

Standards

on

RADIO WAVE PROPAGATION

—
MEASURING METHODS
—

1942



THE INSTITUTE OF RADIO ENGINEERS

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INTRODUCTION

The Technical Committee on Radio Wave Propagation has formulated these standard measuring methods in frequent meetings and correspondence under the general guidance of the Standards Committee. Published with the approval of the Board of Directors, the report embodies the Institute's official recommendations to its members and the industry at large.

Suggestions and comments will be welcomed as an aid to committees preparing future reports. Correspondence should be addressed to the Institute of Radio Engineers.

CONCERNING THE INSTITUTE AND ITS STANDARDS ACTIVITIES

The Institute appointed its first standards committee in 1912, and the next year published a report dealing with definitions of terms, letter and graphical symbols, and methods of testing and rating equipment. Expanded reports appeared in 1915, 1922, 1926, 1928, 1931, and 1933, each of which combined, in a single document, data on all branches of the art.

Publication of the current series of standards, of which this one is a part, was begun in 1938.* It differs from earlier reports in that each individual booklet deals with a separate field. Under present policies, subdivision is being carried even farther and separate booklets are being issued in each field for definitions of terms, for symbols, and for measuring and testing methods.

Beginning with 1942, all standards are being published in the 8 1/2- \times 11-inch size to conform with the new format for the PROCEEDINGS of the I.R.E.

Distribution of Standards Reports

The Institute is mailing one copy of this report to every member who is in good standing for 1942.

Additional copies, if available, may be obtained by members or nonmembers from the Institute office at the price mentioned on the inside back cover.

Co-operation with Other Organizations

Throughout its life, the Institute has co-operated with other bodies in the establishment of standards. Last year, for instance, there were more than 50 official I.R.E. delegates to other standardization groups. The Institute is also the sponsor for the American Standards Association's Sectional Committee on Radio.

The Institute of Radio Engineers

The Institute of Radio Engineers was founded in 1912 to advance the theory and practice of radio and allied branches of engineering and of the related arts and sciences, their application to human needs, and the maintenance of a high professional standing among its members. Although dominantly in the United States of America, the Institute membership of over 7000 persons is distributed throughout the world.

The PROCEEDINGS, which has been published since 1913, is issued monthly and contains contributions from the leading workers in the theoretical and practical fields of radio communication. It is forwarded to all members, who receive also the various standards reports which are published at irregular intervals.

Applications for membership are invited from those interested in radio. Full information may be obtained from the Secretary.

* For a detailed list of current standards reports, see the inside back cover.

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SECTION 1. METHODS OF MEASURING RADIO FIELD INTENSITY

1.1 GENERAL

Most measurements with which radio wave propagation is concerned involve the measurement of radio field intensity. Thus, the determination of power radiated from an antenna (Section 2) and the measurement of noise field intensity (Section 3) depend principally upon the measurement of field intensity. Standard methods for the measurement of this fundamental quantity are outlined here.

The general symbols and units used in this section are given in the following list. Where more specific or restrictive meanings are indicated by subscripts, etc., they are further defined after the equation in which used. In some cases a symbol definition is repeated where used, merely for convenience.

- C = capacitance, in farads
- d = distance from transmitter to receiver, in meters
- E = radio field intensity, in volts per meter
- f = frequency, in cycles per second
- I = current, in amperes
- l_L = effective length of loop antenna, in meters
- l_D = effective length of dipole antenna, in meters
- L_D = over-all physical length of a linear dipole antenna, in meters
- l_V = effective length of grounded vertical antenna, in meters
- L_V = over-all physical length of grounded vertical antenna, in meters
- M = mutual inductance, in henrys
- N = number of turns
- P = power, in watts
- Q = ratio of reactance to resistance in a resonant circuit
- R = resistance, in ohms
- S = area of loop antenna, in square meters
- V = voltage, in volts
- α = attenuator ratio (equal to or less than unity)
- λ = wavelength, in meters

As may be seen in this list, all units used are those of the mks electromagnetic system. A person employing other units must reduce to these units before using the equations herein. For convenience in making such reductions a few relations are given here:

- 1 mile = 1609. meters
- 1 meter = 0.0006214 mile
- 1 square inch = 0.0006452 square meter
- 1 square meter = 1550. square inches

PREFIXES

- | | |
|------------------------|---------------------|
| micro = one millionth | deka = ten |
| milli = one thousandth | hecto = one hundred |
| centi = one hundredth | kilo = one thousand |
| deci = one tenth | mega = one million |

Quantity	Name of mks unit	Number of cgs units in 1 mks unit
Length	meter	100
Area	square meter	10,000
Frequency	cycle per second	1
Voltage	volt	10^8
Radio field intensity	volt per meter	10^6
Current	ampere	1/10
Power	watt	10^7
Resistance	ohm	10^9
Conductivity	mho per meter	10^{-11}
Inductance	henry	10^9
Capacitance	farad	10^{-9}

1.11 THE TWO BASIC METHODS

Two general methods are applicable to the measurement of radio field intensity. One consists of measuring the voltage produced in a standard antenna by the field to be measured and computing the radio field intensity from the measured voltage and the dimensions and form of the standard antenna. The other consists of comparing voltages produced in an antenna by the field to be measured and by a standard field. The measuring sets for the two methods are of the same general form. For the standard-antenna method there are special requirements for the receiving antenna and the voltage-measuring equipment.

1.111 Standard-Antenna Method

The receiving antenna is of some standard form such that the voltage produced in it by a field of given intensity and polarization may be readily computed. The method of coupling the standard antenna to the voltage-measuring instrument is generally such that the voltage measured is not the voltage produced in the antenna by the field but bears a fixed ratio to it. This ratio (i.e., ratio of the voltage measured to the voltage produced in the antenna by the field) is called the voltage-transfer ratio; its magnitude is dependent upon the point of introduction of the calibrating voltage into the measuring circuit. Separate determination of it may be required.

A standard voltage source is provided, usually as part of the radio field-intensity-measuring apparatus, for calibrating the voltmeter. The term voltmeter is here used to mean the radio receiving portion of the equipment. The calibrating voltage may be fixed or it may be variable over a wide range. It may be inserted in series with the standard antenna or at some point in the coupling circuit, or it may be applied to the input

terminals of the voltmeter in place of the coupling circuit. When a fixed calibrating voltage is employed, the voltmeter is calibrated at a fixed sensitivity level, and a calibrated voltage attenuator is employed in conjunction with the voltmeter in order to measure voltages over the wide range required. Alternately, the voltage attenuator may be included in the standard voltage source; the calibrating voltage is then itself variable over a wide range and the voltmeter is calibrated at sensitivities corresponding to the voltages being measured. In either case, the measurement resolves itself into the comparison of two voltages, the known voltage and the voltage produced by the field, generally introduced at different points in the measuring circuit. The method used in determining the voltage-transfer ratio is generally dependent upon the particular form of antenna and the circuit arrangement employed.

The radio field intensity is computed on the basis of the antenna dimensions and form, the voltage-transfer ratio, the voltage from the standard voltage source, and the voltage-attenuator ratio.

1.112 *Standard-Field Method*

The standard field may be set up by a local transmitter. The field at the receiving antenna is computed from the dimensions of the transmitting antenna, its current and current distribution, the distance, and the effect of the ground. The measuring equipment associated with the receiving antenna generally consists of a sensitive vacuum-tube voltmeter employing double detection and with an indicator in the output of the second detector. While it is possible to adjust the standard field to equality with the field to be measured by varying the distance of the transmitter, it is usually more convenient to include an attenuator in the measuring equipment for comparing the voltages produced by the known and unknown fields and, hence, the two fields. When the angles of arrival of the standard and measured fields differ, a correction must be applied for any resultant difference in the voltages caused by directivity of the receiving antenna and effects of the ground.

1.12 SIMPLIFICATIONS AND PRECAUTIONS

The problem of radio field-intensity measurement is generally complicated by the varying nature of the field resulting from variability of the transmission medium, by the complex nature of the emission, and by the influence of the ground and of disturbing structures. Simplifications are introduced into measurement methods to keep the measuring apparatus from becoming unduly complex or unduly difficult to use or to facilitate analysis of the data.

In the case of ionospheric-wave fields, a really complete measurement would involve determination, from instant to instant, of the intensity of the vertical,

longitudinal, and lateral electric- and magnetic-field components in each wave arriving at the receiving point; of the phase angles between the different components; and of the direction of arrival of each wave component. Fortunately, considerable practical information may be obtained by measuring only the vector components of the field which are used for communication and by treating the data statistically so as to determine over-all effects. Simple forms of receiving antennas thus become useful, the type of antenna used being dependent upon the component of the field. Statistical treatment of the data may be facilitated by employing a recorder in the radio field-intensity-measuring apparatus.

A further example of simplification is in the measurement of complex emissions. Thus, with frequency- or amplitude-modulated waves, it is desirable to remove the modulation so that a single-frequency field (the carrier) is measured. In emissions without carrier waves, such as a single-sideband wave, it is desirable to restrict the modulation to a single frequency, so that a single-frequency field is again measured. Occasions arise, however, when it is necessary to retain the normal modulation; for example, when considering the interfering effect of the over-modulation products of an amplitude-modulated wave or the interfering effect of a single-sideband emission.

