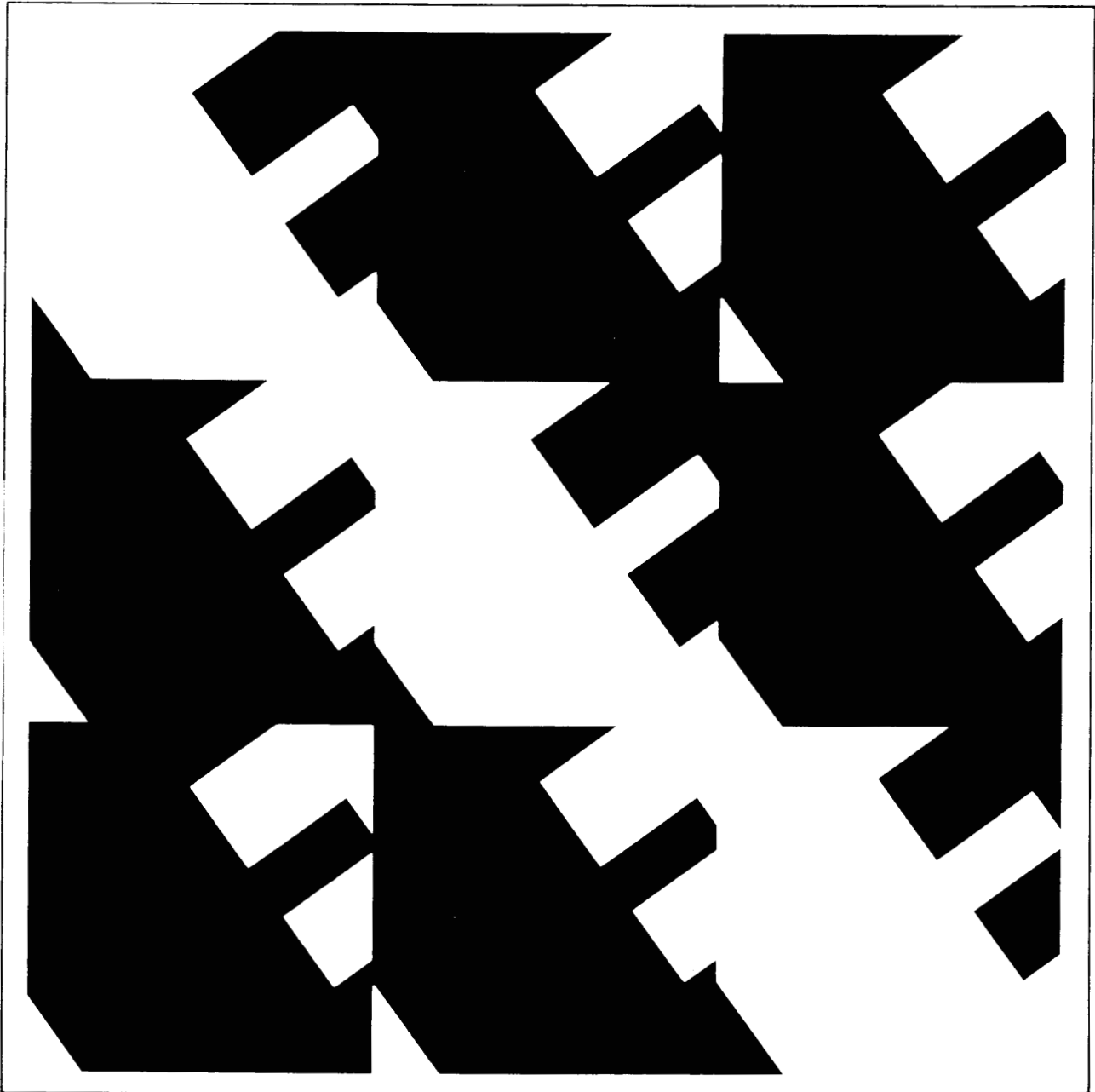


IEEE Standards Report on Measuring Field Strength in Radio Wave Propagation



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IEEE Standards Board

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MEASURING FIELD STRENGTH IN RADIO WAVE PROPAGATION

1. INTRODUCTION

1.1. General. Most measurements with which radio wave propagation is concerned involve the measurement of field strength. Thus, the determination of power radiated from an antenna (Section 3) depends principally upon the measurement of field strength, especially in the low-frequency and medium-frequency bands. Standard methods for the measurement of this fundamental quantity are outlined.

1.2. Symbols and Units. The general symbols and units used 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.

Symbols

- C = Capacitance, in farads.
 d = Distance from transmitter to receiver, in meters.
 D = Conductor diameter of dipole antenna, in meters.
 E = Root-mean-square electric field strength of a radio wave, in volts per meter.
 f = Frequency, in hertz.
 g = Power gain of an antenna (over that of an ideal isotropic antenna) considering only its directivity but not its losses.
 g_r = Power gain of an antenna (over that of an ideal isotropic antenna) considering both its directivity and its losses.
 H = Root-mean-square magnetic field strength, in amperes per meter.
 h = Height above ground of antenna center of radiation, in meters.
 I = Root-mean-square antenna current, in amperes.
 K = Calibration factor of a commercial field-strength meter.
 l_d = Effective length of dipole antenna, in meters.
 L_d = Physical length of a linear dipole antenna, in meters.
 l_L = Effective length of loop antenna, in meters.
 l_v = Effective length of grounded vertical antenna, in meters.
 L_v = Physical length of grounded vertical antenna, in meters.
 N = Number of turns.
 P = Power, in watts.
 Q = 2π times the ratio of energy stored to energy dissipated per cycle (Q is normally expressed as the ratio of inductive reactance to resistance at resonance).

- R = Resistance, in ohms.
 S = Mean area per turn of loop, in square meters.
 V = Root-mean-square voltage, in volts.
 α = Attenuator ratio (equal to, or greater than, unity).
 λ = Wavelength, in meters.
 ϵ_r = Relative dielectric constant of the ground, i.e., the ratio of permittivity (dielectric constant) of ground to that of vacuum.
 σ = Ground conductivity, in mhos per meter.
 c = Velocity of propagation of an electromagnetic wave in a vacuum ($2.997\,925 \pm 0.000\,003 \times 10^8$ meters per second).
 Z_0 = Impedance of free space ($4\pi c \times 10^{-7} = 376.7304 \pm 0.0004$ ohms).

Unless otherwise stated, quantities are assumed to be those of the International System. For convenience, several relationships and prefixes are tabulated.

- 1 inch = 0.0254 meter.
 1 mile = 1609.344 meters.
 1 meter = 0.000 621 371 2 mile.
 1 square inch = 0.000 645 16 square meter.
 1 square meter = 1550.0031 square inches.

- | | |
|-------------------|------------------|
| pico = 10^{-12} | deka = 10 |
| nano = 10^{-9} | hecto = 10^2 |
| micro = 10^{-6} | kilo = 10^3 |
| milli = 10^{-3} | mega = 10^6 |
| centi = 10^{-2} | giga = 10^9 |
| deci = 10^{-1} | tera = 10^{12} |

Quantity	Name of SI Unit	Number of CGS Electromagnetic Units in 1 SI Unit
length	meter	100
area	square meter	10 000
frequency	hertz	1
voltage	volt	10^8
electric field strength	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}
magnetic field strength	ampere per meter	$4\pi \times 10^{-3}$

2. METHODS OF MEASURING FIELD STRENGTH

2.1. General. Two general methods are applicable to the measurement of field strength [1]–[4]. One consists of measuring the voltage developed in a standard 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 other 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 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. Field-strength measurements or surveys are often made using commercially available meters that have been previously calibrated* in a known field determined by either of these methods.

2.1.1. Standard-Antenna Method. In the standard-antenna method, the receiving antenna is of some standard form such that the voltage induced in it by a wave of given field strength and polarization may be computed readily [1]–[5], [77]. The ratio of this voltage to the component of the field producing it is called the effective length (or the effective height), i.e.,

$$l \equiv V/E \quad (1)$$

of the antenna. The method of coupling the standard antenna to the voltage-measuring instrument is generally such that the voltage measured is not the voltage induced in the antenna by the field but bears a fixed ratio to it. The ratio of the voltage measured to the voltage induced 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 this ratio may be required in some instances.

