distribution between the individual wires is different. As expected the radiation resistance increases near the plane.

7. Multistage Antenna. The method of induced emfs may be applied to more complicated systems, particularly multistage antennas. Let us consider for example a three-stage antenna of the type employed by Marconi.

A unit of such an antenna is a system of three synphase vibrators, spaced along a straight line. These vibrators are connected through antiresonant coils. Let us compute the power due to the emf induced by such an antenna unit in another one spaced at a distance d (Fig. 9). We assume the currents to be equal and in phase.

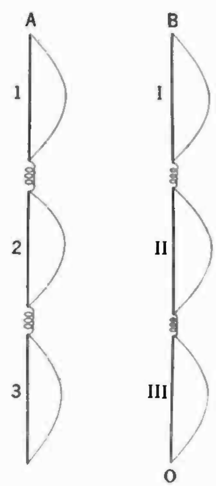

Fig. 9

The power induced in vibrator I of the wire B may be resolved into three parts due to the vibrators 1—3, respectively, of the wire A. Using our notation we may write:

$$P_{AI} = P(d,0) + P\left(d, \frac{\lambda}{2}\right) + (P,\lambda) \tag{36}$$

Similarly for the II and III vibrators:

$$\left.\begin{aligned} P_{AII} &= P(d,0) + 2P\left(d, \frac{\lambda}{2}\right) \\ P_{III} &= P_{AI}. \end{aligned}\right\} \tag{37}$$

The whole power induced in the wire B will be

$$P_{AB}=3P(d,\lambda)+4P\left(d,\frac{\lambda}{2}\right)+2P(d,\lambda) \tag{38}$$

and generally in the case of n-stage wire

$$P_{AB}=nP(d,0)+2(n-1)P\left(d,\frac{\lambda}{2}\right)+2(n-2)P(d,\lambda) + \cdots +2P\left(d,\ (n-1)\frac{\lambda}{2}\right). \tag{39}$$

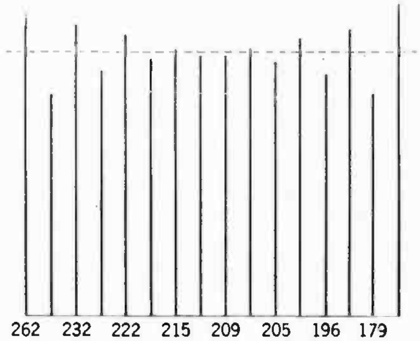

Fig. 10

The radiation resistance of single three-stage wire is obtained by substituting $d=0$.

$$P_0=3P(0,\ 0)+4P\left(0,\frac{\lambda}{2}\right)+2P(0,\ \lambda)=317.1\,\Omega \tag{40}$$

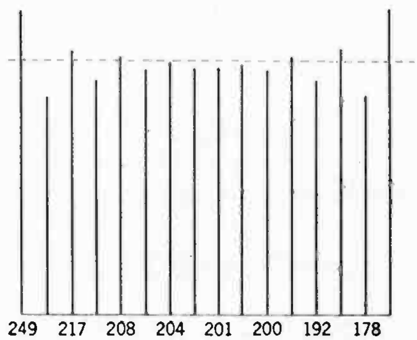

Fig. 11

In order to calculate the radiation resistance of different wires and of the whole antenna, formulas may be used analogous to those obtained above.

The author has performed these calculations for the case of a 16-wire antenna, the distance between the wires being assumed to be $\frac{\lambda}{2}\cdot$ The results are shown graphically in Fig. 10; the numbers below give the radiation resistance in ohms. The mean value of this resistance (214 ohms) is marked by a dotted line. Analogous calculations were also made for this antenna elevated at $\frac{\lambda}{4}$ over a perfectly conducting earth. The mean value of the radiation resistance for one wire is then 206 Ω. The energy distribution is shown in Fig. 11. In both cases this distribution

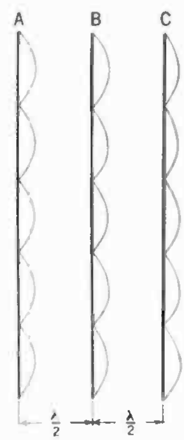

Fig. 12

is very nonuniform in the extreme wires. This means that the design of the feeding devices for the several wires must be quite different, if we wish to obtain equal currents in all vibrators.

8. Table A. Various other types of antennas may be computed in the same manner. To simplify the calculations a table is appended (Table A), containing the functions $R(d, h)$ for values of d and h, which are multiples of a half-wavelength. This table will be found useful in the calculation of many practical types of directive antennas.

As an example let us calculate the radiation resistance of an antenna formed by three five-stage wires (Fig. 12) spaced at a distance of a half-wavelength from each other. Proceeding exactly as in Sect. 7 for the three-stage antenna we shall obtain for the radiation resistance component R_1 of the wire A due to the wire B the following expression:

$$R_1 = 5R\left(\frac{\lambda}{2}, 0\right) + 8R\left(\frac{\lambda}{2}, \frac{\lambda}{2}\right) + 6R\left(\frac{\lambda}{2}, \lambda\right) + 4R\left(\frac{\lambda}{2}, \frac{3}{2}\lambda\right) + 2R\left(\frac{\lambda}{2}, 2\lambda\right) \tag{41}$$

The values of $R(d, h)$ may be taken from the table. Thus we obtain

$$R_1 = 5\cdot(-12.36) + 8\cdot(-11.80) + 6\cdot(-0.78) + 4\cdot(+0.80) + 2\cdot(-1.00) = -159.7\,\Omega \tag{42}$$