In the case of complete modulation by telegraph-code signals, a good approximation may be obtained by using a voltage-measuring device with a perfectly linear and highly damped response, taking account of the fact that such a device will measure one half (=6 decibels below) the maximum or "mark" field, if the average keying is 50-per-cent marking.

In analyzing or reporting measured data, it is important to take into account the influence of the receiving site and surroundings (including topography), electrical properties of the ground, the proximity of disturbing structures, etc., and the orientation and height above ground of the receiving antenna. In view of the effect of ground reflection, the question arises as to whether the measured values of the resultant field should be reported or an attempt should be made to measure (or compute) the value of the incident field. In the case of a well-defined incident angle and when the electrical properties of the ground are accurately known, such a measurement would indicate the actual variation of the field at points equidistant from the transmitter without regard to the nature of the ground at various receiving points. In general, dealing with the incident field will eliminate confusion in the study of laws of attenuation and in the measurement of the directional characteristics of antennas. However, the measurement of the incident field is always an indirect measurement involving a knowledge of the angle or angles of arrival and the electrical properties of the ground, and its proper determination thus introduces some difficulty.

A useful expedient under such circumstances is to use a horizontal doublet antenna for the measurement of resultant sky-wave fields, regardless of whether vertical or horizontal polarization is used. Practically, an equal amount of each type of polarization is present in the incident ionospheric-wave field for any condition of polarization at the transmitter. The advantage gained by receiving the resultant horizontal component is that the measured field is then practically independent of differences in the electrical properties of the ground at different receiving points. Hence, so long as the height of the receiving antenna above ground is stated or standardized, measurements (on a

given frequency) at different sites may be directly compared.

In some cases, even though the resultant field is largely influenced by the nature of the ground, it should nevertheless be the field measured since it provides a more nearly correct picture of the actual conditions encountered in service. This is particularly true for measurements at standard broadcast frequencies (550 to 1600 kilocycles) where the antenna used by the average listener is principally responsive only to the resultant vertical component of the ionospheric waves.

1.2 STANDARD-ANTENNA METHOD

1.21 THE ANTENNA

The form of the standard receiving antenna which may be employed is governed by the polarization of the field component to be measured, by the nature of the field (i.e., high or low intensity, fading or steady, frequency, etc.), and by the degree of convenience of handling the antenna. The types generally employed are the loop antenna, the vertical- or horizontal-dipole antenna with a length of one-half wavelength or less, and the simple vertical antenna with output between one end and ground. Other types of antennas are frequently used, in which case they are calibrated in terms of one of the simpler antennas just enumerated or in terms of a standard field.^{1,2}

The loop antenna may be used from the lowest frequency into the ultra-high-frequency range. Below about 3 megacycles, it is the practical equivalent of a vertical antenna (for low sky-wave angles), with the advantages of ease of computation of the voltage produced by a given field and convenience of handling (including the availability of a zero-response position). At higher frequencies, the effect of the response of the loop antenna to horizontal components of the electric field becomes more pronounced (since the loop antenna may then be at a substantial fraction of a wavelength above ground) so that the null becomes ill-defined, and there is increasing difficulty in defining the polarity of the component measured. Also, as the frequency is increased, there is increasing difficulty of securing a balanced connection of the loop antenna to the voltage-measuring set; moreover, because of the desirability under some circumstances for maintaining substantially uniform current distribution along the loop antenna, its pickup decreases rapidly with increasing frequency. At ultra-high frequencies, the loop antenna again becomes the practical equivalent of the vertical antenna, since low-angle reception is generally involved; however, technical difficulties in its use are materially increased.

¹ H. Pender and K. McIlwain, "Electrical Engineers Handbook," volume 5, "Electric Communication and Electronics," third edition, John Wiley, New York, N. Y., 1936.

² J. V. Cosman, "Portable field-intensity meter," *Communications*, vol. 18, pp. 22-23; September, 1938.

The shielded type of loop antenna has come into general use for direction finders and has been applied successfully in radio field intensity-measuring work. With this type of antenna, the loop-antenna circuit is generally not symmetrical with respect to ground, but it is desirable that the loop antenna shield be split at the top so that the shield is symmetrical with respect to ground.

The simple vertical antenna with output between one end and ground is conveniently applicable in the range from low frequencies up to about 30 megacycles. Care must be taken to make sure that the indicated voltage is not partly due to voltage induced in the ground system. A small symmetrical counterpoise ground is usually desirable.

The dipole type of antenna is generally applicable at frequencies above about 3 megacycles. It is particularly convenient at frequencies above 40 megacycles.

In addition to the foregoing, a type of antenna is occasionally used consisting of spaced parallel plates with a short conductor between centers.

Measurements of radio field intensity in established radio communication services are often made with more complex types of antennas or arrays. They afford the advantages of operating convenience and noise discrimination. The complex antenna is calibrated by comparison with either a loop antenna or a dipole antenna; however, this calibration may be of limited significance because of difference in the vertical directivity of the array and the comparison antenna.

1.22 CALIBRATION METHODS

In practice, a variety of circuit combinations are employed to carry out the standard-antenna method of radio field-intensity measurement. They are all essentially of the fundamental form previously described but differ primarily in the manner of calibrating the voltmeter.

1.221 Loop-Antenna Calibration

Figs. 1(a) and (b) illustrate two methods of loop-antenna calibration that have been used over the frequency range below 10 or 15 megacycles. In both, the

loop antenna is oriented and tuned for maximum output. The receiver attenuator is adjusted to give any convenient deflection on the output meter *m* and left at this setting. Then, with the loop antenna turned to a right-angle position so that the measured output is

where *M* = mutual inductance of coupled input, in henrys. Substituting from (2), (4) becomes

$$E = 3(10)^8 \frac{\alpha MI}{SN} \tag{5}$$

In Fig. 1(a) and Fig. 1(b) the calibrating voltage injected into the loop antenna may in some instances be a fixed value. In such cases, the relationship between the field and calibrating voltages is determined by a calibrated attenuator in the receiver or by a calibrated output indicator.

Owing to difficulties that have been experienced with attenuator design at frequencies above a few megacycles, another method of calibration, illustrated schematically in Fig. 2(a), has been employed³ extensively in the high-frequency range. The comparison-voltage attenuator is eliminated, and the receiver attenuator (which in the previous instances was not necessarily calibrated) is placed in the intermediate-frequency stages of a superheterodyne amplifier and accurately calibrated. At intermediate frequencies of the order of a few hundred kilocycles this is readily possible. To make a measurement, the loop antenna is oriented and tuned for maximum output, and the calibrated receiver attenuator is adjusted to give any convenient deflection on the meter *m* (Fig. 2(a)), then the attenuator ratio α is recorded, after which considerable attenuation is added and the comparison-voltage generator is turned on and tuned to the

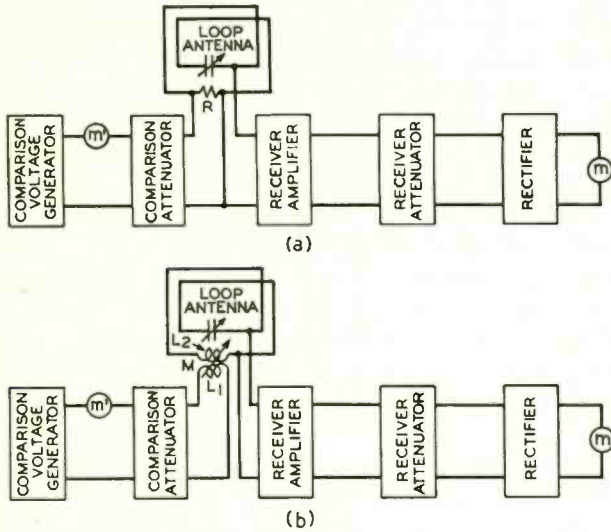


Fig. 1—Measuring sets using calibration input at level of field to be measured.

low, the comparison-voltage generator is turned on and tuned to approximately zero beat with the residual measured field, and the comparison-voltage attenuator is adjusted to give the same indication on meter *m* that was obtained when receiving the measured field. From the indication of meter *m'* and the comparison-attenuator setting, the current through the resistance *R* of Fig. 1(a) or inductance *L*₁ of Fig. 1(b) may be determined.

