NBS Field-Strength Standards and Measurements (30 Hz to 1000 MHz)

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Abstract—A description is given of the CW field-strength standards and associated measurement instrumentation and techniques, used for the calibration of both commercial and military field-strength meters in various frequency bands of the overall range from 30 Hz to 1000 MHz, which have been developed at the National Bureau of Standards during the past 25 to 30 years. The techniques are applicable only for evaluating the strength of steady-state, ac fields varying sinusoidally in time, and are not intended for use in broadband applications of any kind.

Two principal types of field-strength standards and a prototype near-zone field-strength meter are described: 1) magnetic-field-strength standards (30 Hz to 30 MHz), 2) electric-field-strength standards (30 to 1000 MHz), and 3) near-zone electric-field-strength meter and interim field-strength standards (150 kHz to 30 MHz).

I. GENERAL INTRODUCTION

This paper presents a description of the various CW field-strength standards and associated measurement instrumentation and techniques developed during the past 25 to 30 years at the National Bureau of Standards. These are used for the calibration of both commercial and military field-strength meters in various frequency bands of the overall range from 30 Hz to 1000 MHz. 1 The techniques used are applicable only for evaluating the strength of steady-state, ac fields varying sinusoidally in time, and are not intended for use in broadband applications of any kind.

Two principal types of field-strength standards and a prototype near-zone field-strength meter are described. These are as follows.

1) Magnetic-Field-Strength Standards used over the frequency range 30 Hz to 30 MHz for the calibration of CW field-strength meters employing small-loop receiving antennas.

2) Electric-Field-Strength Standards used over the frequency range 30 to 1000 MHz for the calibration of CW field-strength meters employing half-wavelength self-resonant dipole receiving antennas.

3) Near-Zone Electric-Field-Strength Meter and Interim Field-Strength Standards used over the frequency range 150 kHz to 30 MHz for the evaluation of hazards of high-level electromagnetic radiation to ordnance devices and other uses.

The techniques used for calibrating field-strength meters must duplicate, insofar as possible, the conditions normally existing when these meters are used later for making actual measurements. Some of the principal factors that need to be considered are:

1) the spatial distribution of the amplitude and phase of the received wave over the aperture of the measuring antenna [1]–[3];

2) interaction between the measuring antenna and its image in the ground, in a nearby conducting plane, or in a nearby radiator [4];

3) perturbation of the field being measured by the RF transmission line connected between the measuring antenna and the receiver [5].

It is desirable to have at least two independent methods of measuring any physical quantity. From a direct intercomparison of the results of such measurements, then, it is possible to obtain a better estimate of the uncertainty existing in the methods. Basically, there are two independent methods or techniques by which the desired component of field strength can be evaluated. These are called 1) the Standard-Antenna Method, and 2) the Standard-Field Method [6]. The former consists of measuring the voltage induced in a standard receiving antenna by the component of the field being evaluated, and computing the value of the field in terms of this voltage, the dimensions and form of the standard antenna, and its orientation with respect to the field vector. The second method consists of generating and computing the desired component of a standard field in terms of the dimensions and form of a transmitting antenna, its current distribution, the distance from the transmitting antenna to the point at which the field component is being evaluated, and the effect, if any, of the ground.

The procedures described in this paper are used to establish standards of electric or magnetic field strength at a single amplitude level, or at most at a relatively few levels. The complete calibration of a field-strength meter is then made by extending these standard-field values to other levels, using secondary procedures which involve the attenuator calibration and the output-meter linearity determination of the instrument being calibrated. These procedures are then repeated, in part, for each specific frequency for which a calibration is to be carried out. A further discussion of these secondary procedures is given elsewhere [7], [8] and so will not be included in this paper.

All time-varying quantities used in this paper are expressed in terms of their rms values. Rationalized MKS units are used throughout.

Manuscript received March 28, 1967.

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1 Field-strength measurements above 1000 MHz are discussed in a paper by R. R. Bowman elsewhere in this issue.
II. MAGNETIC-FIELD-STRENGTH STANDARDS
(30 Hz to 30 MHz)

A. Introduction

A description will be given in this section of the magnetic-field-strength standards and measurement techniques used for the calibration of field-strength meters employing loop antennas in the frequency range 30 Hz to 30 MHz. As previously stated, these standards involve the use of single-frequency CW fields only.

In order that the calibration conditions duplicate, insofar as possible, those existing when the meters are used later for making measurements, the following specific factors need to be considered for the type of meters used in this frequency range.

1) The type of field (propagation mode and polarization).
2) Any change in the local \( |E/H| \) ratio at the measurement site from the free-space plane-wave value caused by any of the following:
   a) local ground nonhomogeneities, or discontinuities
   b) multipath propagation
   c) measuring in the near-field of a transmitting antenna
   d) reflections or field distortion caused by local foreign objects.
3) Any difference in field distortion caused by the presence of the field-strength meter in the standard calibrating field and in the unknown field measured later.

B. Standard-Field Method

In this frequency range, NBS field-strength calibration services at the present time are limited to field-strength meters using small loop-type receiving antennas [7], [8]. Such antennas are either operated balanced with respect to ground or are electrostatically shielded. In either case their response is proportional to the average normal component of magnetic field strength incident on the loop. An accurately known quasi-static magnetic field can be produced by the Standard-Field Method for calibrating the antennas of such field-strength meters.

A small, single-turn, circular, balanced transmitting loop is used to produce the standard field. The radius of the wire with which the loop is wound is assumed to be negligible compared to the loop radius \( r \). The loop current \( I \) is assumed to be constant in amplitude and phase around the loop.

The loop antenna being calibrated is positioned coaxially with respect to the transmitting loop and is spaced an axial distance, \( d \) meters, from it. The geometry of the calibrating setup is shown in Fig. 1. The two loop antennas can also be positioned in the same plane. While coaxial loops are normally used for calibration purposes, coplanar loops may be useful under certain conditions (e.g., in the calibration of some types of ferrite-core loop antennas [9]).

The rms value of the normal component of the magnetic field \( H \), averaged over the area of the receiving loop, is given (in amperes per meter) by the following equation to within 0.2 percent [lo] provided \( \beta R_0 \leq 1.0 \), and \( r_1 r_2 / R_0^2 \leq 1/16 \):

\[
|H_s| \approx \frac{IS_1}{2\pi R_0^3 \left[ 1 + \frac{15}{8} \left( \frac{r_1 r_2}{R_0^2} \right)^2 + \frac{315}{64} \left( \frac{r_1 r_2}{R_0^2} \right)^4 + \cdots \right]} \left( 1 + \beta^2 R_0^2 \right)^{1/4},
\]

where

\[
R_0 = \left[ d^2 + r_1^2 + r_2^2 \right]^{1/4}
\]

and

\[
I = \text{transmitting loop current, rms amperes}
\]

\[
S_1 = \text{area of transmitting loop, square meters (} S_1 = \pi r_1^2 \text{)}
\]

\[
r_1 = \text{radius of the transmitting loop, meters}
\]

\[
r_2 = \text{radius of the receiving loop, meters}
\]

\[
d = \text{axial spacing between the loops, meters}
\]

\[
\beta = \text{wavelength constant (} \beta = \frac{2\pi}{\lambda} \text{)}
\]

\[
\lambda = \text{free-space wavelength, meters}
\]

\[
f = \text{frequency, hertz.}
\]

The infinite series contained in (1) converges extremely rapidly, more so than most other series solutions found in the literature. It is seldom necessary to use even the first correction term of the series, since if \( d/r_1 \) and \( d/r_2 \) are each greater than 4, the correction is less than 1.0 percent. Equation (2) for evaluating \( R_0 \) is also in an easier form to use than normally found. These factors tend to make this an easy formula to use for computing standard-field values.

For the conditions specified, higher-order terms in \( \beta R_0 \) are negligible and have been omitted from (1). Since the first correction term in the infinite series will contribute less than 1 percent, (1) can be further simplified to

\[
|H_s| \approx \frac{IS_1 (1 + \beta^2 R_0^2)^{1/4}}{2\pi R_0^3} \text{ amperes per meter. (3)}
\]

1) Calibration of Field-Strength Meters: The loop current is measured by means of a vacuum thermocouple previously calibrated with direct current. It is located sym-
The measured value of the quasi-static magnetic field \( H \) produced by the plane-wave impedance \( \eta = \sqrt{\mu/\varepsilon} \approx 120\pi \), such that \( E \approx 120\pi H \). Using this relationship, (3) can be rewritten (in volts per meter) as

\[
|E| \approx \frac{60\pi r^2 I}{R_0^2} (1 + \beta^2 R_0^2)^{\frac{1}{2}}. \tag{4}
\]

The value of field given by (4) is essentially independent of frequency up to about 5 MHz. At higher frequencies, the frequency correction term under the radical (the induction-field component) begins to become appreciable for the spacing in the NBS standard \( (d \geq 1.25 \text{ meters}) \). The value of equivalent field strength \( E \) used for calibration is of the order of 0.1 volt per meter \( (r_1 = 0.1 \text{ meter}, I = 0.1 \text{ ampere}) \).

Portable VLF standard-field calibrating instrumentation has also been recently developed at NBS using the above principles [12]. With this equipment a very-low-frequency field-strength meter can be periodically calibrated during a sequence of measurements in the field.

2) Factors Affecting the Accuracy of Calibration and Use:

Loop-antenna current distribution: The accuracy of the value of the standard field given by (3) or (4) is affected by the constancy of the current \( I \) as well as its phase around the circular transmitting loop. The uniformity depends upon the circumference of the loop in wavelengths, but usually does not become a problem except at frequencies above 5 or 10 MHz [13]. In order to keep the decrease in average current from exceeding 1 percent, the loop circumference should not exceed \( \lambda/16 \) at the highest calibrating frequency [10].

An interesting error analysis was recently made on the standard-field method of loop calibration [14]. The author estimated the uncertainty to be from 2.5 to 4.0 percent, after analyzing possible errors in evaluating the various parameters involved.

Local field distortion: An important factor that can affect the accuracy of calibration and use of a loop-type field-strength meter is the distortion of a field in the immediate vicinity of the instrument by its enclosing metallic case. If the loop antenna of the field-strength meter is mounted a distance less than its own diameter above the case, the field-strength meter must be calibrated and later used with a specific relative angular orientation between the loop antenna, the case, and the incident field being measured. Failure to observe this precaution may result in a measurement error of as much as 5 to 10 percent, depending upon the height of the loop above the case [15], [16]. An example of the variation in this error as a function of orientation between the loop antenna and case is shown in Fig. 4. This is the measured error that would result for one particular make of field-strength meter whose antenna was very close to the case. An even larger error may be encountered when a loop antenna is mounted above the metallic body of an automobile, as, for example, when making mobile field-strength measurements [17].

The field distortion just described is, in general, different when the field-strength meter is being calibrated in the near-zone quasi-static field given by (3) or (4) than when used metrically at the top of the loop winding, and its dc output is measured with a dc millivoltmeter or a precision slide-wire potentiometer as shown in Fig. 2. The RF substitution error of this type of thermocouple, when used for this purpose in a balanced circuit with the thermocouple at essentially ground potential, has been found to be less than 1 percent at frequencies even as high as 100 MHz [11].

A clear space must be used for the calibration such that a distance of at least two or three times the spacing \( d \) between loops exists from either loop to the nearest sizable metallic objects and to the ground. The effect of these objects in distorting the field can be determined by placing metal objects of similar size in the vicinity of the loops and noting the effect on the value of the field at the receiving loop. The calibration setup at NBS, which is located in a small frame building remote from the main laboratory, is shown in Fig. 3. The use of metal and electrical wiring was kept to a minimum in its construction.

The value of the quasi-static magnetic field \( H \) produced by the standard loop is expressed in terms of the equivalent electric component \( E \) (in volts per meter) that would exist in a free-space, plane-wave radiation field. For this case, the magnitudes of these two field components are related.
later to measure a uniform plane wave. In the former case, the instrument is within one or two meters of the standard transmitting loop, in a field that is varying rapidly as 1/d^3. In the latter case, the meter is usually one or more kilometers from the transmitting antenna, in a radiation field that is varying much more slowly and approximately as 1/d. There is therefore a large difference, in these two cases, in the percentage change in field strength along the longitudinal dimension of the field-strength meter. Any resulting difference in local field distortion in the two instances can be interpreted as a calibration error for those field-strength meters with their loop antenna mounted close to the case. While any such error is probably small, in most instances, this is something that should probably be investigated further.

Use of loop-type field-strength meters: The response of a small receiving loop antenna that is either operated balanced with respect to ground, or that is electrostatically shielded, is proportional to the average normal component of magnetic field strength incident on the loop. It can be thought of as a magnetic probe. However, the calibration and subsequent measurements of field strength are expressed in terms of the electric component E that would exist if the measurement were being made in free space (in this case, E ≈ 120πH).

When such a field-strength meter is used to make measurements near the ground, the indicated value of the electric component of field strength may not always be valid. If there are serious local nonhomogeneities, or discontinuities in the electrical properties of the ground (ε, and σ), the free-space relationship between total E and total H does not hold. The same will be true if measurements are made in a multipath field [18] resulting from any type of reflection. Likewise, measurements made with such an instrument in the near field of a transmitting antenna (d ≤ λ) will be of questionable value. In this case, the ratio |E/H| may range from a value much less than that in free space, to one much greater, depending upon the type of transmitting antenna (i.e., whether basically a magnetic dipole, or basically an electric dipole), distance, polarization, etc. This is true in near-field antenna measurements, as well as in very-low-frequency propagation measurements, where the near field may extend many miles from the transmitting antenna [19].

However, in all of these instances, the value of the magnetic component of the field H (in amperes per meter) can be correctly determined if the value of equivalent electric field strength E (in volts per meter), as indicated by the meter, is divided by 120π. If it is a knowledge of the electric component of field strength that is desired in these cases, it must be determined directly using a meter whose response is proportional to the electric component of the field.

C. Standard-Antenna Method

1) General: This is an independent method that can be used for evaluating magnetic field strength at frequencies above a few megahertz. Its use has been limited mainly to the higher frequencies because of the lack of a balanced-voltage standard of suitable sensitivity. Its principal use here is for intercomparison with the standard-field method to determine the agreement between the standards. The normal component of the magnetic field can be evaluated in terms of the rms voltage V_0 that it induces in a standard circular receiving loop antenna of known dimensions from the following (based on the relation V = −N(dφ/dt))

\[ |H_n| = \frac{V_0 \cdot 10^7}{4\pi S_2 N \omega} \text{ amperes per meter}, \]  

where

|H_n| = \text{amperes per meter}

S_2 = \text{area of the receiving loop, square meters (S_2 = \pi r_2^2)}

N = \text{the number of loop turns}

r_2 = \text{radius of the receiving loop, meters}

\omega = 2\pi f_r.

It is necessary that the receiving loop antenna be electrically small (2πr_2 << λ), if the induced voltage is to be equal to the voltage appearing at the antenna terminals. In effect, this means that both the self-inductance and the distributed capacitance should be small, or the operating frequency of the loop should be low compared to its lowest self-resonant frequency.

The distributed capacitance will cause the terminal voltage V' of the loop to be higher than the induced voltage V_0 due to partial resonance. It can be shown from elementary circuit theory [20] that for the case where the distributed capacitance can be replaced by an equivalent lumped capacitance, the relative rise in the terminal voltage will be given quite accurately by (6) so long as \( f_0 \geq f_0 \leq 1/2:

\[ \frac{V'}{V_0} \approx \left[ 1 - \left( \frac{f_0}{f_r} \right)^2 \right]^{-1}, \]  

where \( f_0 \) is the ratio of the operating frequency of the loop antenna to its lowest self-resonant frequency. It can be seen that the ratio \( f_0 \) must be less than 0.1 for the error in terminal voltage to be less than 1 percent.
III. Electric-Field-Strength Standards
(30 to 1000 MHz)

A. Introduction

A description will be given in this section of the electric-field-strength standards and measurement techniques used for the calibration of VHF-UHF field-strength meters employing half-wavelength self-resonant dipole antennas in the frequency range 30 to 1000 MHz. The procedures described are generally carried out only for horizontal polarization for reasons of convenience and maximum accuracy. The techniques are applicable for evaluating steady-state, uniform-plane-wave, CW fields only.

It is necessary here also that the calibration conditions be essentially the same as those under which measurements will be made later. Some of the principal factors involved for the type of field-strength meters used in this frequency range are: 1) the spatial distribution of amplitude and phase in the wave under measurement, 2) the influence of the ground on the self-impedance of the measuring antenna, and 3) interaction between any RF transmission line used and the field being measured.

The standard-antenna and standard-field methods are utilized to evaluate field strength in this frequency range, as discussed in the previous section for the lower frequencies. The techniques are very similar except for obvious differences in the antennas, and in the voltage- and current-measuring instruments.

B. The Standard-Antenna Method

1) Effective Length of the Antenna: The magnitude of the electric component of field strength existing at a given point in space may be determined in terms of the voltage \( V_{\text{ac}} \) induced in a standard receiving dipole immersed in the field, together with certain factors involving the antenna geometry. It will be assumed in the following that the measuring dipole is oriented parallel to the electric-field vector \( E \) and that the voltage induced is referred to the center terminals. The relationship used is (in volts per meter)

\[
|E| = \frac{V_{\text{ac}}}{L_{\text{eff}}},
\]

where \( L_{\text{eff}} \) is the effective length of the antenna in meters.

Assuming a sinusoidal current distribution on a half-wavelength or shorter dipole, its effective length, when measuring a uniform plane wave, is [23]

\[
L_{\text{eff}} = \int_{-l}^{l} \frac{I(x)}{I(0)} \, dx = L \left[ \tan \left( \frac{\beta l}{2} \right) \right] \text{ meters},
\]

where \( I(x)/I(0) \) is the relative current distribution along the antenna (in the transmitting mode), and \( L \) is the physical length in meters \( (L = 2l) \). The effective lengths of a half-wavelength dipole and an electrically short dipole are, respectively,
Equation (9) is only valid and meaningful for the uniform plane wave case, while the approximation (10) is valid when measuring any complex electric field, if $l \leq 0.03 \lambda$.

The current distribution on an antenna is not exactly sinusoidal except for an infinitely thin filament. For cylindrical antennas of radius $a$ and half-length $l$ the departure from a sinusoidal distribution becomes progressively greater as the ratio $2l/a$ decreases (i.e., as the antenna gets fatter [2], [24]). This results in a small proportionate increase in the effective length.

In order to operate a half-wavelength dipole at self-resonance, it is necessary to shorten its physical length somewhat from a full half-wavelength due to the capacitive end effect. This results in a corresponding decrease in the effective length [23]. This decrease and the previous increase tend to cancel each other.

2) Description of the Standard Receiving Antenna: The standard receiving dipoles are shortened the required amount from a physical half-wavelength to make them self-resonant at their operating frequency. The antenna tubing or rod stock used at NBS varies in diameter from 3/8 inch (9.52 millimeters) for the 30-MHz dipoles down to 1/16 inch (1.59 millimeters) or less for the 1000-MHz antennas. The required percentage shortening for self-resonant operation varies from 3.8 percent at 30 MHz to 5.3 percent at 1000 MHz. The percentage increase in effective length, due to the finite radius of these antennas, varies from 5.5 percent at 30 MHz to 8.2 percent at 1000 MHz.

The induced voltage is measured directly by means of a relatively high-impedance balanced voltmeter connected across the gap at the center. In this manner the necessity for a separate measurement of the antenna input impedance is eliminated, which greatly simplifies the problem. The induced voltage is rectified by a low-capacitance point-contact silicon-crystal diode [21] built into the gap as shown in Fig. 6. The crystal output is filtered by means of a balanced resistance-capacitance network, and the dc output voltage is measured on a sensitive dc millivoltmeter. The central portion of one of the standard receiving-antenna assemblies minus the antenna rods is shown in Fig. 7. The input impedance of the resistance-capacitance filter is approximately 10000 ohms in shunt with 0.05 pF.

3) Influence of the Ground: VHF-UHF field-strength measurements generally will be in error if made at receiving antenna heights other than that used when the field-strength meter was calibrated. An error will likewise exist if the electrical ground constants ($\epsilon_r$ and $\sigma$) at the site chosen to make measurements are appreciably different from those existing at the time or place of calibration. This results from a change of the antenna-input impedance $Z_A$ with height above ground (or with changing ground conditions), caused by the interaction between the measuring antenna and its image in the ground. The measurement error is therefore also a function of the antenna load impedance $Z_L$.

If a field-strength meter is calibrated with its receiving antenna at a height greater than two or three wavelengths above the ground, the calibration can be said to have essentially a "free-space" value. That is, the effect of the ground on the calibration will be minor at such an antenna height.

The percentage difference between the true and indicated values of field strength, when making measurements at other antenna heights, can be as large as 10 to 15 percent (for horizontal polarization) at heights appreciably less than one wavelength, as can be seen from Fig. 8 [25]. The error will decrease with increasing antenna height, and will be generally less than 5 percent for heights greater than one wavelength over average ground ($\epsilon_r \approx 15, \sigma/\omega \ll 1$).

This error will also decrease as the antenna load impedance is increased, since any fluctuations in $Z_A$ will become small in comparison. The resulting error will approach zero as $Z_L$ approaches infinity (other factors remaining the
same). If the field-strength meter can be designed to provide a sufficiently large value of \( Z_L \), the calibration will have essentially a "free-space" value [25]. That is, the calibration will be largely independent of the height of the antenna above ground, the antenna polarization, and any changes in the electrical constants of the ground itself.

C. Standard-Field Method

1) General: A predetermined value of field strength may be established at a given point in space in terms of the current distribution in a transmitting antenna, the effect of the ground, and the geometry involved. Horizontally polarized transmission over plane-homogeneous earth having finite values of relative dielectric constant \( \varepsilon_r \) and conductivity \( \sigma \); the receiving-antenna load impedance \( Z_L \), and the antenna height (in wavelengths) above ground \( h_2/\lambda \).

The rms value of the electric component of field strength produced by a horizontal transmitting dipole, in its equatorial plane, at distances greater than about 2\( \lambda \) over plane homogeneous earth is [26]–[28] (in volts per meter)

\[
E \approx -j \frac{60\pi L_{\text{eff}}}{\lambda} \left[ \frac{e^{-j\beta R_1}}{R_1} + \frac{\Gamma e^{-j\beta R_2}}{R_2} \right] \left[ \frac{1 - \Gamma}{A(R)} e^{-j\beta R_2} \right],
\]

in which

- \( L_{\text{eff}} \) = effective length of the antenna, meters
- \( \lambda \) = free-space wavelength, meters
- \( R_1 \) = direct-ray path length, meters
- \( R_2 \) = ground-reflected-ray path length, meters
- \( \Gamma = pe^{-j\theta} \) = complex plane-wave reflection coefficient (horizontal polarization)
- \( A(R) \) = complex surface-wave attenuation factor
- \( I = \text{rms current in amperes at the center of the transmitting antenna} \)
- \( \beta = 2\pi/\lambda \)
- \( j = \sqrt{-1} \).

The first term of (11) represents the field strength that would exist if the transmitting and receiving antennas were located in free space. The remaining terms take into account the presence of the earth. The second term represents the ground-reflected wave which, when added vectorially to the first term of (11), comprises the space wave. The third term of (11) represents the surface wave associated with RF currents actually flowing in the ground. The total field given by (11) is usually referred to as the ground wave. Propagation via the ionosphere or troposphere, which is subject to changing solar or meteorological conditions, is ignored here. The magnitude of the surface wave is usually negligibly small for horizontally polarized transmission at the antenna heights and frequencies involved here [29]. In using (11) for establishing standard electric fields, then, the presence of the surface wave will be neglected entirely.

2) Description of the Standard Transmitting Antenna: The transmitting antenna used is identical to the standard receiving antenna previously described. The RF current flowing at its center can be measured either by means of a calibrated VHF vacuum thermocouple, or a small bead-type thermistor and associated bridge. A thermocouple is satisfactory for use in the lower part of the frequency range, but the thermistor is preferable and can be used over the entire frequency range of interest here with not over a 1- or 2-percent error [30]. The antenna and thermistor, respectively, terminate two sections of 72-ohm balanced, unshielded, twin-lead transmission line, each one-quarter wavelength long, as shown in Fig. 10. A balanced feed-line is connected in common with their sending ends, and a special broadband balun [31] is used to transform the unbalanced output of the RF generator to the balanced transmission system. A suitable thermistor bridge is used to complete the current-measuring instrumentation as shown.

The transfer impedance of a quarter-wavelength lossless line is equal to its characteristic impedance, and is not a function of the terminating impedance. If the characteristic impedances of the two quarter-wavelength sections used are identical, the currents flowing at their receiving ends will also be identical for a given voltage applied to their sending ends. The magnitude of the RF current flowing at the center of the transmitting antenna is thus indicated by the thermistor bead (or thermocouple), \( \lambda/2 \) distant, and is independent of the magnitude and phase angle of the two terminations, namely, the antenna input impedance on the
Fig. 9. Ray-path diagram showing direct ray along $R_1$, and ground-reflected ray along $R_2$ making an angle $\psi = \tan^{-1} \left( \frac{h_1 + h_2}{d} \right)$ with the earth.

Fig. 10. Diagram showing the method used to measure the RF current at the center of the NBS transmitting dipole.

Fig. 11. Variation of the theoretical and measured values of horizontally polarized electric-field strength $|E|$ in volts per meter, versus the height $h_2$, in meters, of the horizontal standard receiving dipole (as used in the standing-wave method).

wave is, in effect, averaged out, yielding directly the free-space field without the need to know the ground-reflection coefficient.

2) Standing-Wave Method: In this method the horizontal transmitting dipole is mounted at the top of a light, wooden, ladder mast at a fixed height of several wavelengths above the ground. In the space beneath, the direct wave and the wave reflected from the ground at vertical incidence combine to produce a standing wave, as shown in Fig. 11. The receiving dipole is mounted parallel to the transmitting dipole, but on a sliding carriage running vertically on the ladder rails. This permits measurement of the resulting variation in field strength with height above ground. The reflection coefficient of the ground for vertical incidence is determined from the resulting standing-wave ratios. The resulting value of $\Gamma$ is then substituted in (11) from which the magnitude of the standard field can be calculated for any height above the ground. The results are then compared with corresponding measured values, as determined using (7), to determine the agreement between the standards.

A separate analysis has been made recently of the errors involved in measuring the reflection coefficient of the ground [33] using the standing-wave method. The error was reported to vary from approximately 5 to 17 percent over the range of the various parameters involved. However, the effect of this error on the final accuracy in evaluating the electric-field strength is considerably less, as can be determined from (11).

3) Field-Averaging Method: In this method, both the transmitting and receiving dipoles are mounted parallel to each other on the sliding carriage. A fixed spacing of approximately two wavelengths is used between the two dipoles, so that essentially far-field conditions will exist. The resulting standing-wave pattern that is present, as the carriage is varied in height, is shown in Fig. 12. Since the spacing between the two antennas is fixed, the direct wave,
or free-space field, given by the first term of (11) will remain constant in magnitude. As the carriage is moved up or down the mast, the resulting value of field strength will oscillate around this free-space value. By properly averaging the measured data based on (7), the free-space field can be determined directly, without the need for knowing the value of the ground-reflection coefficient $\Gamma$.

This is a variation of a method employed by the Federal Communications Commission in connection with one phase of their overall standards program, which includes the design [34] and calibration [35] of VHF-UHF field-strength meters.

E. Uncertainty of the NBS Standards

Error analyses have been made of the standard-antenna and standard-field methods at several frequencies in the range 30 to 1000 MHz. Results of these studies as well as direct intercomparisons between the two methods indicate the uncertainty in the standards to be approximately 1.0 dB. It is hoped that further development planned for the near future will reduce this uncertainty to 0.5 dB.

IV. NEAR-ZONE ELECTRIC-FIELD-STRENGTH METER AND INTERIM FIELD-STRENGTH STANDARDS (150 kHz TO 30 MHz)

A. Introduction

Prototype instrumentation has recently been developed by NBS for the Defense Atomic Support Agency to measure the electric-field components of complex, high-level, near-zone electromagnetic fields [36]. This equipment is capable of measuring both the magnitude and direction of elliptically polarized CW electric fields having strengths in the range from 0.1 to 1000 volts per meter, at frequencies from 150 kHz to 30 MHz. These field-strength meters are intended primarily for use in evaluating the hazards of high-level electromagnetic radiation to electro-explosive ordnance devices on shipboard, or at other military installations. Interim field-strength standards were also developed at NBS for calibrating these near-zone meters, but will also serve for the calibration of certain types of far-zone instruments.

The design of the NBS meters is based on the use of a novel form of telemetry, employing a completely nonmetallic electrical transmission line to avoid perturbing the field being measured. The high line loss involved necessitates miniaturizing the RF portions of the receiving and calibrating instrumentation and placing them and the associated battery supplies inside the measuring antenna. The field information contained in the detected dc-AF output of the receiver is transmitted over the line to a remote readout unit, where the strength of the electric-field component parallel to the axis of the antenna is read directly.

B. The New “Semiconducting” Plastic Transmission Line

1) Errors Caused by Metallic Lines: In the past, electric field-strength meters have usually made use of a long metallic RF transmission line to connect the measuring antenna with its receiver, usually located at a point remote from the antenna. Such metallic lines often cause large measurement errors, especially when measuring near-zone fields having complex spatial distributions. In these cases, it is difficult or impossible to orient the line so that it is everywhere normal to existing electric-field components. Thus, not only may the line perturb the field being measured, but unwanted RF currents induced on the line can be coupled into the antenna and contribute to the total response of the field-strength meter.

2) The Use of a Nonmetallic Line: The previous difficulties were avoided by making use of a special nonmetallic balanced transmission line in which the conductor RF loss was purposely made extremely high compared to that of the usual copper line. If the conductors are made of sufficiently high-resistance material, the line can be made essentially “transparent” to the surrounding field. This can be achieved if the volume resistivity of the conductor material used is of the order of a million times or more higher than that of copper. This is roughly midway (on a logarithmic scale) between the volume resistivity of metals, on the one hand, and that of insulators such as glass or mica on the other. Such materials can therefore be said to be “semiconducting.”

3) Characteristics of the Conductor Material: The material used in the NBS lines is basically polytetrafluoroethylene (PTFE), rendered “semiconducting” by uniformly

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2 The term “semiconducting” will be used in this section to denote a very low level of conductivity when referring to the nonmetallic transmission line developed at NBS.
dispersing finely divided carbon black (approximately 30 percent by weight) throughout the plastic while it is in the semifluid state during its manufacture. The parallel-line conductors are in the form of 0.03-inch (0.76-millimeter) diameter monofilaments in place of the usual copper conductors. This material has a volume resistivity of approximately 3.0 ohm·centimeter (compared to $1.7 \times 10^{-6}$ ohm·centimeter for copper), giving a resistance of approximately 20 000 ohms per lineal foot (65 600 ohms per meter), or a loop resistance of approximately 1.2 megarms for a line 30 feet (9.14 meters) in length. The use of a transmission line of this type has been found to reduce the perturbation of the surrounding field by more than two orders of magnitude below that existing in the case of a copper line. This renders any effect of the line on the field wholly negligible in most instances.

C. Description of the Near-Zone Field-Strength Meters

1) Principles of Operation: Two prototype near-zone field-strength meters were developed for the frequency ranges 150 to 250 kHz and 18 to 30 MHz, respectively. These meters make use of a tuned RF type of receiver to amplify the voltage induced in the receiving antenna by the component of the electric field being measured. A tunable CW reference oscillator is included to permit resetting the overall receiver gain periodically during a sequence of measurements in the field. A block diagram of the basic circuitry is shown in Fig. 13. The meters employ the same basic method of resetting the receiver gain that has been used in CW field-strength meters in this country for many years [37].

The receiver portion of the field-strength meter consists basically of an RF input capacitive step attenuator, a fixed-tuned bandpass RF amplifier (with manual gain control), and a diode detector. The RF output level of the oscillator is monitored by its own detector. When resetting, the receiver gain is simply adjusted until the dc outputs of the two detectors are identical, as read on the remote indicator. In this method, the exact level of the CW oscillator is not important, and does not have to be known. However, it is important that the oscillator monitoring detector remain stable.

2) Design—The Dipole Antenna: The dipole of the near-zone field-strength meter is approximately 12 inches (30 centimeters) in overall length. The miniaturized solid-state receiver and its battery supply are contained in one half, and the solid-state CW reference oscillator and its battery supply are in the other. The balanced "semiconducting" transmission line enters the interior of the hollow dipole through a two-section balanced RC filter to help preserve the electrical symmetry of the dipole and to minimize common-mode RF pickup. The response of the dipole to the cross-polarized component of the electric field is 40 dB or more below the principal response.

The dipole is mounted on a hollow fiber-glass shaft which is perpendicular to the dipole axis. This shaft is in turn supported by a reinforced polyfoam ring, so that manual adjustments in both azimuth and elevation can be readily made in the orientation of the dipole. A view of the complete field-strength meter is shown in Fig. 14. The transmission line runs from the dipole, through the hollow shaft on the right, to the remote indicator unit shown in the foreground.

A measuring dipole must be short both physically and electrically if meaningful measurements are to be made in the near zone of a transmitting antenna. The physical length of the NBS dipole is about 12 inches (30 centimeters), and the electrical length about 0.03 wavelength at the highest operating frequency. Under these conditions, it has been determined at NBS that the effective length of the measuring dipole, when measuring a near-zone field having a highly complex spatial distribution, will not differ by more than 2 or 3 percent (in the worst case) from the effective length when immersed in a uniform plane wave. Likewise, any interaction error [4], resulting from coupling between such a short antenna and its image (in a nearby conducting plane,
or in a nearby radiator) will be small provided the loading is light and that measurements are not made at distances less than 2 or 3 times the length of the measuring dipole from these objects.

D. Development of the Interim Field-Strength Standards

This phase of the NBS program for the development of instrumentation for measuring near-zone electric fields involved the establishment of interim calibration standards and associated techniques for use over the frequency range from 150 kHz to 30 MHz. These were needed in order to properly evaluate the performance of the field-strength meters during their development, and to provide a preliminary calibration of the completed models. It is also planned to eventually use these standards for other purposes including the calibration of electric-field-strength meters having vertical-rod antennas.

Two different antenna configurations were selected to establish independent standard calibrated fields. These were 1) a thin cylindrical monopole over a large metallic ground plane, and 2) a relatively large parallel-plate capacitor system. An electrically short transfer (dipole) probe and field indicator were also developed for use in directly intercomparing these two types of standard fields. The present uncertainty of these standards is believed to be less than ±2 dB. It is hoped that further development effort will reduce this to ±1.0 dB or less and will also extend the usable frequency range [5].

V. SUMMARY AND CONCLUSIONS

A description has been given in this paper of the various CW field-strength standards and associated measurement instrumentation and techniques developed at the National Bureau of Standards during the past 25 to 30 years. Two of the standards are used as the basis of the calibration service maintained by NBS for both commercial and military CW field-strength meters of various types. This service is available over the frequency range 30 Hz to 1000 MHz. These standards and their respective uncertainties are as follows.

1) Magnetic-Field-Strength Standards, used over the frequency range 30 Hz to 30 MHz for the calibration of CW field-strength meters employing small-loop receiving antennas. The limit of uncertainty of the standards is believed to be ±3 percent from 30 Hz to 5 MHz, and ±5 percent from 5 to 30 MHz.

2) Electric-Field-Strength Standards, used over the frequency range 30 to 1000 MHz for the calibration of CW field-strength meters employing half-wavelength, self-resonant, dipole receiving antennas. The limit of uncertainty of these standards is believed to be ±1.0 dB over this frequency range. It is hoped that further development effort in the near future will reduce the uncertainty to ±0.5 dB.

In addition to the above, a prototype Near-Zone Electric-Field-Strength Meter and Interim Field-Strength Standards were recently developed by NBS for the Defense Atomic Support Agency. These are intended for use over the frequency range 150 kHz to 30 MHz for the evaluation of hazards of high-level electromagnetic radiation to ordnance devices and other uses. The limit of uncertainty of these interim standards is believed not to exceed ±2.0 dB over this frequency range. It is hoped that further development effort will reduce the uncertainty to ±1.0 dB and will also extend the usable frequency range.

REFERENCES

[16] F. M. Greene [7], p. 3.
Field Strength Above 1 GHz: Measurement Procedures for Standard Antennas

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Abstract—To calibrate antennas for state-of-the-art field-strength measurements above 1 GHz, standard antennas are needed that have gain values known to within ±0.1 dB. Since this requirement exceeds the verified accuracy of calculated gain values, these standards must be established by making absolute gain measurements. The discussion primarily concerns absolute gain measurements for horn antennas by the two-antenna method. However, much of the discussion is pertinent to high-accuracy field-strength measurements in general. The two-antenna method is considered to be essentially an insertion-loss measurement (with many additional problems and sources of error), and this concept is used to derive a working formula that is suitable for high-accuracy gain measurements. The two most intractable problems—insufficient antenna separation and multipath interference—are discussed in detail. Some important experimental details are included that have previously been overlooked or inadequately discussed, and it is concluded that previous error estimates of less than ±0.1 dB for horn-gain measurements have been somewhat optimistic. To facilitate the design and evaluation of high-accuracy gain measurements, some simple terms, concepts, and formulas are provided that are useful in analyzing multipath interference.

Manuscript received March 8, 1967.
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I. INTRODUCTION

A. Field-Strength Measurements Above 1 GHz: A Review of Some Basic Definitions and Formulas

With reference to field-strength measurements, the terms “above 1 GHz” and “below 1 GHz” usually denote a division between the use of antennas larger than a wavelength and antennas smaller than a wavelength.1,2 Though this division is rather arbitrary as regards frequency,3 it is logical as regards antenna “size” since this factor is of primary importance in determining field strength.4

1 Field-strength measurements and standards below 1 GHz are discussed in a paper by F. M. Greene in this issue.
2 For a general survey of radiation measurements and techniques, see Cumming [5].
3 For absolute field-strength measurements, at least, this choice of frequency is not as arbitrary as it may seem. Even though the use of electrically small antennas at frequencies above 1 GHz is fairly common, this practice is mainly limited to measurements of relative field strength—as when investigating the structure of the field near a large antenna.
Fig. 3. The NBS field-strength calibration site showing: (left) RF generating and measuring instrumentation; (center) the standard transmitting loop antenna; and (right) a field-strength meter under calibration.
Fig. 7. View of the central portion of an experimental standard receiving dipole minus the antenna rods, showing the crystal diode and resistance-capacitance filter network.
Fig. 14. View of the complete near-zone electric-field-strength meter.