TABLE A

$h \diagdown d$	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0	+73.29	−12.36	+4.08	−1.77	+1.18	−0.75	+0.42	−0.33
0.5	+26.40	−11.80	+8.83	−5.75	+3.76	−2.79	+1.86	−1.54
1.0	− 4.065	− 0.78	+3.56	−6.26	+6.05	−5.67	+4.51	−3.94
1.5	+ 1.78	+ 0.80	−2.92	+1.96	+0.16	−2.40	+3.24	−3.76
2.0	− 0.96	− 1.00	+1.13	+0.56	−2.55	+2.74	−2.07	+0.74
2.5	+ 0.58	+ 0.45	−0.42	−0.96	+1.59	−0.28	−1.59	+2.66
3.0	− 0.43	− 0.30	+0.13	+0.85	−0.45	−0.10	+1.74	−1.03

TABLE A (Cont'd)

$h \diagdown d$	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
0	+0.21	−0.18	+0.15	−0.12	+0.12	−0.10	+0.06	−0.03
0.5	+1.08	−0.85	+0.69	−0.57	+0.51	−0.45	+0.36	−0.30
1.0	+3.08	−2.50	+2.10	−1.80	+1.56	−1.18	+1.14	−1.00
1.5	+3.68	−3.40	+3.14	−2.90	+2.61	−2.31	+2.06	−1.86
2.0	+0.51	−1.30	+1.82	−2.24	+2.28	−2.29	+2.26	−2.14
2.5	−2.49	+2.00	−1.35	+0.49	−0.06	−0.45	+0.85	−1.03
3.0	−0.09	+1.12	−1.87	+1.77	−2.02	+1.71	−1.32	+0.66

The values of d and h are given here in parts of the wavelength; those of radiation resistance in ohms.

To find the radiation resistance component R_2 due to the wire C or the radiation resistance of the single five-stage wire R_0 we must substitute in the above expression $d=\lambda$ or $d=0$ instead $d=\dfrac{\lambda}{2}\cdot$ Therefore

$$R_2 = +103.0\,\Omega \quad \text{and} \quad R_0 = 558.5\,\Omega$$

The radiation resistance of the wires A and C will then be:

$$R_A = R_C = R_0 + R_1 + R_2 = 501.8\ \Omega$$

and of the wire B

$$R_B = R_0 + 2R_1 = 239.1\ \Omega\ .$$

The whole radiation resistance of the antenna will be 1242.7 Ω, the mean value for 1 wire = 416.2 Ω and for 1 vibrator = 83.0 Ω.

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Volume 17, Number 3 *March, 1929*

Discussion on
SIMPLE INDUCTANCE FORMULAS FOR RADIO COILS*

(Harold A. Wheeler)

R. R. Batcher[1]: A formula shown in this paper* for the rapid computation of the inductance of air-core radio coils corresponds to one which the writer has used for about six years. Having found by experience that many engineers to whom this and other simple formulas have been disclosed have an aversion to using them because they have insufficient accuracy, it is believed that further analysis might be of interest.

The formula

$$L = an^2Q \tag{1}$$

has been called the universal inductance formula since tables, formulas, and charts have been derived to cover almost every shape of air-core inductance in evaluating Q, which is a factor depending entirely on the physical dimensions of the coil. For a single layer solenoid the Lorenz formula may be used or the tables which have been obtained from it for representative values. This formula is one of the most exact in its field.

An inspection of a curve for Q plotted from these tables indicates that it is probably of a hyperbolic nature. If so a comparison of the relation between $1/Q$ and $b/2a$ would be a straight line. Analysis of this line gives an empirical value for Q (after converting to inch measurements by multiplying by 2.54).

$$Q = \frac{100}{(b/a+0.9)} \tag{2}$$

Substituting (2) in (1) gives

$$L = \frac{a^2n^2 1000}{10b+9a} \text{ centimeters} \tag{3}$$

$$= \frac{a^2n^2}{10b+9a} \text{ microhenries} \tag{4}$$

which is the formula previously reported. The deviation between the curve of $1/Q$ and a straight line is a measure of the accuracy of this equation. For greater accuracy with very short coils the denominator may be changed to $(8.3a+10b)$.

It may be shown that the form of (4) could be obtained from fundamental considerations, and since it brings to light interesting facts it will be derived. One of the basic inductance relations is

$$\text{Inductance} = \frac{4\pi n^2}{\text{Reluctance of path}} \tag{5}$$

For an air core with unit permeability the reluctance is the value of (length of path/area of path). It is this relation that makes the ordinary

* Proc. I. R. E., 16, 1398; October, 1928.
[1] Decatur Mfg. Co., Brooklyn, N. Y.

inductance formula so complicated since both the length and area of the flux path are indeterminate. But the *effective* length and the *effective* area values are interrelated so that their quotient is a constant for any one coil. It is convenient, therefore, to assume a value for the area and from this determine the length of the flux path. It may be assumed that the area of the path is the area enclosed by the average turn, i.e., area $= \pi a^2$, throughout the whole length of the flux path. Then the length of the flux path may be taken to be equal to $(b+q)$ where b is the length of the coil and q is a fictitious length equal to the length of the return path of the flux outside of the coil. Substituting these values in (5) gives

$$L = \frac{4\pi n^2}{\left\{\dfrac{b+q}{\pi a^2}\right\}} 2.54 = \frac{(2\pi a)^2 2.54 n^2}{b+q} \tag{6}$$

Comparing (6) with (4) indicates that the flux return path for the values assumed is equal to $0.9a$ (which may appear paradoxical but the value is due to the small area of the flux path assumed exterior to the coil).

This same procedure has been applied to many other types of coils and may be applied to many more. In many cases it is desirable to derive a simple inductance formula for a system of coils which may be under consideration. In one case such a relation was simply obtained for a special shape of coil antennas which assisted materially with the experiments. If a series of measurements are made to cover representative conditions such a formula may be readily derived.

(a) Determine the value of $1/Q$ from (1) using the available data, for several values of $2a/b$.

