NBS CIRCULAR 517

Calibration of Commercial Radio Field-Strength Meters at the National Bureau of Standards

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Related Publications of the National Bureau of Standards

Basic Radio Propagation Predictions

The Predictions, issued monthly, provide the information necessary for calculating the best frequencies for communication between any two points in the world at any time during the given month. The data are important to all users of long-range radio communications and navigation, including broadcasting, airline, steamship, and wireless services, as well as to investigators of radio propagation and the ionosphere. Each issue, covering a period of 1 month, is released 3 months in advance and contains 16 large pages, including pertinent charts, drawings, and tables. Annual subscription: domestic, $1.00; foreign, $1.25.

NBS Circular 465 Instructions for the Use of Basic Radio Propagation Predictions

This Circular explains how the *Basic Radio Propagation Predictions* may be used in calculations of maximum usable and optimum working frequencies for radio sky-wave transmission. It includes prediction charts for two recent months and sample problems for four paths, with a discussion of differences in results due to length of path, the ionosphere layer controlling reflection, season of the year, and degree of solar activity. An attempt is made to emphasize that the most important case, transmission by the F2-layer over a transmission path more than 4,000 km. in length, can be calculated in a relatively simple manner. The Circular also contains other useful data, including tables, charts, and specimen work sheets. 30¢.

NBS Circular 462 Ionospheric Radio Propagation

In presenting the elementary principles of sky-wave or ionospheric radio wave propagation at high frequencies, this 209-page volume summarizes current knowledge and techniques of making radio-propagation calculations. For persons who have not had advanced courses in electrodynamics, the book sets forth in simple form the physical and mathematical theory underlying the principles of radio communication by reflection from the ionosphere and brings these principles into understandable relation with the practical problems of radio communications. A number of problems are worked out in detail to assist the reader in applying the methods to specific cases. Over 200 figures accompany the text and help clarify the geophysical principles involved. $1.00.

[Continued on cover page 3]

Order all publications from the Superintendent of Documents U. S. Government Printing Office, Washington 25, D. C.

UNITED STATES DEPARTMENT OF COMMERCE • Charles Sawyer, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Acting Director*

Calibration of Commercial Radio Field-Strength Meters at the National Bureau of Standards

Frank M. Greene

National Bureau of Standards Circular 517

Issued December 1951

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.
Price 10 cents

Contents

Calibration of Commercial Radio Field-Strength Meters at the National Bureau of Standards

By Frank M. Greene

A brief description is given of the standards and methods used in the calibration of commercial radio field-strength meters at the National Bureau of Standards in the frequency range 10 kc to 300 Mc. A calibration consists in part of measuring the over-all linearity of the field-strength meter at one or more frequencies and radio-frequency input voltage levels, and in measuring the internal attenuator ratios at one or more frequencies in terms of precision dissipative-type step attenuators, as well as precision mutual-inductance attenuators, depending upon the frequency being used. The remainder of the calibration consists in determining the so-called antenna coefficient or correlation factor of the set relating field strength to the output meter reading. Below about 30 Mc this is done only for sets using loop antennas in terms of a quasi-static magnetic field produced by a single-turn balanced transmitting loop. Above this frequency for sets using only dipole antennas a locally generated radiation field is used and is evaluated in terms of the electromotive force induced in a horizontal receiving dipole. The accuracies of the various parts of the calibration are discussed for different portions of the above frequency range.

1. General

The National Bureau of Standards offers a calibration service [1] for certain types of radio field-strength meters in the frequency range 10 kc to 300 Mc. The calibration consists in measuring the over-all linearity of the instrument at one or more frequencies and radio-frequency (r-f) levels, measuring the internal attenuator ratios at one or more frequencies, and measuring the so-called antenna coefficient or correlation factor relating field strength to the output meter reading under specified conditions of set gain at specified frequencies. All measurements are made in terms of sinusoidal voltages or currents.

In developing the equations used in this paper for determining field strength, the practical rationalized mks units have been used. This is in agreement with recent international action.