In the first case, when the natural resonance frequency of the loop antenna alone is at least two or three times that of the field measured, the measured radio field intensity *E* in volts per meter is

$$E = \frac{\alpha IR}{l_L} \tag{1}$$

where α = comparison-attenuator ratio (equal to or less than unity)

I = current at input to comparison attenuator, in amperes

R = resistance shown in Fig. 1(a), in ohms

*l*_L = effective length of loop antenna, in meters, defined as follows:

$$l_L = 2.094(10)^{-8} fSN \tag{2}$$

or

$$l_L = \frac{2\pi SN}{\lambda} \tag{3}$$

For Fig. 1(b), with a similar precaution concerning design,

$$E = 2\pi \frac{\alpha fMI}{l_L} \tag{4}$$

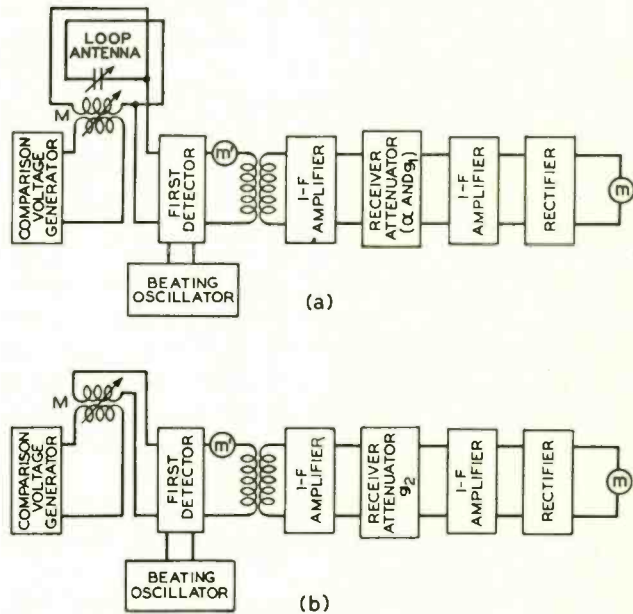


Fig. 2—Measuring set using high-level input for calibration.

frequency of the field to be measured. The beating oscillator is then turned off, and, using the first detector as a vacuum-tube voltmeter, the coupling *M* between the comparison-voltage generator and the loop antenna is adjusted to give *V* volts input as

³ H. T. Friis and E. Bruce, "A radio field-strength measuring system for frequencies up to forty megacycles," Proc. I.R.E., vol. 14, pp. 507-519; August, 1926.

indicated by meter m' (Fig. 2(a)) in the first-detector plate circuit. The beating oscillator is then turned on, and the receiver attenuator is then adjusted to give the same indication of meter m that was used in the field measurement. The attenuator ratio is recorded and considered as "set gain" g_1 .

Without changing the coupling M , a switch is thrown which effectively converts the first part of the circuit in Fig. 2(a) to that shown in Fig. 2(b). The voltage originally produced in the loop antenna is thus measured directly. The loop-antenna step-up or Q is normally so great that this measurement cannot be made on meter m' . It is determined by again adjusting the receiver attenuator to give the original field reading on meter m . This attenuator ratio may be called g_2 . The radio field intensity in volts per meter is

$$E = \frac{g_1^2 V}{\alpha g_2 l_L} \quad (6)$$

where V = voltage input to first detector as read by meter m' (= voltage from comparison-voltage generator multiplied by half the loop-antenna Q factor)

α = receiver-attenuator ratio (equal to or less than unity) to give a convenient deflection of meter m for antenna voltage produced by the field

g_1 = receiver-attenuator ratio (equal to or less than unity) to give same deflection of meter m when V volts are applied to the input of the first detector

g_2 = receiver-attenuator ratio (equal to or less than unity) to give the same deflection of meter m when the voltage from the comparison-voltage generator is applied to the input of the first detector.

If desired, V may be made one volt, all attenuator ratios given in decibels, and the effective length of the loop antenna expressed as decibels above 1 meter as L_L , so that an expression for the field in decibels above 1 volt per meter in this case is

$$E_{db} = 2G_1 - A - G_2 - L_L \quad (7)$$

where all quantities are the equivalent in decibels of those represented by the small letters of (6); the letter A corresponds to α .

An important requirement in connection with the above method of measurement is that the amplification of the amplifier be the same for the high input used during calibration as it is when receiving weak fields. It is also important to avoid nonlinearity of the first detector.

In another method of calibration, the calibrating voltage is applied to the input of the vacuum-tube voltmeter and is adjusted to equality with the voltage developed across the input by the loop antenna. A measurement of the voltage step-up in the loop antenna

is then required for computing the field voltage induced in the loop antenna. The radio field intensity is computed on the basis of the induced-field voltage and the antenna dimensions.

The method of measuring the voltage step-up factor is such as to avoid errors which arise from the distributed capacitance between turns of the loop antenna, when the calibrating voltage is inserted in the center of the antenna. The method utilizes a precision variable condenser of low capacitance connected in parallel with the tuning condenser. The condenser is set at its mid-value for loop-antenna resonance and is adjusted on either side of resonance until the voltage across the condenser drops to 0.707 times its value at resonance. Then, calling C_1 and C_2 the two corresponding capacitance values of the auxiliary condenser, and $\Delta C = C_2 - C_1$, the Q of the loop antenna may be shown to be very nearly equal to

$$Q = \frac{2C}{\Delta C}, \quad (8)$$

where C represents the total tuning capacitance at resonance.

Thus, if V is the voltage across the antenna-tuning condenser, the radio field intensity in volts per meter is

$$E = \frac{V}{l_L Q} = \frac{V \Delta C}{2l_L C}. \quad (9)$$

It should be noted that V is the total voltage across the tuning condenser.

Generally speaking, the errors in the final result depend on four factors, namely, errors in computation of effective length, errors in determination of voltage-transfer ratio, errors in the calibrating current or voltage, and errors in the attenuating means. The error in the determination of voltage-transfer ratio is generally less than 3 per cent if the working frequency is greater than 2.5 times the natural frequency of the loop antenna.

The accuracy of measuring the calibrating current or voltage is dependent on the instrument used. If instruments of the rectifier type such as vacuum-tube voltmeters are used, errors of about 10 per cent (about 1 decibel) can result if the waveform of the voltage-generator output is not sinusoidal.

Errors in the attenuating means depend on design, construction, and calibration.

A loop antenna tuned to a frequency differing by a fixed amount from the operating frequency is particularly suitable for measuring high field intensities of the order of 10 millivolts per meter to 50 volts per meter. The Q factor of the loop antenna may be computed directly from the values of the operating frequency and the frequency to which the loop antenna is tuned. Furthermore, since the operation is considerably off resonance, the error in the determination of voltage-transfer ratio may be made negligible.

In this method the loop antenna is tuned to a known frequency f_1 which differs from the operating frequency f by at least 10 per cent. The calibrating voltage is applied directly to the input circuit of the voltmeter, replacing the loop antenna. A voltage attenuator operating at an intermediate frequency is used to compare the voltage delivered by the loop antenna (across one half the tuning condenser) with

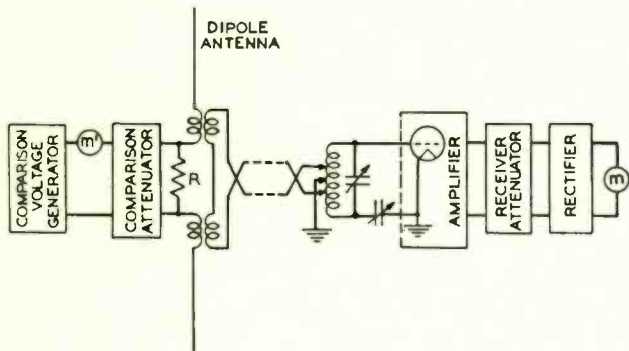


Fig. 3—Measuring set using dipole antenna.

the calibrating voltage. The voltage induced in the loop antenna by the measured field is computed from the measured voltage and a voltage step-up factor derived from the ratio of the operating frequency to the frequency to which the loop antenna is tuned, f/f_1 . The radio field intensity is computed from the induced voltage and the dimensions of the loop antenna.

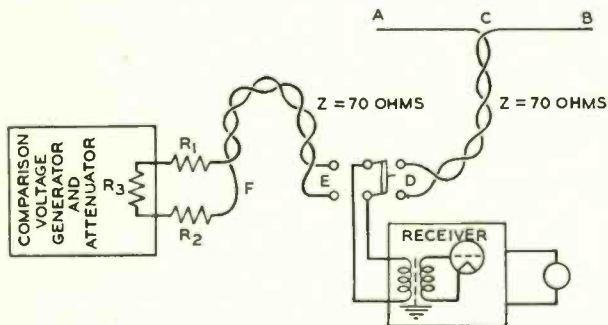


Fig. 4—Measuring set using dipole antenna.

The voltage step-up Q at the operation frequency f is

$$Q = \frac{f_1 Q_1}{2f \sqrt{1 + Q_1^2 \left(\frac{f_1}{f} - \frac{f}{f_1} \right)^2}}, \quad (10)$$

where Q_1 is the voltage step-up at the frequency f_1 to which the loop antenna is tuned.

For $f/f_1 < 0.9$ and usual practical values of Q_1 , the voltage step-up is given within 1 per cent by the simple expression

$$Q = \frac{1}{2(1 - (f/f_1)^2)}. \quad (11)$$

1.222 Dipole-Antenna Calibration

The methods of calibration used in a measuring set with a loop antenna may, in general, be applied to a half-wave dipole antenna.