(b) Determine (k) from two representative values of Q, say Q' and Q'' with their corresponding shape ratios b'/a' and b''/a'', using

$$k = (b'/a' - b''/a'')\frac{Q'Q''}{Q'-Q''} \tag{7}$$

(c) Determine q for several values of Q from

$$q = 1/Q - b/ak \tag{8}$$

The value of q should not change very much over a considerable range of values for $b/2a$.

A multilayer coil presents greater difficulties. Several have been disclosed, such as the Brooks-Turner formula, which is probably the one most commonly used. As a first approximation it can be shown that the geometric mean distance from a point within a rectangle to the rectangle is very nearly equal to $0.223\ (b+c)$. Here c is the winding depth. The g.m.d. from a point on a line to the line is equal to $0.223\ b$. From this it would seem that the factor $(b+c)$ could be substituted in the single layer formula for the factor b, to obtain a multilayer formula:

$$L = \frac{a^2 n^2}{9a + 10(b+c)} \tag{9}$$

This formula gives fair accuracy for short coils, but in some other cases a large error results. A more accurate analysis gives:

$$L = \frac{a^2 n^2}{9a + 10(b+c)\dfrac{2bc}{a}} \tag{10}$$

It has been shown[2] that no great error results when a single layer coil inductance formula is used for flat spirals by substituting (c) for (b). Formula (4) may be used.

It should be kept in mind that all of these formulas are based on current sheet considerations and are subject to other corrections. They are thus not true "empirical" formulas, which are ordinarily designed to fit a given system of measurements.

In conclusion it may be well to call attention to the normal accuracy requirements of an inductance formula. I have seen engineers reject an approximate formula with an admitted error of say 3 per cent and reject slide rule computations in favor of long hand computations, but who nevertheless used an ordinary scale graduated in sixteenths to determine the dimensions of the coil. The nominal diameter of the tube was used (3 inches) for $2a$, whereas the actual diameter was later found to be 3.045 in., and adding the diameter of the wire increased the value to 3.095 in. The length was taken as $2\frac{7}{8}$ in., whereas the actual length (nd). was 2.82 in. The total error due to these measurements was over 6 per cent, although the greatest error in the measurements was less than $\frac{1}{16}$ in.

In this light great accuracy in a formula seems in many cases to be of secondary importance.

Harold A. Wheeler[3]: I believe Mr. Batcher gives insufficient attention to two very important details which I carefully noted for both formulas recommended in my brief paper to which he refers. First, what is the maximum error of the approximate formula? and secondly, within what limits of shape factors does this maximum error obtain? Until these questions are answered, no engineer is justified in using an approximate formula.

The type of formula under discussion has no *theoretical* basis for "short" coils ($b+c<2a$), since only a small part of the total flux links with all the turns. Furthermore, when there are few turns or large spacing between turns, which is often true of "short" coils, one or two corrections cannot be neglected.

Theoretical consideration of a coil of very small winding space yields the following formula of a different type:

$$L=\frac{an^2}{13.5}\log_{10}\left\{\frac{4.9a}{b+c}\right\} \text{ microhenries} \tag{4}$$

(dimensions in inches). On the assumption of uniform current distribution in a rectangular cross-section, the error of this formula is less than 3 per cent when $b+c\leqq a$.

Formula (4) is the only type which remains accurate as the term $b+c$ decreases indefinitely. The Hazeltine formula (1) is the most generally accurate of any of its type, as applied to multilayer coils of medium and small winding space.

Since preparing the above paper, I find that in July, 1920, I first derived formula (2) therein, with almost identically the same constants now recommended. The Hazeltine formula (1) therein was derived about 1916 and published shortly thereafter.

[2] J. A. Fleming, "Wireless Telegraphist's Pocketbook," p. 97.
[3] Hazeltine Service Corporation Laboratory, New York City.

Proceedings of the Institute of Radio Engineers
Volume 17, Number 3 *March, 1929*

MONTHLY LIST OF REFERENCES TO CURRENT RADIO LITERATURE

THIS is a monthly list of references prepared by the radio laboratory of the Bureau of Standards and is intended to cover the more important papers of interest to professional radio engineers which have recently appeared in periodicals, books, etc. The number at the left of each reference classifies the reference by subject, in accordance with the scheme presented in "A Decimal Classification of Radio Subjects—An Extension of the Dewey System," Bureau of Standards Circular No. 138, a copy of which may be obtained for 10 cents from the Superintendent of Documents, Government Printing Office, Washington, D. C. The various articles listed below are not obtainable from the Bureau of Standards. The various periodicals can be consulted at large public libraries.

R100. Radio Principles

R113 Radio transmission and the upper atmosphere (editorial). *Experimental Wireless and Wireless Engineer* (London), **5**, 657–659; December, 1928.

(Abstract of a paper by Appleton comparing the three methods for determining the effective height of the Heaviside layer. The frequency change method, the angle of incidence method, and the group retardation method should give the same equivalent height of the ionized layer.)

R113 Bäumler, M. Feldstärkemessungen auf grosse Entfernungen im Rundfunkwellenbereich. (Field strength measurements at great distances in the broadcasting range). *Elektrische-Nachrichten Technik*, **5**, 473–477; November, 1928.

(Report of cooperative field intensity measurements at Königsberg, Hamburg, Karlsruhe, and Dresden. All these stations took readings of waves (190, 405, and 585 meters) arriving in the form of long dashes (30 seconds duration) from a sending station located at the Reichspostamt at Doeberitz. Day and night effects are reported.)

R113 Sreenivasan, K. Über die Wellenausbreitung in einem dispergierenden Medium. (On the wave propagation in a dispersed medium). *Zeits. für Hochfrequenztechnik*, **32**, 121–124; October, 1928.