[1] For further information and calibration fees, write to Director, National Bureau of Standards, Washington 25, D. C.

2. Measurement of Linearity and Attenuator Ratios

Those quantities involving only r-f voltage ratios are measured in terms of precision dissipative step attenuators or precision mutual-inductance (waveguide-below-cutoff) attenuators, depending on frequency. Use is made of two types of dissipative attenuators comprising "Pi" or "T" sections, one employing wire-wound resistance elements for frequencies below 1 or 2 Mc, the other using coaxial sections of evaporated or deposited metal film for frequencies up to 300 Mc. These step attenuators are standardized on direct current and their ratios determined to within 0.1 percent. Frequency corrections are determined by comparing one standard attenuator used at signal frequency against another used at the intermediate frequency in a receiver. Cross checks are made against the standard mutual-inductance attenuator at frequencies above about five megacycles. This type of attenuator [2] serves as a primary reference standard, since the attenuation is a function only of its linear dimensions which can be precisely determined. The $TE_{1,1}$ mode of excitation is used, the higher order unwanted modes being reduced by means of a strip filter. Errors resulting from the finite conductivity of the cylinder wall, and from the proximity of the operating frequency to the cut-off frequency are less than 0.1 db in a 60-db range in the HF band (3 to 30 Mc) and the VHF band (30 to 300 Mc) and can usually be neglected.

Since the over-all linearity of a field-strength meter will in general be a function of both frequency and r-f input level, it is necessary to determine this dependence. Fortunately, this effect

[2] R. E. Grantham and J. J. Freeman, A standard of attenuation for microwave measurements, Trans. AIEE **67**, 535 (1948).

966860—51

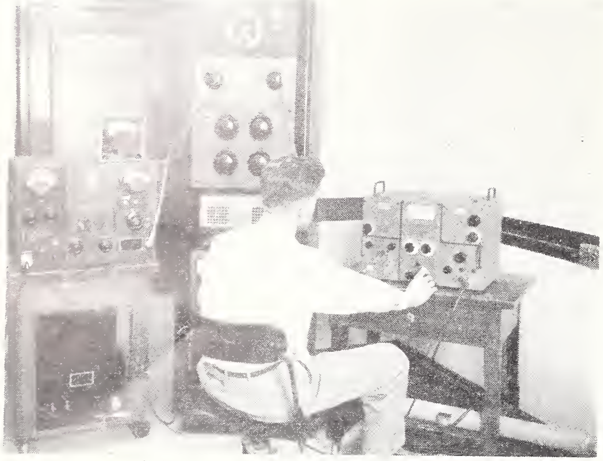

FIGURE 1. *Calibration of the internal attenuators and linearity of a commercial field-strength meter.*

is usually limited to the highest attenuator steps in those types of sets having intermediate-frequency attenuators only. The departure from linearity has been found in general to be less than 2 percent if the signal voltage applied to the mixer grid does not exceed about 5 percent of the injected local oscillator voltage. For practical and economical reasons it is necessary to limit linearity checks on the attenuator steps in question to one or two frequencies as specified by the user.

For those sets also employing r-f attenuators in the antenna input circuit it is necessary to ensure that these ratios are measured under actual operating conditions. Those r-f attenuator steps which may be affected by the changing source impedance of the antenna, or the changing input admittance of the first r-f stage with frequency, are measured with the antenna placed in a field which can be attenuated in known ratios.

The voltage linearity and attenuator ratio measurements made on field-strength meters are usually certified to ±2 percent. The equipment used is shown in figure 1.

3. Measurement of Antenna Coefficients From 10 kc to 30 Mc

At the present time the National Bureau of Standards certifies only field-strength meters using loop antennas below about 30 Mc. The calibration is made in terms of a standard free-space quasi-static magnetic field produced by a single-turn, unshielded, balanced, transmitting loop of known radius and with a known current flowing. The current is measured by means of a vacuum thermocouple[3] at the loop center, which was previously standardized on direct current, the d-c output of the thermocouple being measured by means of a precision slide-wire potentiometer. The frequency error of the type of thermocouple used for this purpose has been found to be less than 1 percent at frequencies even as high as 100 Mc when used in a balanced circuit with the thermocouple at essentially ground potential.