One of the several possible direct methods of calibration is illustrated schematically by Fig. 3. The output of a comparison-voltage generator indicated on meter m' is attenuated by a known amount before passing through the resistance R . If the current through meter m' is I and the comparison-attenuator ratio α , the voltage in the dipole system is αIR . If, without disturbing the receiver, the comparison attenuator is adjusted to give the same deflection on the measuring-set output meter m as was obtained when receiving the field, then the radio field intensity in volts per meter is

$$E = \frac{\alpha IR}{l_D}, \quad (12)$$

where l_D is the effective length of the dipole antenna in meters. It is defined as follows:

$$l_D = \frac{L_D}{2} \frac{\tan \frac{\pi L_D}{2\lambda}}{\frac{\pi L_D}{2\lambda}}, \quad (13)$$

where L_D = the over-all physical length of the dipole antenna, in meters.

The effective length of a half-wave dipole antenna, consequently, λ/π . When the dipole antenna is very short compared to the wavelength, the effective length is practically one half of the over-all physical length.

A calibration of this kind can be accomplished satisfactorily only when the measured field is absent, since the dipole antenna does not offer as convenient a means for suppressing the received field as a loop antenna that may be rotated. To use such a method in the presence of the measured field it is necessary to provide a known attenuation ratio of about 10 (i.e., 20 decibels) or more in the receiving circuit ahead of meter m and to arrange for this to be switched into the circuit when calibrating.

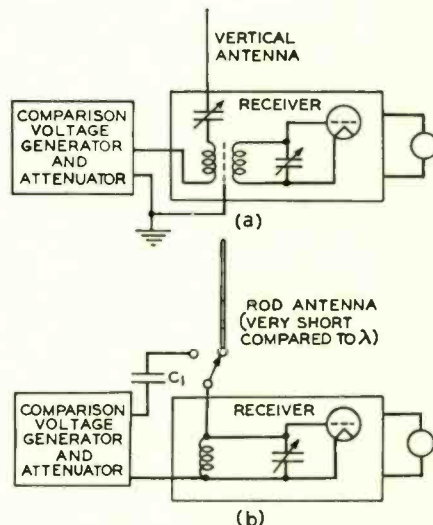
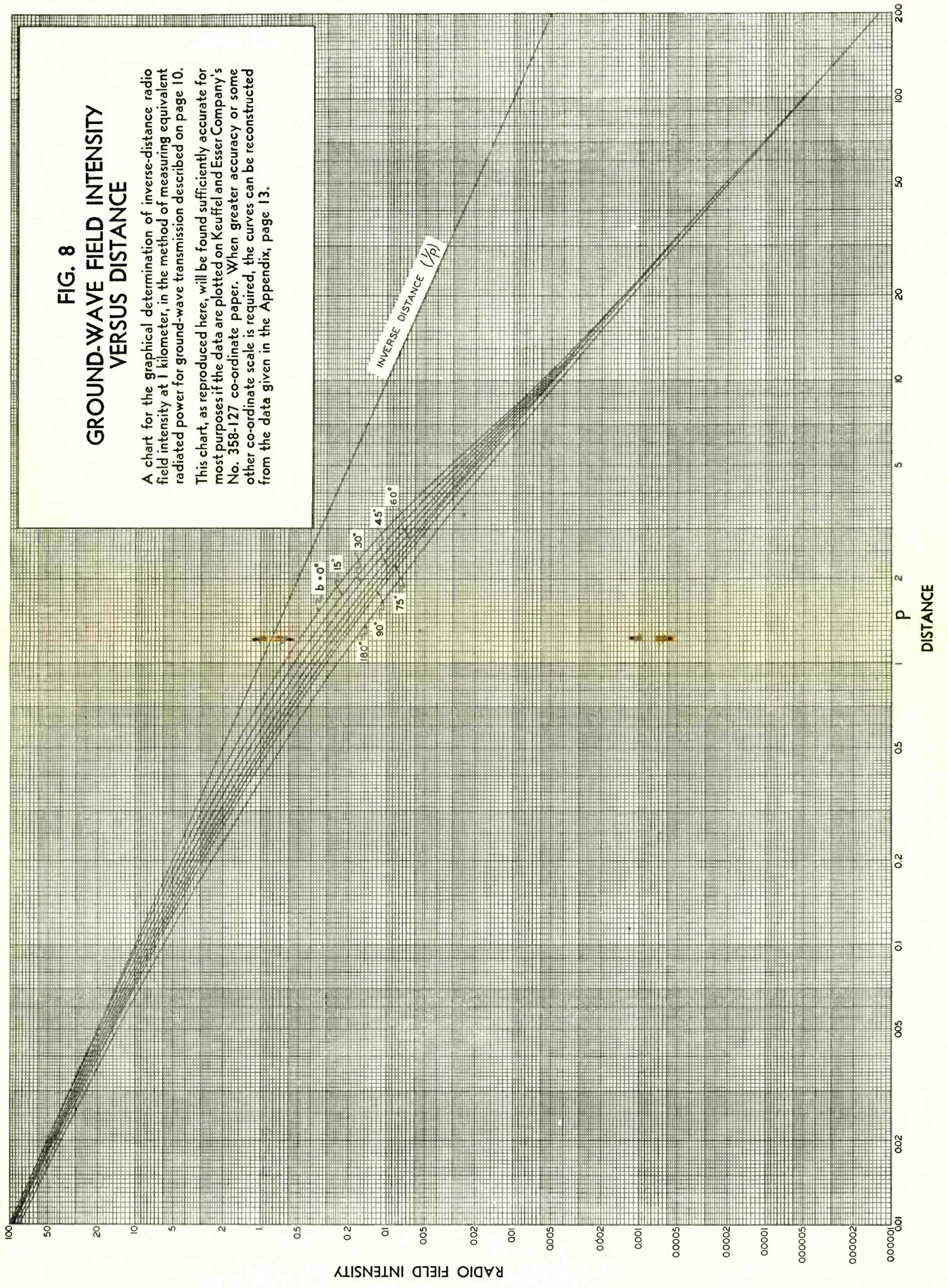


Fig. 5—Measuring sets using a vertical antenna with output from one end against ground. The setup is to be mounted on a tripod or other insulating support. In (b), C_1 is made equal to the capacitance of the rod antenna.

FIG. 8
GROUND-WAVE FIELD INTENSITY
VERSUS DISTANCE

A chart for the graphical determination of inverse-distance radio field intensity at 1 kilometer, in the method of measuring equivalent radiated power for ground-wave transmission described on page 10.

This chart, as reproduced here, will be found sufficiently accurate for most purposes if the data are plotted on Keuffel and Esser Company's No. 358-127 co-ordinate paper. When greater accuracy or some other co-ordinate scale is required, the curves can be reconstructed from the data given in the Appendix, page 13.



Another arrangement for making measurements with a dipole antenna is shown in Fig. 4. This system has been used in the frequency range from 4 megacycles to well above 100 megacycles.

In this arrangement the dipole antenna is operated at half-wave resonance. Generally it will have a length about 95 per cent of a half wavelength. For this condition it will have an impedance Z of about 70 ohms and an effective length of 0.31 wavelength.

For this system the following constants are used:

$$AB = 0.475\lambda$$

$$\text{effective length} = 0.31\lambda$$

$$EF = CD$$

$$R_1 + R_2 + R_3 = 70 \text{ ohms}$$

$$\text{generally } R_3 < R_1 \text{ and } R_2$$

The procedure is to determine the voltage-generator output V to give the same receiver output as given by the field being measured. V is then divided by effective length to give the radio field intensity in volts per meter.

In cases where the voltage drop in line CD is known, line FE may be made short and the voltage drop accounted for in the calculation of results.

It should be noted that the assumption that the

dipole antenna impedance Z is 70 ohms is an approximation subject to appreciable error, if the dipole antenna is operated in a location less than a half wavelength from a reflecting surface.

1.223 Calibration of Simple Vertical Antenna

Arrangements for measuring radio field intensity with a simple vertical antenna with output between one end and ground are shown in Fig. 5 (a) and 5 (b).

The effective length of a grounded vertical antenna (in meters) may be defined as follows:

$$l_v = \frac{L_v}{2} \frac{\tan \frac{\pi L_v}{\lambda}}{\frac{\pi L_v}{\lambda}}, \quad (14)$$

where L_v = over-all physical length of grounded vertical antenna, in meters.

When the vertical antenna is very short compared to the wavelength, the effective length is practically one half of the over-all physical length.

In Fig. 5(b) is shown a method particularly applicable to rod antennas which are very short compared to wavelength. In this arrangement the receiver is calibrated through a capacitance C_1 which is made equal to the capacitance of the rod antenna.

1.3 STANDARD-FIELD METHOD

The standard-field method of radio field-intensity measurements consists of setting up a known field at the receiving antenna, generally through the agency of a local transmitter,⁴ and comparing the voltages induced in the receiving antenna by the known and unknown fields.

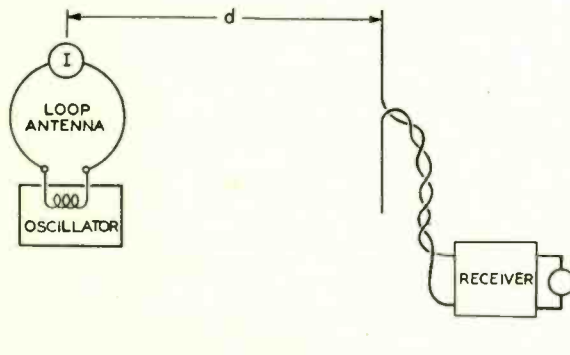


Fig. 6—Over-all calibration by field from a local transmitter.

The local transmitter generally employs a loop antenna, because of the ease in computing its radiation and of checking stray radiation from the transmitter. At frequencies above about 40 megacycles, some form

⁴ J. C. Schelleng, C. R. Burrows, and E. B. Ferrell, "Ultra-short-wave propagation," Proc. I.R.E., vol. 21, pp. 427-463; March, 1933.

of open antenna may be used, as for example the parallel-plate antenna or the rod antenna.

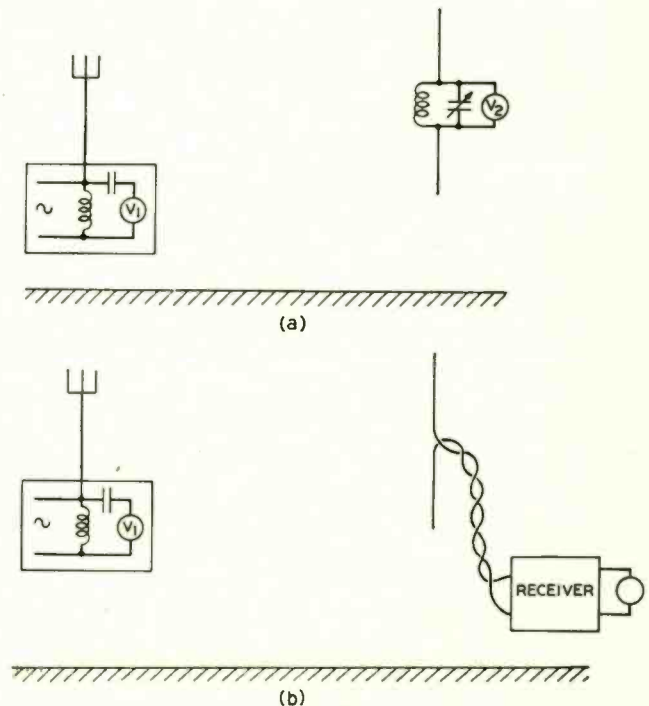


Fig. 7—Over-all calibration by radiated field.

The field at the receiving antenna is computed from the dimensions of the transmitting antenna, its current and current distribution, the distance, and the effects of the ground, taking into account the elevations of the transmitting and receiving antennas.

The method is illustrated in Fig. 6. At the higher frequencies it is generally possible to reduce the effect of ground to a small value by suitable choice of the elevations and distance apart of the transmitting and receiving antennas.

The radio field intensity at short distances from a radiating loop antenna in free space in volts per meter is

$$E = 1.316(10)^{-14} \frac{f^2 N S I}{d} \sqrt{1 + \frac{2.28}{f^2 d^2}} (10)^{15} \quad (15)$$

$$\text{or } E = \frac{120\pi^2 N S I}{\lambda^2 d} \sqrt{1 + \left(\frac{\lambda}{2\pi d}\right)^2} \quad (16)$$

When the distance between the radiating loop antenna and the receiving antenna is a half wavelength, the radical expression becomes $\sqrt{1+0.101}$ which is about 1.05 (0.4 decibel above unity). Hence the sec-

ond term increases the field to 1.05 (=0.4 decibel above) the radiation field at this distance.

Another method of calibration using the field radiated by a local transmitter is shown in Fig. 7. In this system the local transmitter is provided with an instrument having considerable scale range and a reading proportional to antenna current. A vacuum-tube voltmeter V_1 may be used for this purpose. A range of several hundred to one (50 or 60 decibels) is readily obtainable in a multirange instrument. Transmitter output can be adjusted by variation of voltage or other means.

The first step is shown in Fig. 7 (a). Here the transmitter is set to radiate high power and the reading of V_1 observed. The field at a desired location is measured directly by means of a dipole and a simple voltmeter V_2 . This operation gives radio field intensity for that value of V_1 for that location of receiving antenna.

The antenna of the system to be calibrated is then placed in that location (Fig. 7(b)) and the transmitter output reduced by an amount indicated by V_1 . The radio field intensity is now at a value directly derived from the previous operation and may be used to calibrate the over-all sensitivity of the receiving system.

1.4 MISCELLANEOUS

1.41 ACCURACY OF MEASUREMENT

The precision attainable in practice depends not only upon the design of the equipment but upon the conditions under which the measurements are taken. The number of operating steps required in taking a reading, the number of instruments which must be read, and the number of adjustments to be made all have a bearing on the attainable accuracy. Assuming ideal conditions of location, weather, operation personnel, etc., an accuracy to within about 5 per cent (about $\frac{1}{2}$ decibel) can be attained for frequencies below about 3 megacycles per second, and an accuracy to within about 10 per cent (about 1 decibel) for frequencies from about 3 to about 100 megacycles per second. The foregoing estimates are for a range of radio field intensities from about 100 microvolts per meter to about 1 volt per meter. Under usual operating conditions the accuracies may not be better than to within about 10 per cent (about 1 decibel) for frequencies below 3 megacycles per second and to within 40 per cent (3 decibels) for frequencies from 3 to 100 megacycles.

The attainable accuracies cited for ideal conditions appear to be adequate for practical purposes although improvement in the precision of measurements is always acceptable. It is desirable that the accuracy⁵ of measurement of any data reported be stated.

1.42 AUTOMATIC RECORDING

In the measurement of fields of variable intensity, such as ionospheric-wave fields and disturbance fields, the accumulation of data is facilitated by the use of automatic recording methods. Arrangements for adapting the measuring apparatus to provide for recorder operation have been treated in a number of publications. The rectified output of the intermediate-frequency amplifier is used for automatic volume control of the amplifier and also, by direct-current amplification, for operating the recorder. Ordinary receiving equipment may also be adapted for radio field-intensity recording by connecting the recorder in the plate circuit of one or more of the tubes under automatic volume control. In either case, a substantially logarithmic relation between the recorder deflection and the radio field intensity may be obtained and is convenient in view of the great time variation of intensity often encountered.⁶⁻¹⁰

⁵ Harry Diamond, Kenneth A. Norton, and Evan G. Lapham, "On the accuracy of radio field-intensity measurement at broadcast frequencies," *Nat. Bur. Stands. Jour. Res.*, vol. 21, pp. 795-818; December, 1938.

⁶ W. W. Mutch, "A note on an automatic field-strength and static recorder," *PROC. I.R.E.*, vol. 20, pp. 1914-1919; December, 1932.

⁷ K. A. Norton and S. E. Reyrer, "A continuous recorder of radio field intensities," *Nat. Broad. Sys. Jour. Res.*, vol. 11, pp. 373-378; September, 1933.

⁸ R. K. Potter and A. C. Peterson, Jr., "The reliability of

The time constant of the automatic-volume-control circuit will determine whether nearly instantaneous values¹¹ of the field or values representing short-time averages are obtained. The choice of the time constant will depend upon the ultimate use to be made of the measured data. It will be evident from the following remarks that a short time constant should be chosen, if the measured data are to be used in indicating the variations caused by the phase interference of waves arriving over various transmission paths; whereas a time constant long compared to the fading period may be chosen, if the measured data are to be used for showing the effects of variation in the transmission medium from hour to hour, day to day, season to season, etc.

A useful presentation of the measured data for fading fields is obtained by showing graphically the radio field intensities exceeded for various percentages of the time. It is obvious that for an accurate representation of the distribution of radio field intensities over a short time, such a graph must be determined from measurements of instantaneous radio field intensity. This graph will correspond to the Rayleigh distribution curve and will remain the same for time periods during which the layer absorption remains constant (i.e., up to about one hour). However, it can be shown that, if a graph representing the distribution of radio field intensities over a long time period is desired, accurate results will be obtained whether the graph is computed from instantaneous measurements or measurements which correspond to short-time averages of the instantaneous radio field intensities. This arises from the fact that the variations caused by changes in layer absorption are usually much larger and thus of greater influence than the short-time variations due to phase interference. An obvious advantage of using average values is that these may be obtained automatically by a proper choice of time constant in the measuring apparatus, and a material reduction in the work of analyzing the records is thereby obtained.

short-wave radio-telephone circuits," *Bell Sys. Tech. Jour.*, vol. 15, pp. 181-196; April, 1936.

⁹ J. P. Taylor, "Graphic recording of field intensities," *Broadcast News*, vol. 23, pp. 6-9, 28, 33; December, 1936.

¹⁰ Testimony of K. A. Norton, R. Bateman, and C. A. Ellert at Federal Communications Commission hearing on Ship Power, November 14, 1938. (F. C. C. mimeo 30539.)

¹¹ Lord Rayleigh, "On the resultant of a large number of vibrations of the same pitch and of arbitrary phase," *Phil. Mag.*, vol. 10, pp. 73-78; 1880. Also, "Theory of Sound," by Lord Rayleigh, second edition, paragraph 42a, Macmillan and Company, London, England, 1894. This problem is also treated in the "Collected Works" of Lord Rayleigh.

An integrating circuit of about 1 minute charge and 1 minute discharge time constants has been found useful for many purposes.