(It is shown that the group velocity of high-frequency waves varies for different frequencies when passing through a dispersed medium such as the Heaviside layer. It seems, therefore, to be evident that a modulated wave on account of its two side bands should produce distortion after passing through this ionized layer.)

R113 Fuchs, J. Der Einfluss der Erdatmosphäre auf die Ausbreitung kurzer Wellen. (On the influence of earth atmosphere on the propagation of short waves). *Zeits. für Hochfrequenztechnik*, **32**, 125–129; October, 1928.

(It is shown that the strength of the received signal for short waves after passing over sea water depends on the distribution of the pressure of the atmosphere. From this it follows that the atmosphere produces scattering similar to diffused reflection.)

R113.5 Goldstein, S. The influence of the earth's magnetic field on electric transmission in the upper atmosphere. *Proc.* Royal Soc. (London), 121A, 260–285; November, 1928.

(Based on lectures by Prof. J. Larmor. The theory of the effect of the magnetic field of the earth on the propagation of electromagnetic waves in the Heaviside layer is given in much detail.)

R114 Schindelhauer, F. Über elektromagnetische Störungen. (On electromagnetic disturbances). *Elektrische-Nachrichten Technik*, 5, 442–449; November, 1928.

(Study of the clicks and grinders by means of the direction finder due to Watson-Watt. The author concludes that since the direction of the maximal disturbance is either along or perpendicular to the earth's magnetic axis, most of the atmospherics are due to field changes above the surface of the earth. These field changes cause the electron to be drawn from the sun towards the earth and then produce the eddies of the Heaviside layer. The first causes the clicks and the latter the grinders.)

R114 Watson-Watt, R. A. Present status of knowledge of atmospherics. *Experimental Wireless and Wireless Engineer* (London), 5, 629–652; November, 1928.

(Reviews work done on this subject by himself and others up to present date.)

R120 Moser, W. Die Übertragung der Energie vom Sender zur Antenne bei kurzen Wellen. (The transfer of energy of short waves from the transmitting set to the antenna). *Elektrische-Nachrichten Technik*, 5, 422–426; November, 1928.

(Description of the system carrying the high-frequency power to various individual antennas used for beam transmission. The parallel wire and the concentric tube system is used for feeding the power into the antennas and a method is described by means of which the losses of the distributors can be found.)

R125.6 Meissner, A. and Rother, H. Über die Bestimmung des günstigsten Ausstrahlwinkels bei horizontalen Antennen. (On the determination of the favorable radiation angle in horizontal antennas). *Zeits. f. Hochfrequenztechnik*, 32, 113–115; October, 1928.

(The most favorable radiation angle for 15 and 20 meter wavelengths was determined for horizontal polarization at the center using horizontal multiple antennas in connection with a parabolic reflector. It was found that the most favorable radiation happened when it took place along the tangent of the surface of the earth.)

R125.6 Gresky, G. Die Wirkungsweise von Reflektoren bei kurzen elektrischen Wellen. (The operation of reflectors for short electric waves). *Zeits. fur Hochfrequenztechnik*, 32, 149–162; November, 1928.

(The beam effect of a vertical antenna for the case of a cylindrical parabolic reflector and a plane reflector (several vertical wires) along a straight wire is experimentally studied. For the parabolic reflector the ratio of focal length to wavelength should be 0.27 and for the plane reflector 0.2. The tuned reflectors give smaller dimensions.)

R125.6 Böhm, O. Die Bündelung der Energie kurzer Wellen. (The concentration of the energy of short waves). *Elektrische-Nachrichten Technik*, 5, 413–421; November, 1928.

(Explains the beam transmission system employed by the Telefunken Co. A very clear presentation of the underlying principles giving at first the radiation characteristic of the dipole, then that of a group of dipoles along a straight line and in a plane.)

R125.6 Gothe, A. Über Drahtreflektoren. (On wire reflectors). *Elektrische-Nachrichten Technik*, 5, pp. 427–430; November, 1928.

(Description of the action of reflector antennas. Wire reflectors reduce the strength of the backward beam considerably. Complete screening by means of reflectors is only possible if the radiation coupling between antenna and reflector is variable so that the amplitude and the phase of the reflector current can be properly adjusted.)

R130 Podliasky. Equilibres instables et regimes statiques parasites dans les circuits electriques associes aux triodes. (Unstable equilibrium and regular static parasites in electric circuits associated with tubes). *L'Onde Electrique*, 7, 475–487; November, 1928.

(Conclusion of the paper on pp.287–306 of the July, 1928 issue of this periodical.)

R131 Rajski, C. Les capacities internes de la lampe a plusieurs electrodes. (Interelectrode capacities of multi-electrode tubes). *L'Onde Electrique*, 7, 461–474; November, 1928.

(Expressions are derived for the interelectrode capacities of electron tubes taking the space charge into consideration. If the tube is not burning the usual interelectrode capacities (filament-grid, filament-plate, and grid-plate) are observed but when the filament is emitting electrons it is necessary to consider four capacities, the grid capacity, the plate capacity, the grid-plate capacity, and the plate-grid capacity.)

R134.75 Boella, M. Sur le calcul des amplificateurs a moyenne frequence superheterodyne. (On the calculation of the intermediate frequency amplifier stages of a superheterodyne). *L'Onde Electrique*, 7, 500–508; November, 1928.

(Analytical treatment of the amplifier stages of a superheterodyne used for the amplification of the intermediate frequency.)

R134.75 Ramsay, J. F. A double superheterodyne. *Experimental Wireless and Wireless Engineer* (London), 5, 669–672; December, 1928.

(Description of a two-fold superheterodyne. The first superheterodyne changes the received high frequency to a 600-kc current which is then amplified by two stages of radio-frequency amplification after which another heterodyne produces a 150-kc current. This is passed through three stages of radio-frequency amplification rectified and amplified by a two stage audio-frequency amplifier.)