The magnitude of the field strength produced by a single-turn circular transmitting loop is given by eq (1) for the case of coaxial transmitting and receiving loops as shown in figure 2. The actual value of the quasi-static magnetic field, H, produced by the loop is expressed in terms of the equivalent electric component, E, that would exist in a free-space radiation field. The relationship used is $E=ZH$, where Z is the impedance of free space ($Z=376.7$ ohms).

$$|E|\cong\frac{60\pi r_1^2 I}{(d^2+r_1^2+r_2^2)^{3/2}}\sqrt{1+\left(\frac{2\pi d}{\lambda}\right)^2}, \qquad (1)$$

where

E = equivalent free-space electric field strength in rms volts per meter

r_1 = radius of transmitting loop, meters. To keep a uniform current in the transmitting loop make $2\pi r_1<\lambda/8$

r_2 = radius of receiving loop, meters. If receiving loop is rectangular use equivalent radius of circle having same area

d = axial spacing (meters) between coaxial loops (make $d>7r_1$ and $d>7r_2$)

I = transmitting loop current, rms amperes

λ = free-space wavelength in meters.

The value of field given by eq (1) is essentially independent of frequency up to about 5 Mc, above which the frequency correction term under the radical (the induction-field component) begins to become appreciable for the spacing used in the NBS standard ($d\cong 1.25$ m). The value of field strength used for calibration is of the order of 0.1 v/m, ($r_1=0.1$ m, $I=0.1$ amp).

The magnitude of the field, $|E|$, predicted by eq (1) was verified at several frequencies up to 30 Mc by measuring the electromotive force, e, induced in a single-turn untuned balanced receiving loop immersed in the field. The relationship used was

$$|E|=\frac{e}{l_L}, \qquad (2)$$

where l_L is the effective length of the single-turn loop in meters.

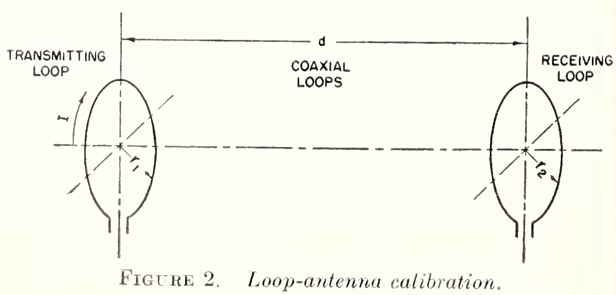

FIGURE 2. *Loop-antenna calibration.*

[3] This refers to a four-terminal unit having an r-f heater electrically insulated from the thermocouple.

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

where A is the loop area in square meters, and λ is the operating wavelength in meters. Agreements were obtained between these two methods of determining the field to within 3 percent.

It is known that the case of the field-strength meter will distort the field being measured. There is reason to believe that this distortion will not be the same when the instrument is placed in the above quasi-static field ($E \propto 1/d^3$) as when placed near the ground in a radiation field, ($E \propto 1/d^x$), where usually $1 \leq x \leq 2$ for plane earth depending upon frequency, distance, and the ground constants.[4] It is believed that this difference is probably not great. Previous comparisons of instruments calibrated in both types of fields have agreed to within considerably better than 5 percent at broadcast frequencies. However, orientation of the receiving loop antenna relative to the instrument case must be specified since if later used in other positions an error of as much as 5 to 10 percent may be introduced into subsequent measurements depending upon the height of the loop above the case.[5] This error is usually negligible if this height is greater than the loop diameter. It does not appear feasible to attempt to establish standard radiation fields using the standard-field method at frequencies much below 30 Mc because of the difficulties in accurately taking into account the ground effects.

