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Redesignation of IEEE Std 284-1968 and IEEE Std 302-1969)

IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz

Sponsor

**Wave Propagation Standards Committee
of the
IEEE Antennas and Propagation Society**

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Abstract: Two standard methods for field-strength measurement are described. The standard-antenna method consists of measuring the received power or open-circuit voltage developed in a standard receiving antenna by the field to be measured and computing the field strength from the measured voltage and the dimensions and form of the standard antenna. The standard-field method consists of comparing voltages produced in an antenna by the field to be measured and by a standard field, the magnitude of which is computed from the dimensions of the transmitting antenna, its current distribution, the distance of separation, and effect of the ground. The measurement procedures are outlined, including calibration of commercial field strength and extension of the methods to microwave frequencies. Methods for measuring power radiated from an antenna under several different conditions are briefly presented, and the important considerations for securing useful and accurate measurements are described.

Keywords: Field strength, receiving antenna, transmitting antenna

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Foreword

(This Foreword is not a part of IEEE Std 291-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves.)

IEEE Standard 291-1991, on the measurement of electromagnetic field strength, updates, consolidates, and supersedes three previously issued standards: 1) IEEE Std 284-1968, 2) IEEE Std 291-1969, and 3) IEEE Std 302-1969. Within the IEEE, this work has been coordinated with the Antennas and Propagation Society Standards Committee, the Broadcast Technology Society, the Electromagnetic Compatibility Society, and the Instrumentation and Measurement Society. The standard has also been coordinated with the FCC and with the international organizations of CCIR (International Radio Consultative Committee) and URSI (International Union of Radio Sciences).

SI (rationalized MKS) units have been used throughout the document.

This standard was prepared by the Subcommittee on Field Strength Measurement of the Wave Propagations Standards Committee. At the time that this standard was approved, the Subcommittee on Field Strength Measurement had the following membership:

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The subcommittee, the WPSC, and the APS appreciate the assistance of all those who contributed to this standard.

The final conditions for approval of this standard were met on April 2, 1991. This standard was conditionally approved by the IEEE Standards Board on March 21, 1991 with the following membership:

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IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz

1. Introduction

1.1 General

Most measurements relating to radio wave propagation involve the measurement of field strength. Standard methods for the measurement of this fundamental quantity are described in this document. The power radiated from an antenna (Section 3) also may be determined by measurement of field strength.

1.2 Symbols and Units

The general symbols used are given in the following list, together with units to be used when the symbols appear in equations containing numerical coefficients. When more specific or restrictive meanings are indicated by subscripts, the symbols are further defined after the equation in which they are used.

a	= Attenuation, numeric.
A	= Amperes.
A	= Area of a loop antenna, in m ² .
A	= Norton approximation to Sommerfeld attenuation function, numeric.
A	= Cable attenuation, in dB.
b	= Effective noise power bandwidth, in Hz.
b_i	= Impulse bandwidth, in Hz.
c	= Velocity of propagation of an electromagnetic wave in a vacuum = $2.9979246 \cdot 10^8$ m/s.
C	= Capacitance, in F.
C_{inc}	= Incident coupling factor for 4-port dual directional coupler, numeric.
C_{refl}	= Reflected coupling factor for 4-port dual directional coupler, numeric.
d	= Distance from transmitter to receiver, in m.
D	= Maximum dimension of an antenna, in m.
E	= Root-mean-square (RMS) value of electric field strength, in V/m.

E_o	= Direct wave electric field strength, in V/m.
$EIRP$	= Effective isotropically radiated power, in W.
f	= Frequency, in Hz.
g	= Intrinsic power gain of an antenna over that of an isotropic antenna, considering its directive gain minus dissipative losses but not its loss caused by impedance mismatches, numeric. The gain of a transmitting antenna is equal to 4π times the ratio of the power density in a given direction to the net power delivered to the antenna from the transmitter.
g_d	= Gain of a short dipole at the surface of a lossy ground, numeric.
g_e	= Equivalent gain relative to an isotropic antenna, numeric.
g_T	= Power gain of the transmitting antenna in a given direction, numeric.
g'	= Standardized receiver gain, numeric.
G	= $10 \log_{10} g$ = Antenna gain, in dB, relative to an isotropic antenna (dBi).
G_e	= $10 \log_{10} g_e$ = Equivalent gain, dBi.
h	= Height of a grounded vertical monopole antenna, in m.
h	= Height of an antenna above ground, in m.
H	= Root-mean-square (RMS) magnetic field strength, in A/m.
H	= Inductance, in H.
I	= Root-mean-square (RMS) antenna current, in A.
k	= Antenna factor, in reciprocal meters (m^{-1}).
K	= Antenna factor, in $Db(m^{-1})$.
L_{eff}	= Effective length of an antenna, in m.
L	= Physical length of an antenna, in m.
N	= Number of loop turns, numeric.
p	= Numerical distance.
P	= Power, in W.
q	= Impedance mismatch factor, numeric.
Q	= 2π times the ratio of energy stored to energy dissipated per cycle. Q is also expressed as the ratio of reactance to series resistance at resonance.
r_1	= Radius of a transmitting loop antenna, in m.
r_2	= Radius (or mean radius) of a receiving loop antenna, in m.
R	= Resistance, in Ω ; real part of antenna input impedance, in W.
R_L	= Real part of load impedance, in Ω
S	= Power flux density of an electromagnetic wave, in W/m^2 .
V	= Root-mean-square (RMS) voltage, in V.
$VSWR$	= Voltage standing wave ratio, numeric.
V_{oc}	= Open-circuit voltage across the center gap of a dipole, in V.
X	= Imaginary part of antenna input impedance, in Ω
X_L	= Imaginary part of load impedance, in Ω
Z	= Antenna input impedance, in Ω
Z_L	= Load input impedance, in Ω
Z_o	= Characteristic impedance, in Ω
Γ	= Voltage reflection coefficient.
ϵ_o	= Permittivity of free space = $(\mu_o c^2)^{-1} \cong 8.854 \cdot 10^{-12}$ F/m $\cong (36\pi(10^9))^{-1}$ F/m.
ϵ_r	= Real part of ground permittivity relative to that of vacuum.
η	= Radiation efficiency of an antenna, in percent.
η_o	= Intrinsic wave impedance of free space = $\sqrt{\mu_o/\epsilon_o}$ = $4\pi c \cdot 10^{-7}$ = $376.7303 (\cong 120\pi) \Omega$
λ	= Wavelength, in m.
μ_o	= Permeability of free space = $4\pi \cdot 10^{-7}$ H/m.
σ	= Real part of ground conductivity, in S/m.