R144 Waite, G. R., Brickwedde, F. G., Hall, E. L. Electrical resistance and magnetic permeability of iron wire at radio frequencies. *Physical Review*, 32, 967–73; December, 1928.

(Discussion of the results of B. Wwednensky and K. Theodortschik and those of the authors of this paper who could not detect a critical variation in the resistance of iron wire in the vicinity of 3000 kc.)

R144 Jackson, W. The effect of frequency on the value of high resistances of the grid leak type. *Experimental Wireless and Wireless Engineer* (London), 5, 677–679; December, 1928.

(The very high resistance of a grid leak consists in reality of a pure resistance with a small capacity (a few $\mu\mu f$) in parallel. It is shown that above 10^6 cycles/sec. the effective resistance changes and the parasitic capacity current becomes pronounced.)

R200. Radio Measurements and Standardization

R250 Moullin, E. B. An ampere meter for measuring alternating currents of very high frequency. *Proc.* Royal Soc. (London), 121A, 41–71; November, 1928.

(Gives the theory and construction of a new high-frequency ammeter which is based on the repulsion between two parallel conductors carrying the current to be measured. The frequency effect can be calculated. One conductor is fixed and the other one can move against a small elastic constant. This motion is a measure of the repulsion force and therefore of the current. It is noted by means of a microscope.)

R261 Aiken, C. B. A sensitive vacuum tube voltmeter. *Jnl.* Optical Soc. of American and Review of Sci. Instruments, **17**, pp. 440–450; December, 1928.

(A vacuum-tube voltmeter is described which utilizes the heterodyne principle for obtaining increased sensitivity.)

R300. Radio Apparatus and Equipment

R342.15 Koehler, G. The design of transformers for audio-frequency amplifiers with preassigned characteristics. Proc. I. R. E., **16**, 1742–1770; December, 1928.

(Requirements of ideal transformer are stated and difficulties encountered in attempting to build transformers for interstage coupling units which will meet these requirements are pointed out.)

R343 Küpfmüller, K. Über die Dynamik der selbsttätigen Verstärkungsregler. (On the dynamics of the automatic amplifier stabilizers). *Elektrische-Nachrichten Technik*, **5**, 459–467; November, 1928.

(A system is described by means of which the amplified intensity is automatically kept constant. Based on the principle developed a receiving set has been built which produces the same output intensities during times at which the input voltage (due to fading) varies up and down.)

R344 Eller, K. B. On the variation of generated frequency of a triode oscillator due to changes in filament, current, grid voltage, plate voltage, or external resistance. Proc. I. R. E., **16**, 1706–1728; December, 1928.

(General expressions developed for generated frequency of grid-tuned and plate-tuned generators.)

R344.4 Ritz, M. Essais sur ondes tres courtes. (Tests on very short waves). *L'Onde Electrique*, **7**, 488–499; November, 1928.

(Study of transmission of waves of 2 to 8 meter length. Gives generator diagrams. The experimental results agree with those due to R. Mesny.)

R344.4 Uber eine Methode zur Erzeugung von sehr kurzen elektromagnetischen Wellen. (On a method for the production of short electromagnetic waves). *Zeits. fur Hochfrequenztechnik*, **32**, 172; November, 1928.

(Description of magnetron oscillator for the production of very short waves, $\lambda = 29$ cm.)

R359 Hahnemann, W. Uber die neuere Entwicklung des Maschinensenders fur kleine Wellenlangen. (On the new development of machine transmitters for short wavelengths). *Elektrische-Nachrichten Technik*, **5**, 431–437; November, 1928.

(Description of the latest development of the Lorentz alternators with frequency multiplication. The improvements consist in producing frequencies in the broadcast band; filters for reducing the effect of the side bands; increase of the life of the frequency multipliers and reduction of the Thriller effect which causes a periodic change in the frequency.)

R376.3 Wolff, I. Sound measurements and loudspeaker characteristics. Proc. I. R. E., **16**, 1729–41; December, 1928.

(Description given of methods used to measure loud speaker response. Typica characteristic curves given.)

R400. Radio Communication Systems

R412 Bailey, A., Dean, S. W., Wintringham, W. T. The receiving system for long wave transatlantic radio telephony. Proc. I. R. E., 16, 1645–1705; December, 1928.

(Determinations show that frequencies near 60 kc are best suited for transatlantic radio telephone transmission. Various types of antennas described. Mathematical discussions of wave antenna, antenna arrays, and probability of simultaneous occurrence of telegraph interference are given in appendices.)

R500. Applications of Radio

R526.1 Stowell, E. Z. Unidirectional radio beacon for aircraft. Bureau of Standards Journal of Research, December, 1928. Research Paper No. 35. Reprint copies obtainable for 10 cents from the Superintendent of Documents, Government Printing Office, Washington, D. C.

(Description of one of the schemes tried out by the Bureau of Standards for unidirectional radiobeacon work. Directive and non-directive fields are transmitted simultaneously with the proper phase and amplitude relations in order to obtain unidirectional effects.)

R570 Birnbaum, H. W. Die Fernlenkversuche der Reichsmarine in den Jahren 1916–1918. (The guiding experiments of the German Marine in the years 1916 to 1918). *Zeits. fur Hochfrequenztechnik*, 32, 162–170; November, 1928.

(A description of the system used for guiding airplanes by means of radio.)

R592 Crawley, C. A year's progress in commercial wireless. *Wireless World and Radio Review*, 23, 801–804; December 12, 1928.

(Discusses automatic S.O.S., position finding, jamming of broadcast, beam telephony.)

R800. Non-Radio Subjects

534 Ballantine, S. Note on the effect of reflection by the microphone in sound measurements. Proc. I. R. E., 16, pp. 1639–1644; December, 1928. *Physical Review*, 32, 988–992; December, 1928.