In calibrating a field-strength meter by means of eq (1), the setup is made in a cleared space as shown in figure 3 such that a distance of at least two or three times the loop spacing, d, exists to the nearest sizable metallic objects and to the ground. Their effect in distorting the field can be estimated by moving up metal objects of similar size and noting the effect on the value of the received field. For the above distance and spacing the effect of small objects on the value of field was usually found to be less than 1 percent.

It may be found necessary to shield thoroughly the r-f generator and transmission line to the loop to reduce leakage fields, also to correct the current calibration of the thermocouple for harmonics in the r-f supply. It is preferable that the r-f generator output be balanced to ground at least for frequencies above 1 or 2 Mc.

The "antenna coefficient," K, is evaluated by the relation

$$K = \frac{E_1}{A_1} \times \frac{f}{M_1}, \tag{4}$$

where

E_1 = standard field given by eq (1) usually expressed in microvolts per meter

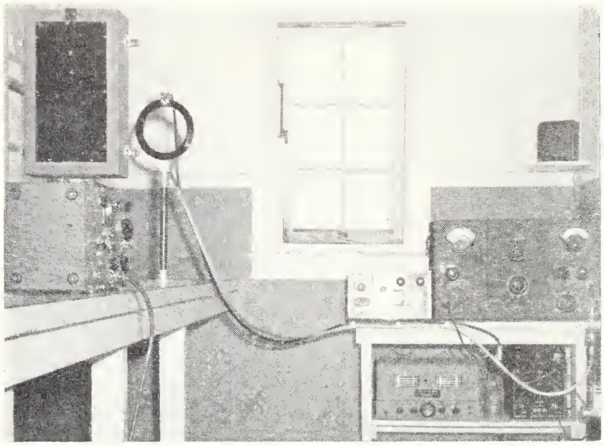

Figure 3. *Determining the loop-antenna coefficient of a commercial field-strength meter.*

A_1 = true attenuator ratio used

M_1 = output meter reading corrected from linearity data

f = frequency, usually in kc or Mc. This frequency factor is introduced arbitrarily as a convenience to make K (theoretically) independent of frequency, since $M_1 \underset{\sim}{\propto} f$.

In using the field-strength meter later for actual measurements, the unknown field in microvolts per meter is given by

$$E = \frac{KM_2A_2}{f}, \tag{5}$$

where K is given by eq (4), and

M_2 = output meter reading corrected from linearity data

A_2 = true attenuator ratio used

f = frequency in same units as used in eq (4).

While the instrument actually measures the magnetic component, H, of the unknown field, the indication is given in terms of the electric component, E, that would exist if the measurement were being made in free space, from the relationship, $E = ZH$, previously given. When the meter is used to measure field strength near the ground, however, this relationship is in general no longer valid. Consequently, the indicated value for the electric component may be subject to question in some cases unless the effect of the ground at the measurement site is considered; the magnetic field is however always correctly given by converting the electric field strength reading by the above simple free-space relation.

The accuracy of antenna coefficients is usually certified to ±3 percent below 5 Mc and ±5 percent between 5 and 30 Mc for sets using loop antennas.

[4] K. A. Norton, The calculation of ground-wave field intensity over a finitely-conducting spherical earth, Proc. IRE **29**, 623 to 639 (Dec. 1941).

[5] H. Diamond, K. A. Norton, E. G. Lapham, On the accuracy of radio field-intensity measurement at broadcast frequencies, J. Research NBS **21**, 795 (1938) RP1156.