τ = Pulse duration, in s.
 θ Angle between L_{eff} , the (vector) effective antenna length and $\vec{E}_o$, the (vector) electric incident field.

Unless otherwise stated, units are assumed to be those of the International System (SI). For convenience, several relationships and prefixes are tabulated below.

1 in = 0.0254 m			
1 mi = 1609.34 m			
1 m = 0.000621371 mi			
1 in ² = 0.00064516 m ²			
1 m ² = 1550.003 in ²			
pico (p)	= 10 ⁻¹²	deka (da)	= 10
nano (n)	= 10 ⁻⁹	hecto (h)	= 10 ²
micro (μ)	= 10 ⁻⁶	kilo (k)	= 10 ³
milli (m)	= 10 ⁻³	mega (M)	= 10 ⁶
centi (c)	= 10 ⁻²	giga (G)	= 10 ⁹
deci (d)	= 10 ⁻¹	tera (T)	= 10 ¹²

1.3 Terms Used in This Document

1.3.1 Field Strength of an Electromagnetic Wave

A general term that usually means the magnitude of the electric field vector (in V/m) at a point in the field, but which may mean the magnitude of the magnetic field vector (in A/m). Field strength has sometimes been called field intensity, but this usage is now deprecated since intensity connotes power in optics and in radiation. At frequencies above about 100 MHz, field strength in the far field is sometimes identified with power density, S . For a linearly polarized plane wave in free space, $S = E^2/\eta_0 = E^2/(\mu_0/\epsilon_0)^{1/2}$, where E is the electric field strength and μ_0 and ϵ_0 are the permeability and permittivity of free space, respectively. When S is expressed in W/m² and E in V/m, the denominator is often rounded off to 120π or 377Ω .

1.3.2 Accuracy

The degree of freedom from error, that is, conformity to the correct value. Accuracy is distinguished from precision, which is defined as the repeatability of measurement data and is usually quantified as the standard deviation of that data. The accuracy of an indicated value is expressed by the ratio of the error of the indicated value to the true value. It is usually expressed in $\pm \%$ or $\pm$ dB. Since the true value cannot be determined exactly, the measured or calculated value of highest available accuracy is taken to be the true value or reference value. Hence, when a meter is calibrated in a given echelon, the measurement made on a meter of a higher accuracy echelon usually will be used as the reference value. Comparison of results obtained by independent measurement procedures is often useful in establishing the true value and its precision.

1.3.3 Echelon

A specific level of accuracy of calibration in a series of levels, the highest of which is represented by an accepted national standard. There may be one or more auxiliary levels between two successive echelons. The classification of accuracy levels into echelons is shown in Section 4

1.3.4 Calibration Factor

The factor that, at a given frequency, expresses the relationship between the field strength of an electromagnetic wave impinging upon the antenna and the indication of the field strength meter. It is a function of the antenna gain and impedance, receiver linearity, etc.

1.3.5 Antenna Factor

That portion of the calibration factor of a field strength meter that is determined by the characteristics of the antenna. It is usually defined as the ratio of the field strength to the voltage developed across a specified receiver resistance, such as 50 Ω . It is often expressed in dB, as in the following equation for the electric-field antenna factor (K) for the special case of an antenna connected to a 50 Ω receiver ($R_L = 50 \Omega$).

$$K = 20 \log_{10} \left(\frac{E \text{ in V/m}}{V \text{ across } 50 \Omega} \right), \text{ in dB (m}^{-1}\text{)} \quad (1)$$

1.4 Complications That are Avoided

This report is limited to the art of measuring field strength of steady-state sinusoidal continuous-wave emissions. Signals that must be measured in practice are not usually in this limited class because they have time variations such as modulation or fading. Furthermore, some signals (such as impulsive interference) may occupy a band of frequencies far wider than the bandwidth of the measuring instrument. Nonsteady-state, nonsinusoidal signals will not be discussed here, except to mention that they may often be measured with instruments calibrated under continuous-wave (CW) conditions, taking into account certain additional factors depending on the behavior of the measuring equipment (see [1] and [2])¹, or with instruments calibrated under special conditions. Care must be exercised when measuring fields that are best described as random variables, for significant errors can occur when such measurements are made using detectors calibrated with CW fields (see 1.5.2).

An electromagnetic field often has a complex structure as a result of the existence of more than one propagation path. Components may arrive at the measuring location from several directions, and they may have different polarizations. The resultant field strength varies with position and may vary in amplitude and phase across the dimensions of the receiving antenna. The indication of a field strength measuring instrument in such a case may not be unique because its calibration is obtained in terms of a plane wave. To avoid confusion, it is necessary to add to the measurement report a statement giving the type, polarization, and size of the receiving antenna, its orientation, and the possible existence of multipath propagation.

Similar considerations apply to measurements made in the near field of a source or reflector of the field. In such regions, the field may be nonuniform within the dimensions of the antenna. The field strength can then be considered to be the indication of a measuring receiver with a stated type and size of antenna when the equipment has been calibrated under conditions equivalent to plane-wave free-space propagation. For measurements related to a particular communication service, it is appropriate to use an antenna typical of those normally used in that service.

1.5 Equipment for Measurement of Field Strength

Field strength measurement is accomplished through the use of a combination of the following elements (see Fig 1):

¹The numbers in brackets correspond to those of the bibliographies in Section 6

- 1) An antenna
- 2) A transmission line, optical link, or other coupling networks
- 3) Frequency-selective circuits
- 4) Amplifying and attenuating circuits
- 5) A detector of known input/output characteristics and sufficient dynamic range
- 6) An indicating device such as a panel meter, chart recorder, cathode ray tube, or digital readout

In addition, unless the amplifying and indicating devices are sufficiently stable in gain and sensitivity to be relied upon throughout the time interval between calibrations, it is necessary to provide a signal source having the required time stability in output level to serve as a reference by which the sensitivity of the equipment may be adjusted to a standard condition. Typically, this signal source is a CW signal generator, an impulse generator, or a random-noise generator.

Measurement of field strength is sometimes performed with an assembly of individual elements such as an antenna, receiver, recorder, and standard signal generator. These measurements, however, are facilitated by the use of a “field strength meter,” a name given to a specialized portable unit containing all the necessary elements, including a reference-level signal source and sometimes a built-in antenna.

1.6 Factors Affecting the Units Used for Reporting the Results of Field Strength Measurements

The components of a basic receiver for measuring field strength affect the quantities measured and the units applied to these quantities. The receivers used for field strength meters (FSMs), less properly called field intensity meters (FIMs), in use today employ the following five basic elements:

- 1) Antenna and related circuits (e.g., baluns, transmission lines)
- 2) Receiver (rf and IF)
- 3) Detector
- 4) Metering or data processing device
- 5) Calibrator (which may be internal or external to the receiver, see Fig 1)

The antenna and receiver (through the IF amplifier) select the signal spatially and spectrally, respectively, and provide amplification. In the case of a relatively narrow-band antenna and wide-band receiver, the antenna may also contribute to the spectral filtering process. The antenna polarization, of course, is also important. The units used to describe the results of a given measurement are determined primarily by the calibrator, the detector, and the meter. The antenna and receiver characteristics, however, are often used to normalize the data in a way that directly affects the units used to report the results. These normalizations will be considered first.

The antenna normalization, which relates electromagnetic field quantities and their units to circuit quantities and their units, involves converting a known (measured) circuit quantity (e.g., voltage) to a field quantity (e.g., electric field strength) by means of a known antenna factor (see 1.3.5). Hence, a standard (or calibrated) antenna must be employed in order to be able to properly perform this normalization that relates the received voltage in V to an incident electric field in V/m. Other units for field strength include $\mu\text{V/m}$ and dB above 1 $\mu\text{V/m}$, often written as dB (1 $\mu\text{V/m}$). If the antenna effective area is used to normalize a receiver power, typical units for the power density would be W/m^2 and dB above 1 W/m^2 .

The receiver normalization involves the effective bandwidth when the spectral range of the wave whose field strength is being measured exceeds the receiver's bandwidth. The measured voltage (or power) is observed in some bandwidth, and results may be normalized in terms of a unit bandwidth (1 Hz, 1 kHz, or 1 MHz). This approach is relatively straightforward for white noise (i.e., noise with a constant power spectral density over the frequency band of interest) and the normalization of average noise power or rms voltage, but it can lead to problems of misinterpretation or error when used in measuring the field strength of signals with nonwhite power spectra. Normalization with respect to bandwidth can be applied to both electromagnetic field and circuit quantities and leads to units such as $\text{W}\cdot\text{m}^{-2}\cdot\text{Hz}^{-1}$ and dB above 1 $\mu\text{V/MHz}$.

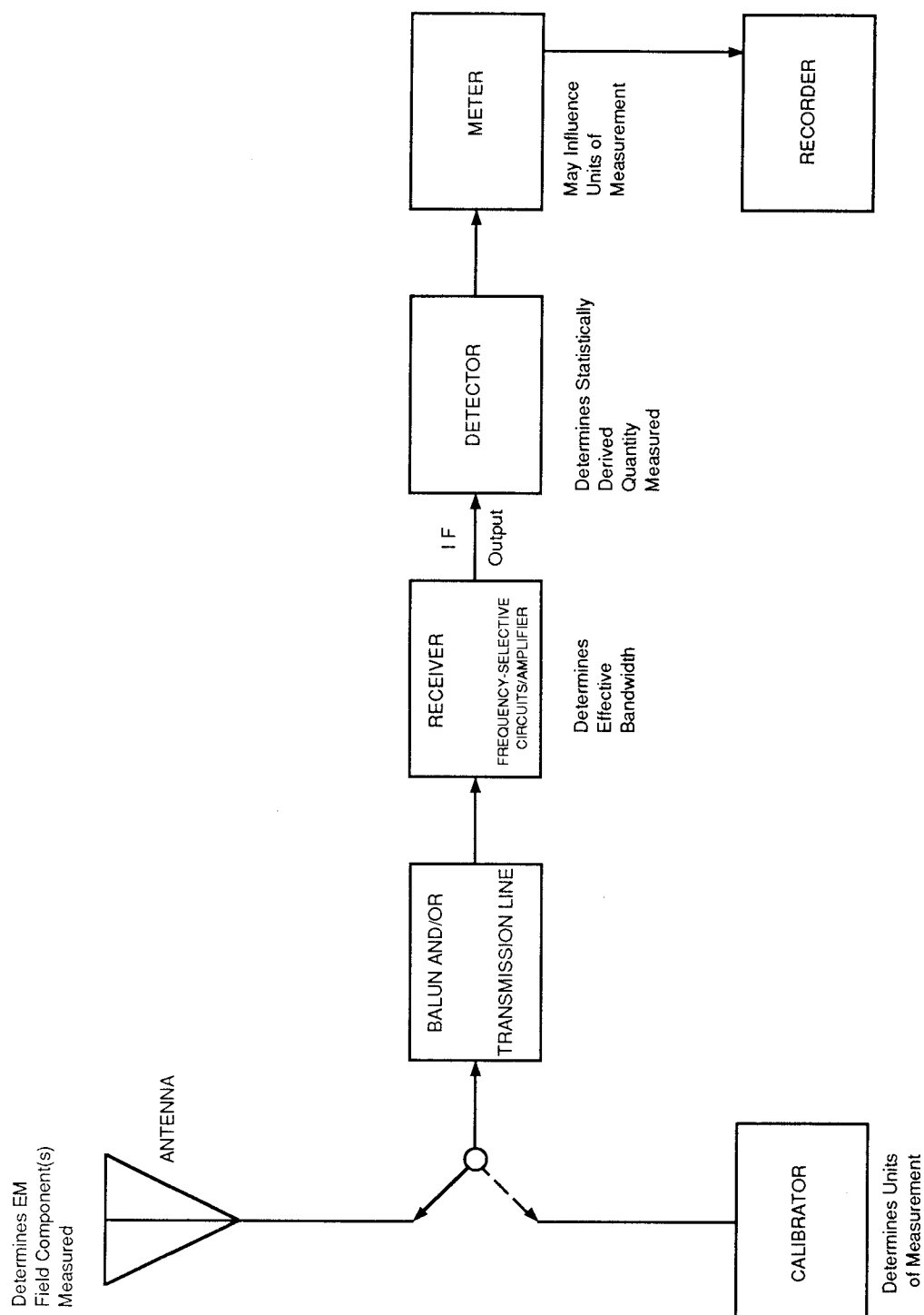


Figure 1—Measurement System Functional Block Diagram

Care must be taken to select the appropriate bandwidth for normalization (e.g., effective noise-power bandwidth, b , or impulse bandwidth, b_i). It is well known that the peak response at the output of a narrowband linear receiver to a noise impulse at the receiver input is proportional to the area under the voltage-time waveform of the impulse. This peak response is independent of the exact shape of the input waveform, provided the duration of the impulse is small relative to the inverse of the impulse bandwidth of the receiver, b_i . For example, if the output of a pulse generator is a single rectangular pulse of amplitude AV and duration τ s, then the peak of the output waveform of the receiver can be expressed as

$$V(\text{peak}) = (k \cdot A \cdot \tau) b_i, \text{ in V} \quad (2)$$

where

k is the constant of proportionality.

The impulse bandwidth can be computed from

$$\frac{1}{b_i} = \frac{1}{V(\text{peak})} \int_0^{\infty} V(t) dt \quad (3)$$

where

$V(t)$ is the envelope of the receiver's impulse response measured at the receiver IF output.

Notice that an input of twice the amplitude ($2A$) lasting but half the duration ($\tau/2$) would have produced an identical output. The observed quantity, $V(\text{peak})$, can give information only about the impulse strength in volt-seconds, but not information about the exact amplitude, duration, or shape of the impulse. For this reason, it is expedient to calibrate peak detectors intended for use in measuring nonoverlapping noise impulses with impulse calibrators. The output of the calibrator is given in volt-seconds, or dB ($1 \mu\text{V}/\text{MHz}$).

The detector in Fig 1 is designed to produce the desired statistic of the noise envelope to be measured. This gives rise to the basic quantity to be metered (e.g., rms voltage, average voltage, quasi-peak voltage, or peak voltage). The units in which the statistics are measured depend upon the calibration source, the detector, and the meter (or data processor or both). As an example, consider rms-voltage, peak-voltage, and average-voltage detectors. The importance of the calibration waveform is illustrated in Table 1 (see [B65]), which gives the error produced for several selected waveforms when rms, peak, and average detectors are calibrated with the rms value of a sine wave from a CW signal generator.

Table 1—Examples of Errors When Using Average and Peak Meters Calibrated With the RMS Value From a Sine Generator to Observe Other Waveforms

Waveform	RMS Meter Indicates	Rectified Average Meter (Calibrated in RMS) Indicates	Peak Meter (Calibrated in RMS) Indicates	Error (dB)	
				Average Meter	Peak Meter
Sine wave	0.707	0.707	0.707	0.00	0.00
Sine wave plus 100% Third Harmonic					
In phase	1.000	0.944	1.09	-0.50	0.75
Out of phase	1.000	0.472	0.382	-6.52	-8.36
Square wave	1.000	1.111	0.707	+0.91	-3.00
Gaussian noise	1.000	0.887	—	-1.05	—
Pulse train					
Duty cycle = 0.1	0.318	0.111	0.707	-9.14	+6.10
Duty cycle = 0.01	0.100	0.011	0.707	-19.17	+16.99

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1.7 Division into Frequency Ranges

It is convenient to classify techniques for measurement of field strength into three approximate frequency ranges as follows:

- 1) Frequencies below 30 MHz
- 2) Frequencies from 30 MHz to 1 GHz
- 3) Frequencies from 1 GHz to 30 GHz
- 4) Frequencies above 30 GHz (beyond the scope of this standard)

This division is useful because the optimum technique is determined by the dimensions of practical antennas, the wavelengths of signals to be measured, and the effects of the terrain at and near the measurement location.

Below about 30 MHz, practical antennas are usually small compared to one wavelength. A common measuring antenna is a loop having one or more turns, often electrically shielded, with a diameter of 0.3 to 1 m. Another type is the short monopole (rod or whip) antenna with a length of 0.1 to 3 m. Both of these antenna types are electrically small and have low efficiency. That is, the radiation resistance is low compared with the loss resistance.

Also, below 30 MHz, it is usually necessary to measure field strength at heights that are electrically near the earth. The characteristics of the ground and nearby vegetation, conductors, and structures affect differently the polarization, angle of arrival, and the strength of the electric and magnetic components of the field. They may also influence the antenna input impedance. Measurements using electrically-shielded loop antennas are usually influenced less by nearby objects than those using rod antennas.

From about 30 MHz to 1 GHz, practical antennas have dimensions that are comparable to one wavelength. A common antenna for field-strength measurements in this range is a half-wave ($\lambda/2$) resonant dipole. The dipole is usually connected to the measuring instrument by use of a balanced-to-unbalanced transformer (balun) and a coaxial transmission line. A $\lambda/2$ dipole differs from the loop and rod antennas in that it is more efficient. Broadband antennas or highly-directional antennas are sometimes used in the upper portion of this frequency range.

Above about 1 GHz, the collecting area of a dipole becomes too small to provide the desired sensitivity. At these frequencies, it is common to employ antennas collecting energy from apertures that are large compared with one wavelength, such as horns. These antennas are usually characterized by high efficiency and appreciable directivity. Coaxial or waveguide transmission lines are usually employed.

1.8 Calibration Procedures and Standards

When a field-strength measuring instrument is adjusted to standard sensitivity by using a reference source, the reading of the indicating device is converted to field strength by application of a calibration factor that usually varies with frequency. Typical general-purpose field strength meters have several continuously-tuned frequency ranges and an amplitude range of 80 to 120 dB. The calibration of such an instrument at only a modest sampling of frequencies and signal levels may require a large number of measurements.

Calibration methods may be classified into the following two basic types:

- 1) *Direct Calibration.* The antenna is exposed to an electromagnetic field, the strength of which is accurately known, see [B77] , [B93] . The field strength may be known by computation from the measured current in, or power delivered to, a transmitting antenna of known dimensions and current distribution or gain. In this approach, known as the standard-field method, the effects of ground reflections or reflections from the walls of an anechoic chamber (if present) must be accounted for. This can be achieved by averaging the in-phase and out-of-phase reflections (see [B69]) as the separation distance between the transmitting and receiving antennas is varied. Alternatively, the field strength may be determined from the voltage induced in (or power available from) a special receiving antenna of known dimensions or gain. This latter approach is called the standard-antenna method. In principle, a field-strength meter may be directly calibrated by the use of known field strengths at all levels and frequencies in its range. For practical reasons, however, such calibrations are usually performed at only one or two levels at each required frequency. These measurements are supplemented by measurements of attenuator step accuracy, dial scale accuracy, etc.
- 2) *Indirect Calibration.* In indirect calibrations, the calibration factor is calculated from the computed or measured characteristics of the receiving antenna and measured instrument characteristics. The antenna is removed from the field-strength measuring equipment and replaced by a calibrated standard-signal generator having an impedance equal to that of the antenna. The equipment is calibrated as an rf voltmeter (or power meter) against the standard signal generator. An antenna factor is computed for each frequency from the dimensions and current distribution of the antenna, from consideration of the antenna as an aperture, or from the measured gain of the antenna. If a transmission line is used between the antenna and receiver, it is possible to consider it as part of the receiver and connect the calibrating generator to it, thus avoiding the need for separately determining the transmission line loss and compensating for such loss.

The theoretical computation of the receiving antenna factor is facilitated by the use of simple types of antennas. For example, a thin, short, vertical-monopole antenna (shorter than 0.1 wavelength) located over an extensive ground plane may be assumed to have a linear current distribution, making its effective length equal to half its physical length. Its impedance can be simulated approximately by a series capacitor connected between the standard signal generator and the input of the measuring receiver. A second example is the thin half-wave dipole antenna with assumed sinusoidal current distribution. This antenna has a theoretical effective length of λ/π and a radiation resistance of approximately $70\ \Omega$ in free space.

A standard thin cylindrical dipole must have a length several percent shorter than a half wavelength in order to achieve self-resonance. Its radiation resistance is then less than that of an infinitesimally thin $\lambda/2$ antenna. This is due to the effect of finite cylinder thickness on the current distribution. The directional pattern of a practical dipole, however, does not differ much from that of an infinitesimally thin dipole, and thus its gain and available power remain close to the theoretical values. A practical dipole may therefore be considered essentially equivalent to a theoretical thin dipole plus a transformer to account for the change in radiation resistance. A balun is an additional transformer that may introduce error unless its impedance-matching characteristics are optimized and its loss taken into account, see [B75] .

The gain of an antenna may be measured by comparison with a standard-gain antenna that has been calibrated previously or whose gain can be calculated theoretically. The gain also may be determined from measurements using two “identical” antennas, one for transmitting and the other for receiving, see [B11]. Similar to a two-antenna gain calibration, the more general three-antenna technique can be used. In this case, it is not necessary to have two identical antennas. The gains of all three antennas are obtained from three sets of measurements, each involving a pair of two antennas, see [B69]. Measurements of antenna gain should include the loss of any associated balun, isolator, or impedance-matching devices that are used.

Calibrated-signal generators, attenuators, power meters, and thermoelements for measurement of rf current in terms of direct-current standards are the principal reference standards used in the calibration of instruments for measuring field strength. Accurate scales are used to determine antenna separation distance and the dimensions of standard-field transmitting loops, aperture antennas, and standard receiving dipoles. Other calibrated standard-gain transmitting antennas also may be required.

2. Methods of Measuring Field Strength

2.1 General

Two general methods are applicable to the measurement of field strength, see [B39], [B85] and [B93]. One method consists of measuring the received power or open-circuit voltage induced in a standard receiving antenna by the EM field to be measured, and then computing the field strength in terms of the measured power or voltage and the dimensions and form of the standard receiving antenna. The other method consists of comparing voltages produced in an antenna by the field to be measured and by a standard field, the magnitude of which is computed from the type and dimensions of the transmitting antenna, the net power delivered to the transmitting antenna (or its current distribution), the antenna separation distance, and the effect of the ground. For the standard receiving antenna method, there are special requirements for the antenna and the power or voltage measuring equipment. Field-strength measurements are often made using commercially available meters that have been calibrated in a known field determined by either of the two above methods. A calibration service is maintained by the National Institute of Standards and Technology for field-strength meters in the frequency range of 30 Hz to 30 GHz. For information, write to the National Institute of Standards and Technology, Electromagnetic Fields Division, 325 Broadway, Boulder, CO 80303, USA.

2.1.1 Standard Receiving Antenna Methods

In the standard receiving antenna method (see [B77] and [B85]), the antenna is of some standard form such as a thin dipole or a pyramidal horn (see [B49]) of known gain. The open-circuit rf voltage, V_{oc} , induced in a dipole by an incident field, E_{inc} , of given strength and polarization can be calculated theoretically, see [B77]. The ratio of this voltage to the component of electric field producing it is called the effective length, L_{eff} , of the antenna. If the direction of polarization of E_{inc} is parallel to the dipole,

$$L_{eff} = V_{oc}/E_{inc} \quad (4)$$

Effective length is usually defined as a vector such that $\vec{V}_{oc} = \vec{L}_{eff} \cdot \vec{E}_{inc}$. The scalar, L_{eff} , is equal to the magnitude of $\vec{L}_{eff}$ times the cosine of θ , where θ is the angle between $\vec{L}_{eff}$ and $\vec{E}_{inc}$, the incident vector field.

The method of coupling a standard dipole to the voltage-measuring instrument is generally such that the voltage measured is not the total voltage induced by the field but is a fixed fraction of it. For example, the ratio of the detected dc voltage to the rf voltage induced in the antenna by the field is called the voltage transfer ratio. A separate determination of this ratio is usually required, see [B19].

A standard voltage source is often provided as part of the field-strength measuring apparatus for calibrating the voltmeter. The term “voltmeter” is used here for the radio receiving portion of the overall instrumentation. The calibrating voltage may be fixed or adjustable 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. The voltmeter is calibrated at various levels corresponding to the voltages being measured. The method used to determine the voltage-transfer ratio generally depends on the particular form of antenna and circuit arrangement employed.

The field-strength value is calculated on the basis of the antenna gain or its effective length and voltage-transfer ratio. In some instances, it is difficult to calculate accurately the effective length of an antenna being used. In such cases, the product of the effective length and voltage-transfer ratio can be determined directly from a measurement of the output voltage of the antenna across a specified load impedance when it is placed in a standard field. The reciprocal of this product is called the antenna factor. This is the procedure usually followed in the calibration of commercial field-strength meters. The value of the antenna factor includes the gain of the receiver.

The form of standard receiving antenna that may be used is governed by the signal frequency, by the polarization of the field component to be measured, by the nature of the field (i.e., high or low strength, fading or steady, etc.), and by the ease of handling the antenna, see [B23], [B24], [B38], [B68], [B77] and [B78]. The types generally employed are the loop antenna, the vertical or horizontal dipole having a length of $\lambda/2$ or less, a vertical monopole with output between its lower end and ground, a pyramidal horn, and an open-ended waveguide (OEG). Other types of antennas can also be used, in which case they are calibrated in terms of one of the simpler antennas just mentioned.

Measurements of field strength in radio communication services are often made with complex types of antennas and arrays. They generally offer the advantages of operating convenience, increased sensitivity, and interference discrimination. The complex antenna can be calibrated by comparison with a simple standard antenna. This calibration, however, may be in error because of differences in the directivity of the antenna under test and the simpler comparison antenna. For example, a standard dipole will not discriminate as effectively against a ground-reflected ray as will a high-gain log periodic antenna.

2.1.2 Standard Transmitting Antenna Methods

In this method a standard (known) field is produced by a local transmitter. The field at the receiving antenna location is computed from the gain or effective length of the transmitting antenna, its radiated power or current distribution, the distance from the transmitting antenna to the field point, and the effect of reflections from the ground, chamber surfaces, or other objects, see [B39] and [B85]. The measuring equipment associated with the receiving antenna generally consists of a power meter or a frequency-selective voltmeter, such as a spectrum analyzer or an interference meter (receiver). When the angles of arrival of the transmitted standard and measured fields differ, a correction must be applied for any resultant difference in the voltages caused by directivity of the antennas and effects of the ground.

2.1.3 Simplifications and Precautions

The problem of field-strength measurement is generally complicated by the complex nature of the field resulting from variability of the transmission medium (see [B11], [B19], [B69], and [B75]), by the nature of the emission (see [B21] and [B24]), and by the influence of the ground or disturbing structures, see [B24], [B38], and [B87]–[B89]. Simplifying approximations are introduced into measurement methods to keep the instrumentation from becoming unduly complex and to facilitate analysis of the data.

In the case of ionospheric or tropospheric wave fields, a complete measurement would involve determination of

- 1) The field strength of the vertical, longitudinal, and lateral electric and magnetic field components for each signal frequency at the receiving point
- 2) The phase angles between the different field components
- 3) The direction of arrival of each signal component

Fortunately, considerable practical information can be obtained by measuring only three mutually-orthogonal components of the field, see [B23]. Simple forms of receiving antennas are especially useful, employing (for example) three crossed dipoles or three crossed loops to measure the “total magnitude” of the electric or magnetic field strength.

A simplification in the measurement of complex emissions may often be achieved by removing the transmitter's modulation so that a single-frequency field (the carrier) is measured. In emissions without a carrier wave, such as a single-sideband transmission, it is sometimes desirable to restrict the modulation to a single frequency so that a single-frequency field is measured. Occasions arise, however, when it is necessary to retain the normal modulation, such as when considering the interfering effect of cross-modulation products or single-sideband emissions. When measuring the harmonic content of a given field, special precautions should be taken to avoid errors caused by harmonics and other spurious responses that may be produced within the measuring receiver.

A typical field-strength measuring system is a frequency-selective voltmeter designed to indicate the average, peak, and/or quasi-peak value over a chosen time interval of the voltage of a signal that has passed through the receiver's frequency-selective circuits. For single-frequency fields, the RMS voltage value is measured, usually with an average-indicating circuit calibrated by a single-frequency signal of known RMS voltage. For pulse-modulated signals, the value during the pulse on-time is usually measured by means of a peak-indicating circuit calibrated with an unmodulated single-frequency signal of known RMS value. In this case, the necessary receiver bandwidth and the optimum charge and discharge time constants of the indicating circuit depend on the pulse duration and repetition rate, see [B1], [B2], [B4], [B5], [B9], [B71], and [B72]. Calibrated oscilloscopes are also employed to determine pulse-peak values.

In the case of frequency-modulated waves, the effect of modulation on the measured field-strength value may be essentially eliminated if the receiver has an overall passband slightly greater than twice the maximum frequency deviation. When making field strength measurements of television video transmissions, the RMS value of the maximum levels that occur during synchronizing pulses is usually measured, see [B32], [B36], and [B48]. The time constant of the second detector and the overall receiver bandwidth should be such that the meter essentially will be peak reading. If it indicates at least 85% of the peak levels, the reading will be essentially independent of the modulation content. A measurement of the RMS value of the video carrier can be made but, because the result depends on the modulation percentage, this measurement is seldom used. Measurement of the sound carrier of a television station is more easily accomplished because of the narrower receiver bandwidth required and the lack of amplitude variation with modulation. The latter method often yields sufficient information for field survey purposes, provided that the radiation pattern of the transmitting antenna is essentially the same for the video-carrier and sound-carrier frequencies.

In analyzing or reporting measured data, it is important to consider the influence of the receiving site and surrounding topography, electrical properties of the ground (see [B38], [B87]–[B89]), the proximity of any disturbing structures (see [B24]), and the orientation and height above ground of the receiving antenna. The true measurement of an incident field is often an indirect measurement involving a knowledge of the angle of arrival and electrical properties of the ground.

In the case of ionospheric waves at frequencies above 3 MHz, a useful expedient is to use a horizontal receiving dipole for measuring field strength (see [B23], [B24], and [B32]) regardless of whether vertical or horizontal polarization is transmitted. Similar values of each polarization are often present in the ionospheric field incident upon the receiving antenna for any type of polarization at the transmitting antenna. The advantage of measuring only the horizontal component is that the measured field strength is practically independent of differences in the electrical properties of the ground at different receiving points. Hence, as long as the height of the receiving antenna above ground is stated, measurements at different sites (at a given frequency) may be directly compared.

In some cases, even though the vertical component of the electric field is greatly influenced by the nature of the ground, it should nevertheless be the field component measured since it provides a more accurate picture of the actual conditions encountered in service. This is particularly true for measurements in the AM broadcast band (540 to 1600 kHz) where the antenna generally responds mainly to the vertical component of the E field.

When a shielded loop antenna is employed for measuring field strength, it is the magnetic field component (H) that is being measured. Unfortunately, the results are often erroneously expressed in V/m of an electric field (E) by means of the following relation, which does not necessarily apply except for a linearly polarized plane wave in free space:

$$E = \eta_0 H \quad (5)$$

where

η_0 = impedance of free space, equal to approximately $377 \, \Omega$
 H = magnetic field strength in A/m

It should be emphasized that the above relationship is not necessarily valid near a discontinuity such as the surface of the earth or near other reflecting surfaces. Under some conditions, standing waves may exist where the field is composed of two or more traveling waves for which Eq 5 also is not valid. Consequently, inconsistent results may be obtained if measurements of field strength are made using both a loop antenna and a vertical monopole or a horizontal (or vertical) dipole. In cases where the magnitude of the electric field is desired, and Eq 5 is not applicable, a calibrated E field antenna should be used with appropriate correction for proximity of the ground.

2.2 Field Strength Calibrations Using Loop Antennas, 30 Hz to 30 MHz

2.2.1 Standard Receiving Loop

A loop antenna may be used to measure magnetic field strength from about 30 Hz up to about 30 MHz. Below about 3 MHz, especially for low-arrival angles, the loop antenna has the advantage of convenience in handling, availability of a zero-response orientation, and a simple expression for the voltage produced by a given field strength. At higher frequencies, above about 100 MHz, a loop of practical size may no longer be electrically small. The loop then has a significant response to the electric field as well as the magnetic field, see [B91]. The characteristics expected for an electrically small loop are no longer present (e.g., a figure-eight field pattern with sharp nulls). Thus, a position of minimum response is ill-defined, and there is difficulty in defining the polarization for the field component being measured. Also, as the frequency is increased, there is difficulty in securing a balanced connection of the loop antenna to the voltage-measuring receiver.

The shielded-loop antenna has come into general use for direction finders and can be used for measuring field strength. It is desirable that the shield have a gap at the top so that the antenna is symmetrical with respect to ground. This also minimizes the response of the loop to a vertically-polarized electric field, see [B91].

Figs 2 and 3 illustrate methods of calibration for balanced and shielded unbalanced loops, respectively. These employ direct voltage substitution in which the rf voltage induced in the receiving loop is compared directly against a known rf voltage obtained from a standard signal generator. In this case the receiver is used merely as an uncalibrated comparison voltmeter. The loop antenna is oriented and the receiver is tuned for maximum response at the carrier frequency. The receiver gain is adjusted to produce a convenient indication and is left at this setting. The loop antenna is then turned until the receiver indication is a minimum. The standard signal generator is turned on and tuned to the frequency of the field to be measured. The signal generator voltage is adjusted to give the same indication as that obtained when receiving the unknown field. The signal-generator voltage then equals the induced voltage acting in series with the loop. If the signal-generator impedance is mismatched, or if resistors are added in series with the loop resistor to match the output, a special voltage calibration of the generator will be required.

When the self-resonant frequency of the loop antenna is several times the frequency of the field being measured and the electric and magnetic fields are related by Eq 5, the value of field strength E in V/m is