1.43 RECEIVING-ANTENNA POWER OUTPUT

When using certain types of antennas, a consideration of the relation between impressed radio field intensity and power output of the receiving antenna is sometimes of more practical use than a determination of open-circuit voltage. The receiver with a calibrated resonant circuit at its input then simulates a wattmeter rather than a voltmeter. The antenna is connected either directly or through a transmission line to this wattmeter, and, if the transmission loss is known, the power in the antenna may be determined. When the antenna impedance matches that of the connected circuits, half of the power is dissipated in the antenna and the remainder in the connected system including the wattmeter.

The maximum power output in watts of a receiving dipole antenna operated at half-wave resonance is, very nearly:

$$P = 3.12(10)^{13} \frac{E^2}{f^2} \quad (17)$$

or,

$$P = \frac{\lambda^2 E^2}{2885}. \quad (18)$$

1.44 PRESENTATION OF THE DATA OF MEASUREMENT

In view of the several factors which influence measured values of radio field intensity, information pertaining to the following should be provided to render measurement data generally useful:

- (a) statement of which vector component of the field is measured;
- (b) complete description of the measuring location and antenna setup, including topography, electrical properties of the ground, the proximity of disturbing structures, orientation of the receiving antenna and its height above ground, etc.;
- (c) detailed description of the measuring equipment and procedure;
- (d) in the case of ionospheric-wave fields, the time distribution of instantaneous or short-time-averaged radio field intensities throughout the time occupied by the measurements;
- (e) for measurements made in the proximity of the ground, statement of which field is measured, i.e., incident or resultant;
- (f) estimated accuracy of the measurements.

1.5 ADDITIONAL REFERENCES

A. A. Pistolkors, "The radiation resistance of beam antennas," *Proc. I.R.E.*, vol. 17, pp. 562-579; March, 1929.

P. S. Carter, "Circuit relations in radiating systems and ap-

plications to antenna problems," *Proc. I.R.E.*, vol. 20, pp. 1004-1041; June, 1932.

S. Goldman, "Dipoles and reflectors, a short review," *Electronics*, vol. 13, pp. 20-22; May, 1940.

SECTION 2. METHODS OF MEASURING POWER RADIATED FROM AN ANTENNA

2.1 GENERAL

This section outlines briefly methods of measuring the radiated power of an antenna and describes the important considerations for securing useful and accurate measurements. In all the methods, radiated power is calculated from measured radio field intensities.

The general symbols used in this chapter are the same as those used in Section 1 (page 1). The following additional symbols are used in this Section:

E_D = radio field intensity of direct wave, in volts per meter

F = radiation efficiency of antenna system

h_1 = elevation above ground of transmitting antenna, in meters

h_2 = elevation above ground of receiving antenna, in meters

P_e = equivalent radiated power, in watts

P_i = power input to antenna, in watts

ϵ = specific inductive capacitance of the ground, i.e., ratio of permittivity (dielectric constant) of the ground to that of air

σ = ground conductivity, in mhos per meter

2.2 EQUIVALENT RADIATED POWER FOR GROUND-WAVE TRANSMISSION

This method is primarily useful at frequencies below 5 megacycles. The equivalent radiated power for ground-wave transmission may best be determined by the measurement of radio field intensity near the antenna. The method applies for the antenna at the ground or not more than 1 wavelength above the ground. If the soil were a perfect conductor; if the radiation pattern of the antenna were perfectly circular; if all measuring points gave absolutely reliable results; and if the distance of the measuring point from the antenna were determined with perfect accuracy; the radiated power could be obtained by the measurement of the radio field intensity at a single point and by using the following general relation between radiated power and measured radio field intensity:

$$P_e = \frac{E_1^2}{E_2^2} \quad (19)$$

where E_1 = measured inverse-distance radio field intensity at 1 kilometer

E_2 = radio field intensity from an ideal antenna having the same effective length as the actual antenna, at 1 kilometer, for 1 watt radiated, from Fig. 9.

The relation between radio field intensity and effective length^{12,13} shown by Fig. 9 assumes an ideal antenna having a sinusoidal current distribution.

Actually the theoretical measuring conditions enumerated above cannot be expected in practice, and the accurate determination of the 1-kilometer radio field intensity is considerably more involved than the making of a single measurement of radio field intensity. Possible errors in measuring the radio field intensity near the antenna include (a) errors in determining the exact distance of the measuring point from the an-

tenna; (b) the possibility that the value of radio field intensity at that particular measuring point is not representative but is influenced by directivity of the radiated pattern, uneven terrain, proximity of overhead wires, and in some cases underground conductors; and (c) inherent inaccuracy of the radio field-intensity meter plus the inaccuracy caused by the observer in the operation of the equipment.

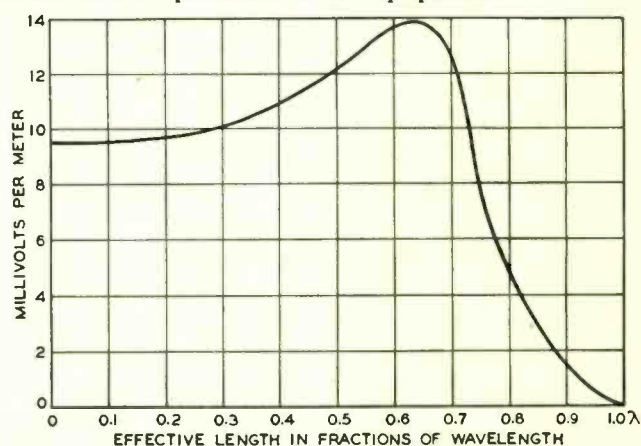


Fig. 9—Unattenuated radio field intensity at 1 kilometer from an ideal antenna, for 1 watt radiated.

The measurements of radio field intensity should be made on a number of equally spaced radials, each extending from about 0.8 kilometer (about $\frac{1}{2}$ mile) to about 25 kilometers (about 15 miles) from the antenna. These distances may be reduced, for frequencies above 1600 kilocycles, approximately in the square of the ratio of 1600 to the frequency in kilocycles. The number of radials, the distance to which each radial is carried, and the number of measurements to be made on each radial, will depend inversely upon how good the measurement points are. In general, 8 radials should be used and 30 to 40 measurements should be made on each radial. An approximate guide which may be followed is to make the distance interval between successive points along the radials approximately equal to 10 per cent of the distance of these

¹² Stuart Ballantine, "On the optimum transmitting wave length for a vertical antenna over perfect earth," PROC. I.R.E., vol. 12, pp. 833-840; December, 1924.

¹³ Stuart Ballantine, "High quality radio broadcasting," PROC. I.R.E., vol. 22, pp. 564-629; May, 1934.

points to the transmitting antenna. The data corresponding to each radial should be plotted on log-log co-ordinate paper similar to that of Fig. 8 with the values of radio field intensity as ordinates and distances as abscissas. Radio field intensity and distance may be in any units. It is preferable to use thin, almost transparent, co-ordinate paper unless a light-table is available.

The data should be plotted only for distances greater than 1 wavelength (or, for single antennas higher than 0.2 wavelength, five times the vertical height of the antenna; or for directional antennas, ten times the spacing between elements). The graph paper plotting the measured data is superimposed upon the curves of Fig. 8, shifting the data sheet vertically and horizontally (keeping the vertical lines on both sheets parallel) until the plotted data fit best one of the curves of Fig. 8. If it is found desirable to reconstruct Fig. 8 with a different scale of co-ordinates, the data given in the Appendix, page 13, may be used.

On account of the irregularities of data obtained in practice it may be difficult to determine which of the curves is best fitted by the plotted data. In such case it is desirable to aid the choice by calculation based on whatever may be known or estimated regarding the ground conductivity and the specific inductive capacitance of the terrain over which the measurements are made. One calculates the angle whose tangent is $1/1.8(10)^{10} (\epsilon f/\sigma)$. In fitting the plotted data to the curves, one then gives preference to that

curve marked with the angle nearest this value.

When the data sheet is finally adjusted, the value of radio field intensity corresponding to the intersection of the inverse-distance line of Fig. 8 with the 1-kilometer ordinate on the data sheet is the inverse-distance radio field intensity at 1 kilometer. (The value of radio field intensity corresponding to the intersection of the curve of best fit of Fig. 8 with the 1-kilometer ordinate on the data sheet is the attenuated radio field intensity at 1 kilometer.)

When the data for all the radials have been analyzed in this manner, a curve should be drawn on polar co-ordinate paper from the inverse-distance 1-kilometer radio field intensities obtained, which gives the unabsorbed field pattern at 1 kilometer. The radius of a circle, the area of which is equal to the area bounded by this pattern, is the effective unabsorbed radio field intensity at 1 kilometer. This value of radio field intensity corresponds to E_1 in (19). E_2 is next determined from Fig. 9 based on the assumed effective length of the actual antenna. The equivalent radiated power in watts P_e may now be computed from (19).

The radiation efficiency of the antenna system in per cent is

$$F = 100 \frac{P_e}{P_i} \quad (20)$$

While making the radio field-intensity survey, the output power of the station should be maintained constant.

2.3 EQUIVALENT RADIATED POWER FOR IONOSPHERIC TRANSMISSION

This method is primarily useful at frequencies above 3 megacycles. The radiation from antennas at these frequencies is usually greater at some angle to the horizon than it is along the horizon. For this reason measurements made along the ground are not usually indicative of the main power which is used for transmission.

One of the methods used to measure the equivalent radiated power from a high-frequency antenna is to compare the radiation at a distant point after reflection from the ionosphere with the radiation from an antenna of known characteristics such as a half-wave dipole antenna. This can be done by shifting from one antenna to the other and recording the radio field intensity continuously. This should be done a sufficient number of times, sufficiently spaced, to average out the errors caused by fading. The comparison antenna should be placed at the same height from the ground as the height of the center of the antenna being tested.

A refinement of this method is to measure the difference in gain of the two transmitting antennas by connecting the two antennas to two transmitters operating on the same frequency and keyed alternately by fast dots,¹⁴ e.g., 100 words per minute, of unequal

lengths. The resulting field is observed at the receiving station by means of a cathode-ray oscillograph. During the observations the power of the transmitter supplying the antenna of greater gain is reduced until the two fields are equal at the receiving station. Then the relative power supplied to the two antennas is the measure of gain.

The equivalent radiated power from a half-wave dipole antenna in free space, in watts, is

$$P_e = 70 \cdot I^2, \quad (21)$$

where I is the current measured at center of dipole antenna, in amperes. When the dipole antenna is less than approximately 1 wavelength from surrounding objects the radiation resistance is slightly different and

¹⁴ Andrew Alford, "A method for measuring the gain of transmitting antennas," Presented, Joint Meeting, U.R.S.I.-I.R.E., Washington, D. C., April 28, 1939. Not published. Abstract:

"Difference in gain of two transmitting antennas may be accurately measured by connecting the two antennas to two transmitters operating on the same frequency and keyed alternately by fast dots, e.g., 100 words per minute, of unequal lengths. The resulting signal is observed at the receiving station by means of a cathode-ray oscillograph. During the observations the power of the transmitter supplying the antenna of greater gain is reduced until the two signals are equal at the receiving station. Then the relative power supplied to the two antennas is the measure of gain."

a correction factor must be used¹⁵⁻¹⁷ with (21). When using a dipole antenna to determine the gain of a directive antenna, considerable care must be exercised to eliminate all stray coupling between the directive antenna and the comparison antenna.¹⁸

It is possible to measure the equivalent radiated power of a high-frequency antenna by measuring the direct-wave field using an airplane or balloon to support the receiving antenna. If an airplane is used, care must be taken to make sure that the receiving-antenna pattern is not distorted by the presence of the airplane, or, if it is distorted, this must be taken into

¹⁵ P. S. Carter, "Circuit relations in radiating systems and applications to antenna problems," *PROC. I.R.E.*, vol. 20, pp. 1004-1041; June, 1932.

consideration. The direct-wave radio field intensity¹⁹ from a half-wave dipole antenna suspended in free space, in volts per meter, is

$$E_D = \frac{7.0\sqrt{P_e}}{d} \quad (22)$$

¹⁶ H. T. Friis, C. B. Feldman, and W. M. Sharpless, "The determination of the direction of arrival of short radio waves," *PROC. I.R.E.*, vol. 22, pp. 47-78; January, 1934.

¹⁷ C. R. Burrows, "Radio propagation over plane earth,—Field strength curves," *Bell Sys. Tech. Jour.*, vol. 16, pp. 45-77 and 574-577; June and October, 1937.

¹⁸ E. J. Sterba, "Theoretical and practical aspects of directional transmitting systems," *PROC. I.R.E.*, vol. 19, pp. 1184-1215; July, 1931.

¹⁹ B. Trevor and P. S. Carter, "Notes on propagation of waves below ten meters in length," *PROC. I.R.E.*, vol. 21, pp. 387-426; March, 1933.

2.4 EQUIVALENT RADIATED POWER FOR ULTRA-HIGH FREQUENCIES

These methods are for frequencies over 30 megacycles. The equivalent radiated power may be calculated from (22), if the direct-wave field is known. The measurement of the direct-wave field is ordinarily difficult on the ground, since the field at any point is the sum of the fields of the direct wave and the ground-reflected wave. Two methods have been used on ultra-high frequencies to evaluate the direct-wave field. They may be called the variable-height method and the variable-distance method.

With the first method,²⁰ the receiving antenna is set up about 10 or 12 wavelengths away from the transmitting antenna. The receiving-antenna height is changed and, hence, the phase relations between the direct and ground-reflected waves varied, so that both the sum and difference of these two components are obtained. The direct-wave component is then

$$E_D = \frac{E_3 + E_4}{2}, \quad (23)$$

where E_D = direct-wave radio field intensity,

E_3 = measured radio field intensity when the height of the receiving antenna is adjusted for maximum field intensity,

E_4 = measured radio field intensity when the height of receiving antenna is adjusted for minimum field intensity.

Care should be taken when using this method to make the radio field-intensity measurements over fairly level terrain, since an uneven terrain will introduce a possibility of error.

The second method of measuring the direct-wave

field, called the variable-distance method, has been used on ultra-high frequencies below 300 megacycles (1 meter).²¹ The procedure is to move the receiving antenna away from the transmitting antenna, measuring the maximum and minimum values of the received field E_3 and E_4 , respectively, and recording the respective distances d_3 and d_4 . The receiving and transmitting antennas should be kept several wavelengths above the ground and the data carried out to about 50 wavelengths from the transmitter. Then the direct-wave radio field intensity at an intermediate distance d is

$$E_D = \frac{E_3d_3 + E_4d_4}{2d} \quad (24)$$

The equivalent radiated power can then be calculated using (22).

The comparison method of measuring equivalent radiated power described in Section 2.2 may also be used for ultra-high frequencies. The principal application of this method is to compare directive or special (wide-band etc.) antennas with simple antennas. These comparisons should be made somewhat inside the horizon so as to minimize possible errors due to fading.

Another method of measuring the equivalent radiated power on ultra-high frequencies is to take a large number of measurements of radio field intensity on a radial from the transmitter out to 30 or 40 kilometers (about 20 or 25 miles). It is preferable to make continuous recordings using mobile recording equipment.²² The measurements should be made over level ground free from major obstructions. The recording of radio

²¹ B. Trevor and R. W. George, "Notes on propagation at a wavelength of seventy-three centimeters," *PROC. I.R.E.*, vol. 23, pp. 461-469; May, 1935.

²² G. S. Wickizer, "Field-strength survey 52.75 megacycles from Empire State Building," *PROC. I.R.E.*, vol. 28, pp. 291-296; July, 1940.

²⁰ C. R. Burrows, A. Decino, and L. E. Hunt, "Ultra-short-wave propagation over land," *PROC. I.R.E.*, vol. 23, pp. 1507-1535; December, 1935.

field intensity will, of course, show considerable variations caused by multiple reflections. By averaging the data it is possible to arrive at the following relation:

The received radio field intensity in volts per meter from a half-wave dipole antenna at grazing angles and at distances within the horizon may be shown to be²³

$$E = 2.93(10)^{-7} \frac{\sqrt{P_e} f h_1 h_2}{d^2}, \quad (25)$$

or

$$E = \frac{88\sqrt{P_e} h_1 h_2}{\lambda d^2}, \quad (26)$$

where h_1 = elevation above ground of the transmitting antenna, in meters, and

h_2 = elevation above ground of the receiving antenna, in meters.

²³ H. H. Beverage, "Some notes on ultra-high-frequency propagation," *RCA Rev.*, vol. 1, pp. 76-87; January, 1937.

From (25) or (26) it will be noted that for the conditions assumed, the radio field intensity is inversely proportional to the square of the distance.

The averaged data obtained from the mobile recordings are plotted on logarithmic co-ordinate paper with radio field intensities as ordinates and distance as abscissas. A straight line, having an inverse-square slope is drawn through the averaged data. From any point on this line the equivalent radiated power may be calculated using (25) or (26).

Substituting the value of P_e measured by one of the other methods, the equivalent elevations of the antennas above ground can be calculated from this relation. If the receiving locations are free from interfering objects, the equivalent elevation h_2 is the actual elevation, and the equation permits calculating h_1 .

On account of possible effects from buildings and other objects near the antennas, the method must be used with caution.

2.5 ADDITIONAL REFERENCE

J. A. Stratton, "Electromagnetic Theory," McGraw-Hill Book Company, New York, N. Y., 1941.

2.6 APPENDIX

Users of this process of measuring the power radiated from an antenna may prefer to make their own copies of Fig. 8 on co-ordinate paper of their own choosing and thus have the figure on paper of the exact size as that on which they plot their measurement data. Fig. 8 itself has co-ordinates that match approximately those of Keuffel and Esser log-log co-ordinate

paper No. 358-127 (translucent sheet) and 358-127G (opaque sheet). Table I of the data from which Fig. 8 was constructed will permit anyone to draw the curves on any paper desired. Data are not given for the 180-degree curve, as that is not used in cases which occur in actual practice.

TABLE I

Distance	Inverse Distance	RADIO FIELD INTENSITY																			
		0 degrees	5 degrees	10 degrees	15 degrees	20 degrees	25 degrees	30 degrees	35 degrees	40 degrees	45 degrees	50 degrees	55 degrees	60 degrees	65 degrees	70 degrees	75 degrees	80 degrees	85 degrees	90 degrees	
0.01	100.	99.57	98.80	98.04	97.30	96.56	95.85	95.17	94.48	93.82	93.17	92.54	91.92	91.33	90.76	90.21	89.78	89.17	88.68	88.24	
0.0121		82.22																			
0.0144		69.02																			
0.0169		58.74																			
0.0196		50.59																			
0.02		49.57	49.05	48.50	48.00	47.45	46.95	46.50	46.00	45.55	45.15	44.70	44.30	43.90	43.55	43.20	42.87	42.54	42.21	41.89	
0.0225		44.02																			
0.0256		38.64																			
0.0289		34.18																			
0.0324		30.44																			
0.0361		27.28																			
0.04		24.57																			
0.0441		22.25																			
0.0484		20.24																			
0.05		19.58	19.24	18.92	18.60	18.30	18.02	17.74	17.46	17.20	16.94	16.70	16.47	16.24	16.03	15.82	15.65	15.49	15.32	15.15	
0.0529		18.48																			
0.0576		16.94																			
0.06		16.24																			
0.0625		15.58																			
0.0676		14.37																			
0.09		10.69																			
0.10		9.581	9.35	9.13	8.92	8.72	8.53	8.34	8.16	7.99	7.840	7.680	7.545	7.410	7.285	7.160	7.055	6.950	6.845	6.740	
0.16		5.836																			
0.24		3.754																			
0.25		3.595	3.464	3.34	3.228	3.120	3.02	2.924	2.832	2.752	2.676	2.600	2.534	2.468	2.412	2.356	2.305	2.254	2.204	2.153	
0.26		3.442																			
0.30		2.382																			
0.49		1.657																			
0.50		1.617	1.538	1.466	1.398	1.336	1.28	1.226	1.178	1.132	1.094	1.054	1.021	0.988	0.959	0.930	0.9075	0.885	0.8625	0.84	
0.64		1.185																			
0.74		0.9878																			
0.75		0.9693																			
0.76		0.9539																			
0.81		0.8767																			
1.00		0.6565	0.616	0.579	0.546	0.516	0.489	0.465	0.443	0.423	0.406	0.389	0.375	0.361	0.3495	0.338	0.3286	0.3192	0.3097	0.3003	
1.21		0.4978																			
1.44		0.3811																			
1.50		0.3567																			
1.69		0.2939																			
1.96		0.2279																			
2.00		0.2199	0.204	0.1905	0.1785	0.1680	0.1585	0.1505	0.143	0.136	0.1305	0.125	0.1205	0.116	0.1122	0.1085	0.1056	0.1027	0.09976	0.09685	
2.25		0.1776																			
2.50		0.1454	0.1352	0.1264	0.1188	0.1120	0.1060	0.1004	0.0960	0.0916	0.088	0.0844	0.0814	0.0784	0.076	0.0736	0.07164	0.06968	0.06772	0.06576	
2.56		0.1389																			
2.89		0.1090																			
3.00		0.1009	0.094	0.0880	0.0830	0.07867	0.0730	0.0710	0.0680	0.0650	0.06267	0.0600	0.0580	0.0560	0.05433	0.05267	0.05139	0.05012	0.04884	0.04757	
3.24		0.08581																			
3.61		0.06783																			
4.00		0.05384	0.05075	0.048	0.0455	0.04350	0.0415	0.03975	0.03825	0.0370	0.03575	0.03475	0.03375	0.03275	0.03188	0.031	0.03029	0.02958	0.02886	0.02815	
5.00		0.03186	0.0304	0.0292	0.0280	0.02700	0.0262	0.02540	0.02460	0.0238	0.0232	0.0226	0.02210	0.0216	0.0211	0.0206	0.02009	0.01958	0.01907	0.01856	
6.00		0.02047																			
7.00		0.01406	0.01005	0.009888	0.009725	0.009563	0.009363	0.009225	0.009063	0.008900	0.008738	0.008575	0.008425	0.008275	0.008138	0.008	0.007886	0.007772	0.007659	0.007545	
8.00		0.01020																			
9.00		0.007733	0.00604	0.00602	0.00599	0.00595	0.00588	0.00577	0.00567	0.00556	0.00545	0.00535	0.00525	0.00515	0.005075	0.0050	0.004971	0.004942	0.004913	0.004884	
10.00		0.006060																			
11.00		0.004900																			
12.00		0.004042																			
13.00		0.003392	0.003392	0.003392	0.003385	0.003377	0.003369	0.003354	0.003331	0.003308	0.003269	0.003231	0.003181	0.003131	0.003073	0.003015	0.00299	0.002965	0.002939	0.002914	
15.00		0.002493																			
18.00		0.001694	0.001694	0.001694	0.001694	0.001694	0.001694	0.001694	0.001689	0.001689	0.001678	0.001672	0.001656	0.001639	0.001619	0.0016	0.001582	0.001565	0.001547	0.001529	
20.00		0.001360																			
30.00		0.0005867																			
40.00		0.0003250																			
50.00		0.0002064	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	0.000206	
100.0		0.000050																			
200.00		0.0000125																			

SECTION 3. METHODS OF MEASURING NOISE FIELD INTENSITY

3.1 GENERAL

The measurement of noise field intensity, while involving the same basic procedure as the measurement of radio field intensity, presents additional problems because of the fact that, in general, the direction of propagation, polarization, relative phases, and amplitudes of the components of noise fields are not well defined and are subject to variations with reference to time and space.

The measuring apparatus, including the antenna, is identical with that employed in measuring radio field intensity, except that the output circuit must satisfy special requirements as to time constant, and the effective bandwidth and phase characteristics of the selective circuits must be taken into account.

The measuring apparatus is tuned to the frequency at which the noise field intensity is to be measured, and the voltage produced in the receiving antenna by the noise is measured. Since the voltmeter is usually calibrated in terms of a known voltage of single frequency, the noise field intensity is measured in terms of the equivalent effect of a single-frequency field and

of the effective bandwidth of the radio receiver. The time constants of the output circuit and the nature of the rectifier determine whether the average, root-mean-square, peak, or quasi-peak value of the noise field intensity is measured. Since the noise field is generally distributed over a wide frequency range, the noise field intensity measured is a function of the effective bandwidth of the radio receiver; hence, accurate specification of the effective bandwidth of the measuring set is important.

The general method of determining the effective bandwidth of the measuring set, and the manner in which it influences the measured value of noise field intensity, are indicated in the definitions of effective bandwidth and noise intensity.

It is also of importance to record a classification of the noise (e.g., ignition noise, atmospherics, random noise, impulse noise), since there may be a difference in the radio-field-to-noise ratio required for operation through various types of noise.

3.2 MEASUREMENT METHODS

The measurement of particular characteristics of noise field intensity which bear a definite relationship to the disturbing effects of the noise would, if found feasible, provide means for establishing the degree of disturbance which the noise causes to the different types of communication. Specialized methods in this category have been developed for measurement of the disturbance caused by noise to telephone (voice and music) signals. This apparatus takes the form of a field-intensity-measuring set of the standard-antenna type with a special output circuit which includes a rectifier, an integrating circuit, and an indicating instrument. From experience gained with such measurements, it has been determined that the effect of noise in telephony (voice or music) is more nearly proportional to the peak intensity than to the average intensity. A joint committee of the Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association accordingly recommended²⁴ the measurement of a quasi-peak value, the specified time constants of the output indicator circuit being 10 milliseconds charge and 600 milliseconds discharge; an effective bandwidth of 10 kilocycles was recommended.

A single quasi-peak value is not in general proportional to the disturbing effect of all types of radio noise and for all types of signals. Thus, for wide-band service requirements, it may be desirable to make noise

measurements with apparatus of greater effective bandwidth and indicating devices with the equivalent of lower time constants.

A cathode-ray oscillograph may be advantageously used in measuring noise peaks. It has the advantage of showing the noise wave shape. It has the disadvantage, however, that if the noise peak is very short the top of the peak is hard to read, unless the room is darkened, because of the low illumination for a transient pulse.

3.21 ATMOSPHERICS

Both short-time and long-time distributions of the noise field intensity of atmospherics are of interest. Measurements by automatic-recorder methods of the time distribution of both the average and peak values provide data in a desirable form for most purposes.

For recorder operation, it is possible to measure the average intensity by using approximately equal charge and discharge time constants of the order of 1 minute.

It is possible to measure the instantaneous peak intensity in terms of a quasi-peak value of very short duration, of the order of 0.1 millisecond; for recorder operation, a discharge time constant of the order of 1 minute has been found desirable.

The average or quasi-peak data (or both) may be presented in the form of time distribution curves, as in recording received intensities from radio stations which are fading; and provide information on the noise field intensity of atmospherics at a given place for a given percentage of time of the period considered.

²⁴ C. V. Aggers, D. E. Foster, and C. S. Young, "Instruments and methods of measuring radio noise," *Trans. A.I.E.E. (Elec. Eng., March, 1940)*, vol. 59, pp. 178-192; March, 1940.

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