(Attention is called to the fact that ordinary microphones will not indicate the true pressure of an undisturbed sound wave for the entire audio-frequency band. The correction can, however, be found by employing a standard spherical mounting of which the diagram occupies a small area at the pole. A method of this type can, therefore, be used instead of obtaining the calibration curve with the Raleigh disk.)

534.3 Watanabe, Y. Über die vermittels einer Stimmgabel erregten Rohrenoszillatoren. (On tuning fork vacuum tube oscillators). *Zeits. für Hochfrequenztechnik*, 32, 116–121; October, 1928.

(The equations for these oscillators are derived and the mechanical as well as electrical oscillations are compared in order to give an expression for the frequency obtained in terms of the true frequency of the tuning fork.)

535.3 Barnard, G. P. The selenium cell: Its properties and applications. *Jnl.* I. E. E. (London), 67, 97–120; December, 1928.

(Gives the historical review on the work done with the selenium cell and describes the several factors affecting the conductance. Gives applications to photometric and relay problems and shows applications to the optophone, photophone, talking film and television. An extended list of references is given at the end of this paper.)

537.55 Pardue, L. A., Webb, J. S. Ionic oscillations in the glow discharge. *Physical Review*, 32, 946–49; December, 1928.

(A detailed experimental study of ionic oscillations in the glow discharge which was originally found by Widdington and Appleton.)

537.65 Tawill, E. P. Nouveau mode de developpement d'electricite par torsion dans les cristaux de quartz. (New method of production of electricity by torsion on quartz crystals). *Comptes Rendus*, 187, 1042–1044; December 3, 1928.

(A way was found of producing charges on a quartz cylinder axis along the optical axis when applying a torsion about this axis. Suggests calling it strepho-electricity, because it is different from ordinary piezo-electricity. Shows that for a twist in one direction charges of opposite polarity appear on the surface of the envelope of the cylinder and the faces perpendicular to the axis. A twist in the opposite direction reverses the polarity. The polarity also depends on the optical rotation.)

537.65 Mandell, W. The determination of the piezo-electric moduli of ammonium Seignette salt. *Proc.* Royal Society (London), 121A, 130–140; November, 1928.

(Theory and determination of the piezo-electric constants of ammonium Seignette salt.)

621.374.2 Landon, V. D. A bridge circuit for measuring the inductance of coils while passing direct current. Proc. I. R. E., 16, 1771–1775; December, 1928.

(Bridge circuit described in which inductance of coil is compared to resistances and a capacitance.)

CONTRIBUTORS TO THIS ISSUE

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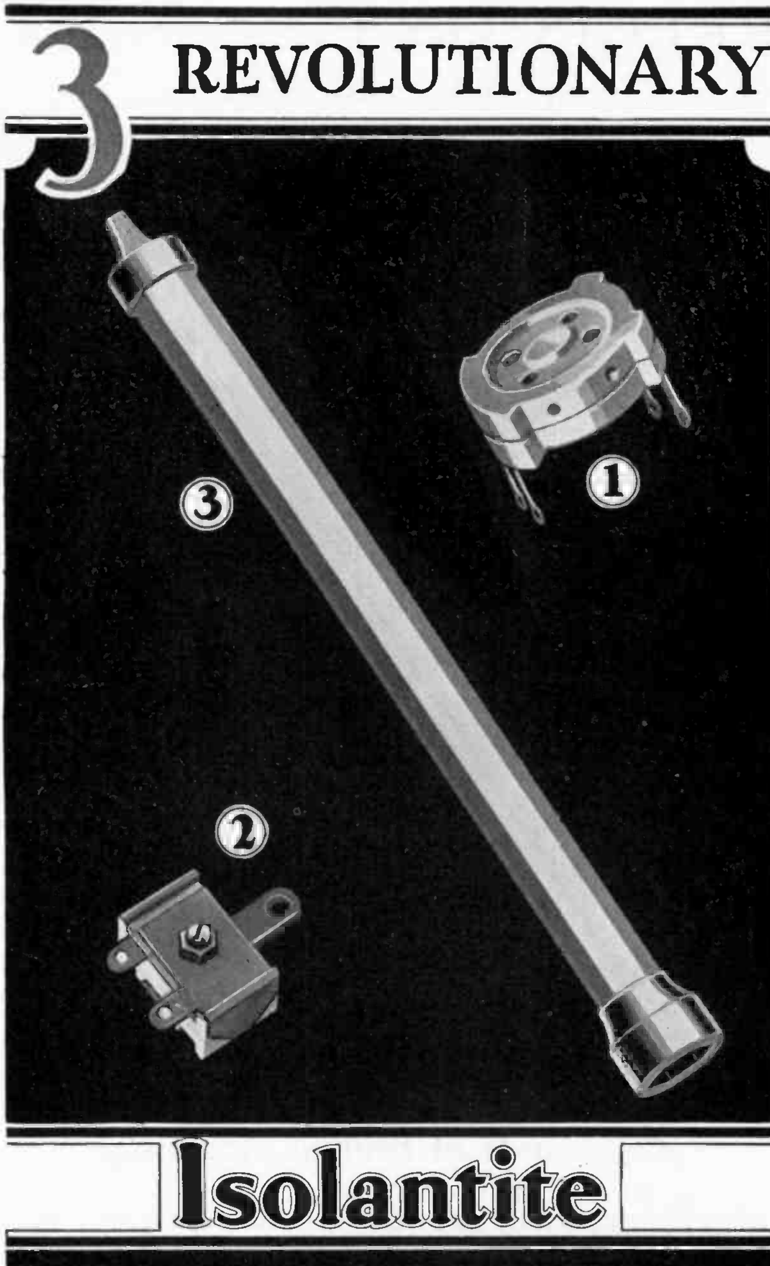
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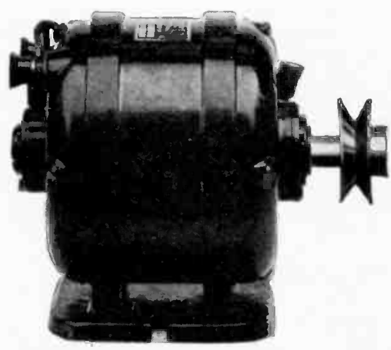

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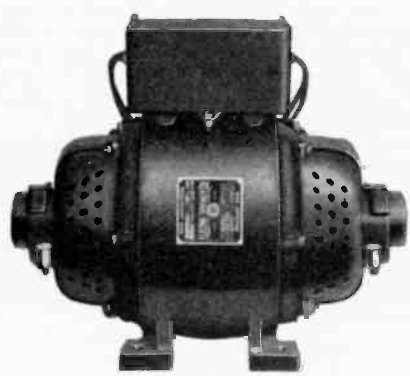

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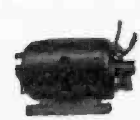

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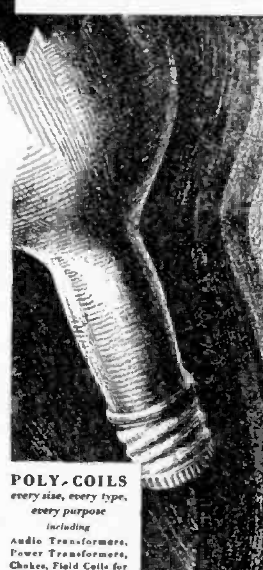

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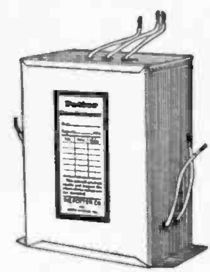

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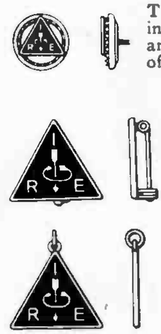

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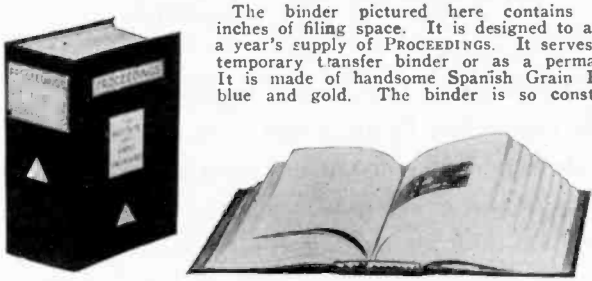

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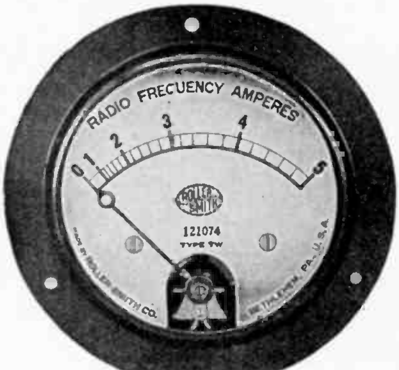
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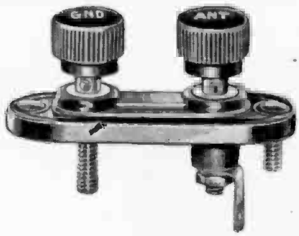

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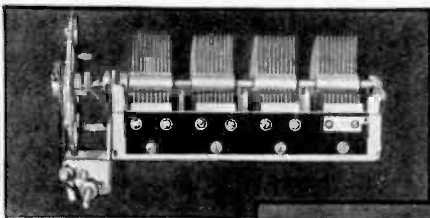

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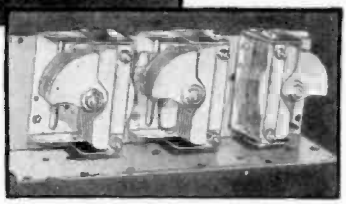

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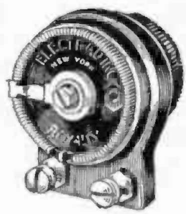

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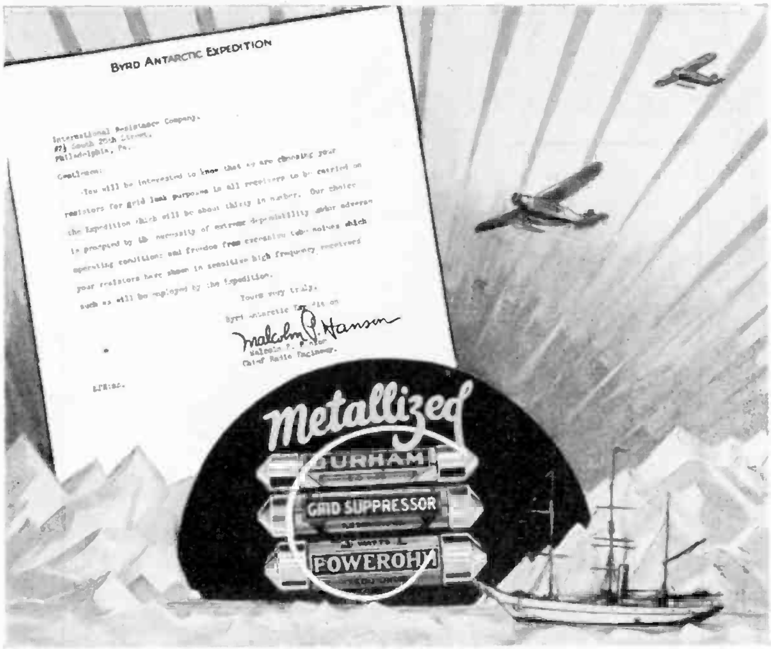

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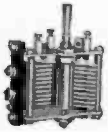

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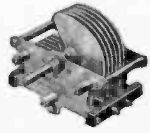

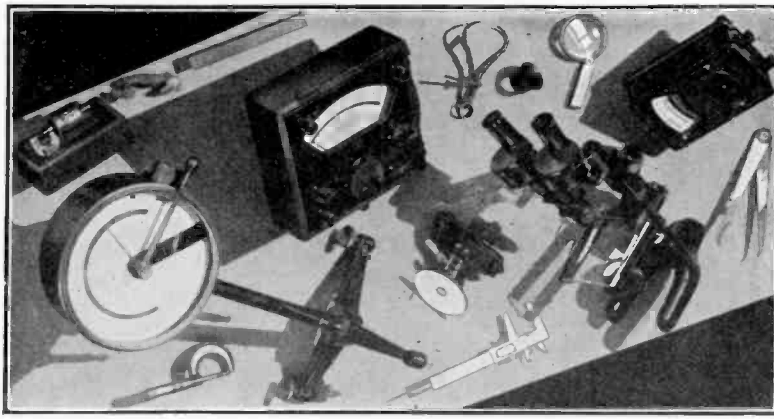

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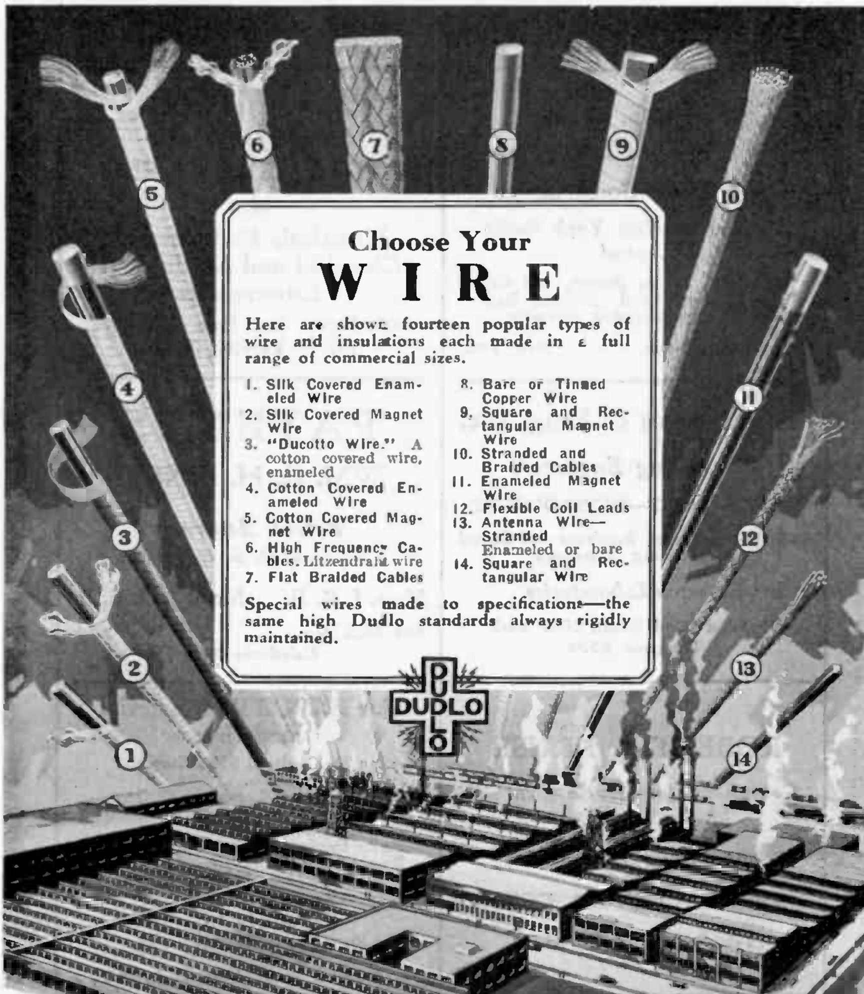

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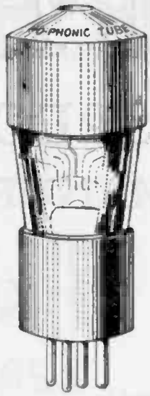

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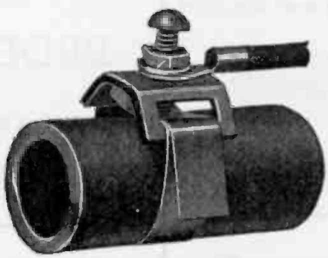

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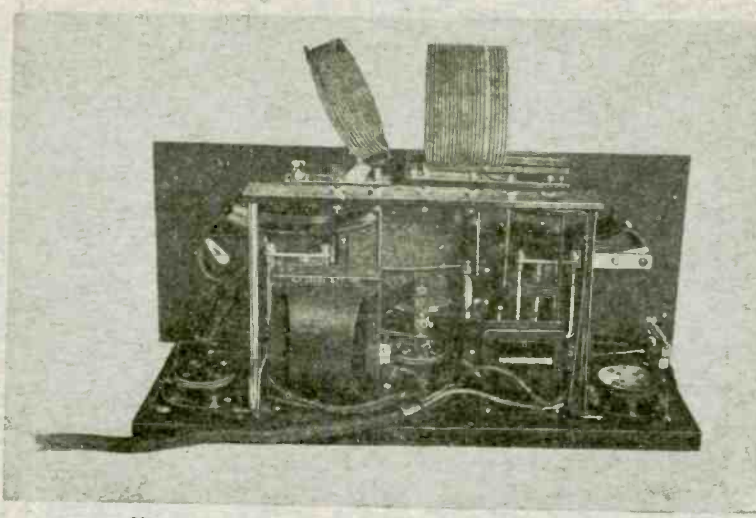

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