4. Measurement of Antenna Coefficients From 30 to 300 Mc

At the frequencies in the VHF band, the National Bureau of Standards certifies only field-strength meters using dipole antennas. The determination of antenna coefficients is made in terms of a radiation field by either the standard-field method or the standard-antenna method using half-wave dipoles and horizontally polarized transmission in either case. These two methods were intercompared and excellent agreement was obtained over most of the range of antenna heights and distances of separation used between transmitting and receiving antennas.[6]

In using the VHF standard-field method it was necessary to select a flat graded site free of any reflecting objects such as trees, buildings or wires within a radius of at least several hundred feet around the transmitting and receiving antennas. With these conditions approaching the ideal, the absolute magnitude of the field at the receiving antenna was accurately computed at these frequencies by considering only the direct and ground-reflected waves from the transmitting antenna, as indicated in figure 4. Both horizontal half-wave dipoles are assumed oriented normal to a line joining their centers, and spaced a horizontal distance, d, greater than 2λ. The resulting rms field strength [7] in volts per meter at the receiving antenna is

$$|E| \cong \frac{60\pi l_H I}{\lambda}\left[\left(\frac{1}{R_1}+\frac{\rho}{R_2}\right)^2 - \frac{4\rho}{R_1 R_2}\sin^2\left(\frac{k(R_2-R_1)+\phi}{2}\right)\right]^{\frac{1}{2}}, \tag{6}$$

where

l_H = effective length of antenna in meters $\cong \lambda/\pi$ meters for a half-wave dipole

λ = wavelength in meters

$R_1 = [(h_1-h_2)^2+d^2]^{\frac{1}{2}}$ = direct-ray path-length in meters

$R_2 = [(h_1+h_2)^2+d^2]^{\frac{1}{2}}$ = ground-reflected-ray path-length in meters

d = horizontal distance of separation, meters

h_1 and h_2 = the heights in meters above ground of the transmitting and receiving antennas, respectively

ρ = magnitude of the plane-wave reflection coefficient of the ground (horizontal polarization), and ϕ is the angle of phase lag on reflection

I = rms current in amperes at the center of the transmitting antenna

$k = 2\pi/\lambda$.

The phase shift on reflection, ϕ, is very nearly 180 degrees for many types of ground over a large

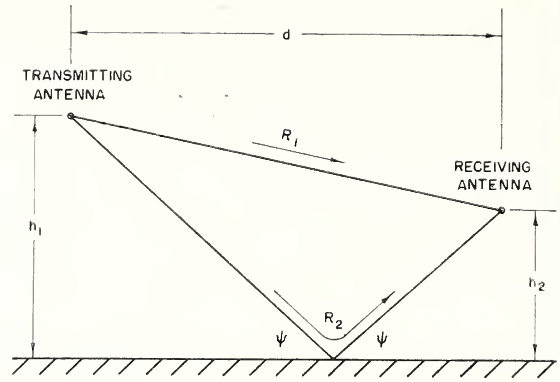

Figure 4. *Dipole-antenna calibration.*

portion of the VHF band. In this case, eq (6) may be written

$$|E| \cong \frac{60\pi l_H I}{\lambda}\left[\left(\frac{1}{R_1}-\frac{\rho}{R_2}\right)^2 + \frac{4\rho}{R_1 R_2}\sin^2\left(\frac{k(R_2-R_1)}{2}\right)\right]^{\frac{1}{2}}. \tag{7}$$

Unless $(h_1+h_2)/d<0.05$, it may be necessary to determine accurately the actual dielectric constant or reflection coefficient of the ground. For instance, if $(h_1+h_2)/d=0.2$, the magnitude of the reflection coefficient may have any value in the range 0.85 to 0.93, depending upon the moisture content of the top layers of the soil at the measurement site. If $(h_1+h_2)/d=0.1$, this range may be roughly 0.93 to 0.96. For $(h_1+h_2)/d<0.05$, the reflection coefficient will usually be greater than 0.96. For this condition, and if further $2\pi h_1 h_2/\lambda d<1/4$, eq (7) will reduce to

$$|E| \cong \frac{240\pi^2 l_H I}{d^2}\left(\frac{h_1 h_2}{\lambda^2}\right), \tag{8}$$

giving the field to within ± 2 percent of the value obtained from eq (7) for these conditions.