A standard voltage source is provided, usually as part of the field-strength measuring apparatus, for calibrating the voltmeter. The term voltmeter is used here to mean the radio-receiving portion of the equipment. The calibrating voltage may be fixed or it may be 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. When a fixed calibrating voltage is employed, the voltmeter is calibrated at a fixed sensitivity level, and a calibrated attenuator is employed in conjunction with the voltmeter, in order to measure voltages over the wide range required.

* A public calibration service is maintained by the National Bureau of Standards, Boulder, Colo., for field-strength meters in the frequency range of 10 kilohertz–300 megahertz. For information write: Director, National Bureau of Standards, Washington 25, D.C.

Alternatively, the 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 field strength is computed on the basis of the effective length of the antenna, the voltage-transfer ratio, the voltage from the standard voltage source, and the attenuator ratio. In some instances it may be difficult to calculate accurately the effective length of the antenna being used. In such cases, the product of the effective length and the voltage-transfer ratio can be determined directly from a single measurement of the terminal voltage of the antenna when placed in a standard field. The reciprocal of this product is sometimes called the antenna coefficient. This is the procedure usually followed in the calibration of commercial field-strength meters. In this case, the value of the “antenna coefficient” determined usually includes the gain factor of the receiver.

2.1.2. Standard-Field Method. In the standard-field method the standard field may be set up by a local transmitter. The field at the receiving antenna may be computed from the dimensions of the transmitting antenna, its current and current distribution, the distance, and the effect of the ground, or it may be determined by direct measurement with a standard antenna [1]–[4]. The measuring equipment associated with the receiving antenna generally consists of a sensitive vacuum-tube voltmeter employing double detection and having an indicator in the output of the second detector. While it is possible to adjust the strength of the standard field to equality with the field to be measured by varying the distance of the local 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. 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.

2.1.3. Simplifications and Precautions. The problem of field-strength measurement is generally complicated by the varying nature of the field resulting from variability of the transmission medium [6]–[9], by the complex nature of the emission [10], [11], and by the influence of the ground and of disturbing structures [11]–[15]. Simplifying approximations 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 or tropospheric wave fields, a really complete measurement would involve determination of:

- (a) the field strength of the vertical, longitudinal and lateral electric- and magnetic-field components in each wave arriving at the receiving point;
- (b) the phase angles between the different components;
- (c) the direction of arrival of each wave component.

Fortunately, considerable practical information may be obtained by measuring only the vector components of the field [16] which are used for communication. Simple forms of receiving antennas thus become useful, the type of antenna used being dependent upon the component of the field to be measured.

A simplification in the measurement of complex emissions may be achieved by removing the modulation so that a single-frequency field (the carrier) is measured. In emissions without a carrier wave, such as a single-sideband wave, it is sometimes 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 cross-modulation products of an amplitude-modulated wave or the interfering effect of single-sideband emission. When measuring the harmonic content of a given field, special precautions should be taken to avoid errors due to harmonics that may be produced within the measuring equipment.

The typical measuring system is a frequency-selective voltmeter arranged to indicate the average, peak, or quasi-peak value, over a suitable short time interval, of the root-mean-square voltage of the signal that has passed through the frequency-selective circuits. For single-frequency fields the root-mean-square value is measured, usually, by use of an average-indicating circuit calibrated by a single-frequency signal of known root-mean-square voltage. For pulse-modulated signals, the root-mean-square value during the peak of the pulse is usually measured by means of a peak-indicating circuit calibrated by an unmodulated single-frequency signal of known root-mean-square value. In this case, the necessary charge and discharge time constants of the indicating circuit depend upon the pulse duration and the pulse repetition rate [17]–[21]. Calibrated oscilloscopes are also employed to determine peak values. In the case of frequency-modulated waves, the effect of modulation on the measured value may be essentially eliminated if the receiver has an overall passband slightly greater than twice the peak frequency deviation. When making field-strength measurements of television video broadcast transmissions, the root-mean-square value of the peak levels that occur during synchronizing pulses is usually measured [10], [61], [62], [67]. The time constant of the second detector diode load, and the overall receiver bandwidth should be such that the meter will be essentially peak reading. If it indicates at

least 85 percent of the peak levels the reading will be essentially independent of the program content. A measurement of the root-mean-square or average value of the video carrier may be made, but the result will depend upon the modulation percentage and 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 survey purposes, provided that the radiation patterns of the transmitting antenna are near enough to being the same for the two frequencies.

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 [12]–[15], proximity of disturbing structures [11], 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 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 usually 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.

In the case of ionospheric waves at frequencies above about 3 megahertz a useful expedient under some circumstances is to use a horizontal doublet antenna for the measurement of resultant fields [11], [16], [22], regardless of whether vertical or horizontal polarization is transmitted. Similar amounts of each type of polarization are often present in the ionospheric-wave field incident upon the receiving antenna 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 vertical 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 (540–1600 kilohertz) where the antenna generally used is principally responsive to the resultant vertical component of the ionospheric waves, and to the ground wave.

When a shielded loop antenna is employed for making field-strength measurements, it is the magnetic component H of the field that is being measured. Unfortunately, the

results are very often erroneously expressed by means of the following relation, which applies only to plane waves in free space, in terms of an electric component E :

$$E = Z_0 H \quad (2)$$

where Z_0 is the impedance of free space.

It should be emphasized that, strictly speaking, this relationship holds only for free-space conditions and is not valid near a discontinuity such as exists at the surface of the earth or near other reflecting surfaces. Under some conditions standing waves may exist wherein the field is complex and is actually composed of two or more traveling waves for the combination of which (2) is not valid.

Consequently, apparently inconsistent results will often be obtained from the relation (1) if measurements of the electric field strength are made using first a loop antenna and then a rod or doublet antenna. In those cases where a knowledge of the electric field strength is desired, and the relation (2) is not applicable as discussed above, a properly calibrated rod or dipole antenna should be used for the measurements, with appropriate allowance for any changes in current distribution arising from the proximity of the ground.

2.2. Standard-Antenna Method

2.2.1. 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 strength, fading or steady, frequency, etc.), and by the degree of convenience of handling the antenna [5], [11], [12], [16], [23], [24], [78]. 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, or in terms of power gain or effective area.

The loop antenna may be used from the lowest frequency into the very-high-frequency range (up to about 50 megahertz). Below about 3 megahertz it is the practical equivalent of a vertical antenna (for low arrival 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 position of minimum response becomes ill-defined, and there is increasing difficulty in defining the polarization 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 main-

taining substantially uniform current distribution around the loop antenna, the loop must be made smaller in diameter, decreasing its sensitivity. At very 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.

The shielded type of loop antenna has come into general use for direction finders and has been applied successfully in field-strength-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 megahertz. 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 or ground plane is usually desirable.

The dipole type of antenna is generally applicable at frequencies above about 3 megahertz. It is particularly convenient at frequencies above 30 megahertz.

Measurements of field strength 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.

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

2.2.2.1. Loop-Antenna Calibration. Figures 1 and 2 illustrate a method of calibration for both the balanced and the shielded unbalanced loop, respectively, employing direct voltage substitution, wherein the radio-frequency voltage induced in the receiving loop antenna is compared directly with a known radio-frequency voltage obtained from a suitable standard signal generator. In this case the receiver is used merely as an uncalibrated comparison voltmeter. The loop antenna is oriented and tuned for maximum output for the carrier being received. The receiver attenuator is adjusted to give any convenient deflection on the output meter V and left at this setting. Then, with the loop antenna turned to a right-angle position so that the measured output is low, the standard signal generator is turned on and tuned to approximately zero beat with the residual measured field. The standard voltage is adjusted to give the same mean indication on

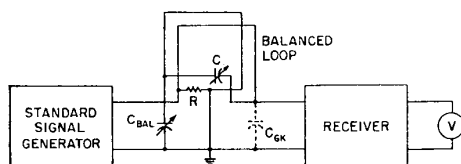


Fig. 1. The direct substitution method of calibration for a balanced loop.

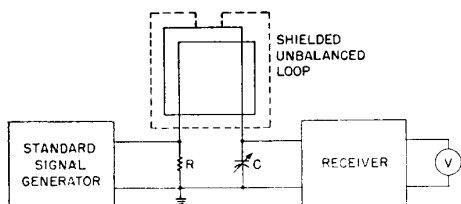


Fig. 2. The direct substitution method of calibration for a shielded unbalanced loop. The resistor R is of the order of 1 ohm.

meter V that was obtained when receiving the unknown field. The standard-generator output voltage then equals the equivalent induced voltage acting in series with the loop. If the standard generator is mismatched, or if resistors are added in series with the loop resistor R to match the output, a special voltage calibration of the generator will be required.

When the natural resonance frequency of the loop antenna alone is several times the frequency of the field being measured, the value of field strength E in volts per meter is

$$E = \frac{V}{l_L} \quad (3)$$

where V = output of the standard-signal generator across the resistor R , in volts; l_L = effective length (or height) of the loop antenna, in meters, and is determined as follows:*

$$\left. \begin{aligned} l_L &\cong \frac{2\pi SN}{\lambda} \\ \text{or} \quad l_L &\cong 2.096 \times 10^{-8} fSN \end{aligned} \right\} \quad (S < 0.01\lambda^2) \quad (4)$$

This method usually requires a signal generator having a low output impedance. The effective value of resistance in series with the loop antenna is usually of the order of 1 ohm so as not to appreciably lower its Q . This value of series resistance should remain the same when the receiver is tuned to the unknown field as when the standard voltage is injected for calibration purposes.

In some instances the calibrating voltage injected into the loop antenna may have a fixed value (high level). It is compared with the induced field-voltage by means of a calibrated attenuator between the mixer and first intermediate-frequency stage of the receiver. The gap be-

tween successive steps of the attenuator is usually spanned by a linear output indicating system comprised of a diode rectifier and indicating meter. Precautions must be taken to insure that the first detector or mixer stage is linear for all receiver input voltages normally used, including the voltage used for calibration.

An error in calibration will generally exist owing to the difference in voltage step-up or Q of a tuned loop antenna for a distributed induced voltage and for a lumped voltage inserted at the center or at one end. This error is caused by the distributed capacitance of the loop antenna, and is a function of the ratio of the operating frequency to the natural frequency of the antenna f/f_0 . It may amount to as much as 15 percent or more for tuned loop antennas operated near their natural frequency; this and other sources of error in broadcast-type field-strength equipment have been studied extensively [1]. For a balanced unshielded loop antenna the correction factor by which one must multiply the lumped voltage introduced at one end of the loop to get its true distributed effect is given approximately by

$$F \cong 1 - \left(\frac{f}{f_0}\right)^2 \quad (6)$$

If the calibrating voltage is injected at the center of the balanced loop, as is usually the case, the correction is given approximately by

$$F \cong 1 + 0.27\left(\frac{f}{f_0}\right)^2 \quad (7)$$

It has been indicated that it is possible to compensate partially for the distributed capacitance effect by operating the loop antenna unbalanced with respect to ground. In such a case, a shield must be employed to eliminate the resulting vertical or antenna effect.

It has also been indicated that the effect of the distributed capacitance of the loop antenna on the accuracy of field-strength measurements may in some instances be minimized by the expedient of using an untuned loop [25].

Another source of error is the distortion of the field caused by the presence of the field-strength meter [11], [25] or vehicle [26] and the current in the loop. Such errors may amount to as much as 10 percent or more. To reduce the influence of the meter and vehicle, the loop antenna is mounted well in the clear.

In another method of calibration, the calibrating voltage is applied to the input of the receiver or vacuum-tube voltmeter and is adjusted to equality with the voltage developed across the input by the loop antenna. A measurement of the Q of the loop antenna is then required for computing the voltage induced in the loop antenna. The field strength is computed on the basis of the induced voltage and the effective length of the antenna.

The method of measuring the Q is designed to avoid errors that 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 capacitor of low capacitance

* A more accurate value of l_L can be obtained by multiplying the right side of (3)–(5) by the factor $1 - \pi S/2\lambda^2$.