In using the standard-antenna method the field strength of a locally generated field is determined by measuring directly the induced emf in a standard receiving dipole oriented for maximum response from the relation

$$|E| = e/l_H, \tag{9}$$

where

e = induced emf in the receiving dipole in volts

l_H = effective length of the dipole, meters, $l_H \cong \lambda/\pi$ meters for a half-wave dipole.

The emf is measured directly by means of a relatively high impedance silicon crystal voltmeter built into the gap at the center of the antenna. This eliminates the necessity for a separate meas-

[6] F. M. Greene and M. Solow, Development of very high-frequency field-intensity standards, J. Research NBS 44, 527 (1950) RP2100.

[7] Based on equation derived from reference 4 in mks units.

urement of the antenna impedance, which greatly simplifies the problem, improving the over-all accuracy of the measurement.

Owing to the lack of selectivity in this method as used, it does not lend itself to calibration work in the vicinity of strong interfering fields that may often be encountered. The site used for VHF calibration work at the National Bureau of Standards is in a partially shielded valley some 15 miles from the nearest interfering station.

While it is possible to use either the standard-field or the standard-antenna method for determining the antenna coefficients, the latter method is used at the National Bureau of Standards at the present time. Field tests have shown the excellent agreement possible between the two methods throughout the VHF band. The choice was largely one of convenience, as it was found somewhat more convenient to provide an accurate calibration of the silicon crystal voltmeter than to ensure an accurate measurement of the transmitting antenna current throughout the VHF band.

The "antenna coefficient" of the field-strength meter under test is determined by placing its dipole antenna at a specified height, usually 10 feet, in the radiation field previously measured using the standard receiving dipole and the relationship given by eq (9). Equations (4) and (5) are used as at lower frequencies, except that the frequency term, f, is usually omitted. Use of the meter later at other antenna heights or over ground having appreciably different constants may require corrections for heights less than about one wavelength.[8]

The accuracy of the antenna coefficients certified by the National Bureau of Standards depends largely upon the merits of the individual meter under test. In general, these coefficients are certified at present to ±10 percent for frequencies between 30 and 150 Mc and to ±15 percent for frequencies between 150 and 300 Mc.

WASHINGTON, May 9, 1951.

[8] F. M. Greene, Influence of the ground on the calibration and use of VHF field-intensity meters, J. Research NBS **44**, 123–130 (1950) RP2062.

Journal of Research

Internationally known as a leading scientific periodical, the Journal presents research papers by authorities in the specialized fields of physics, mathematics, chemistry, and engineering. It gives complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Each of the monthly issues averages 100 two-column illustrated pages. Annual subscription: domestic, $5.50; foreign, $6.75.

NBS Circular 481 High Frequency Voltage Measurement By Myron C. Selby

Dealing primarily with voltage measurement at frequencies from 20,000 cycles to 700 megacycles, this 14-page booklet is limited in scope to principles and methods that have met with some degree of success for both high and moderate precision. Emphasizing, with suitable illustrations, the methods developed at the NBS for primary standard work in this frequency range, the Circular discusses high-precision methods based on d-c measurements; moderate precision methods, including thermionic and other rectifiers; pulse-peak voltage measurement; and miscellaneous methods. 20¢.

NBS Circular 483 Testing by the National Bureau of Standards

Having been authorized by Congress to engage in testing and calibrating services for the Nation, the NBS undertakes tests involving comparison of laboratory standards with the national standards; tests of other critical devices and materials for which suitable testing and calibration facilities are not available elsewhere; and referee tests or investigations where private laboratories are unable to agree, provided that the problem is of national interest, that there is prior agreement to accept and abide by NBS findings, and that the cost is borne by the groups at issue. In addition to presenting a statement of NBS policy and some general information, the 93-page Circular gives fee schedules for tests in electricity, metrology, heat and power, atomic and molecular physics, chemistry, mechanics, radio propagation, and optics. 25¢.

Order all publications from the Superintendent of Documents U. S. Government Printing Office, Washington 25, D. C.

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA