Calibration of Microwave Antenna Gain Standards

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Invited Paper

Techniques for precision calibration of microwave antenna gain standards are described with discussions of applicability and associated uncertainties. Included are the three-antenna, extrapolation, swept-frequency, and near-field techniques.

I. INTRODUCTION

Accurate antenna gain standards are needed to evaluate and verify the performance of communications, radar, navigation, remote sensing, and other systems which transmit or receive radiated electromagnetic energy. Gain and polarization are commonly measured by a substitution technique where the response of an antenna to a "plane-wave" field is compared with the response of one or more standard antennas. A different approach, involving a minimum number of assumptions about the antenna and test facility, must be used to determine the characteristics of the standard.

Pyramidal horn antennas are used extensively as standards [1], [2] because the gain can be calculated to an accuracy of about ±0.3 dB which is adequate for many purposes. Gain calculations have also been performed for both smooth and corrugated-walled conical horns [3], [4] to about the same accuracy. The uncertainties in these calculated values are due to computational approximations and imperfect fabrication—problems which are not easily overcome. Consequently, when accurate gain values are required, the antenna must be evaluated by proven measurement techniques. The National Bureau of Standards has opted to develop and employ "standard measurement methods" as opposed to "standard antennas." By means of these methods an arbitrary antenna can be accurately calibrated for use as a transfer standard of gain and polarization. In the following sections, advantages and disadvantages of these techniques are pointed out and some comparisons with other approaches are given.

II. THREE-ANTENNA TECHNIQUE

The three-antenna technique is used to determine the gain and polarization characteristics of an antenna without reference to any antenna standard [5]–[8]. The desired characteristics are obtained by power ratio measurements and a relative phase measurement which may be reduced to the determination of the sign of a phase change when one antenna is rotated [7]. The three-antenna technique does not require *a priori* knowledge of any of the antennas except that one of the antennas must be reciprocal and only one of the antennas may have circular polarization. If all three are nearly linearly polarized, the complete on-axis radiating characteristics of all three antennas may be determined. If one of the antennas is circularly polarized, only that antenna may be completely characterized.

For each antenna pair, two measurements are performed, one with the nominal polarization vectors parallel, and a second with the polarization vectors perpendicular. Measurements of the three possible pairs produce six equations of the form

$$X_m X_n - Y_m Y_n = D'_{nm} \qquad X_m Y_n + X_n Y_m = D''_{nm} \qquad (1)$$

where X and Y represent the x and y components of the transmitting characteristics of the antenna and the subscript indicates the particular antenna. These equations are then solved for the unknown quantities X_i and Y_i. The measured quantities D'_{nm} and D''_{nm} are the asymptotic values of the insertion loss between the antennas and may be found by direct far-field measurements, extrapolation measurements, or transformation of near-field measurements.

III. EXTRAPOLATION MEASUREMENTS

Conventional far-field methods have a number of associated problems including near-zone effects, ground reflections, multipath, and availability of a suitable range. The extrapolation technique [5], [6] provides a rigorous correction of errors due to these problems. In this method, the

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insertion loss between a pair of antennas may be represented by the following convergent series in inverse separation distance:

$$\frac{b_0'(d)}{a_0}^{2} = \frac{1}{|1 - \Gamma_a \Gamma_\ell|^2 d^2}\left(A_{00} + \frac{A_{01}}{d} + \frac{A_{02}}{d^2} + \cdots + \text{multiple reflection terms} \right) \quad (2)$$

where $|b_0'(d)/a_0|^2$ is the insertion loss, Γ_a and Γ_ℓ are the reflection coefficients of the receiving antenna and its load, respectively, and d is the separation between the antennas.

To determine the coefficients of the series, the insertion loss between the antennas is measured as a function of separation distance. Typically, the distance ranges from 1/4 or 1/2 times D_R to 1 or 2 times D_R where $D_R =$ (aperture)^2/wavelength. After removing the effects of the multiple reflections by averaging or filtering, the data are fit to the power series of (2) using standard least squares procedures. It is important to retain only significant terms in the series—too few terms inadequately represent the interaction between the antennas and too many terms will bias the result by fitting random effects. The correct number of terms is usually determined by the Fisher–Snedecor test of statistical significance. The leading term in the series, A_{00}, is then used to calculate D_{nm}. Fig. 1 illustrates a typical set of extrapolation data obtained for a pair of *X*-band standard gain horns.

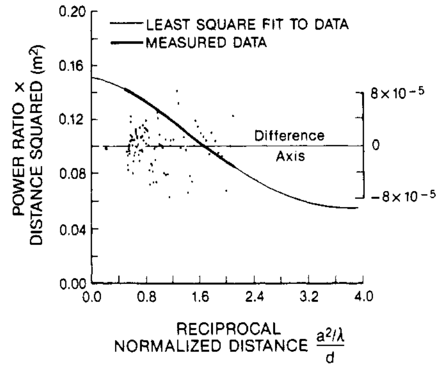

Fig. 1. Example of extrapolation data for an *X*-band standard gain horn (gain 22 dB). Heavy line is measured insertion loss, the lighter line is a five-term polynomial fit to the measured data, and the dots illustrate the magnified difference between the measured data and the polynomial.

The extrapolation technique is capable of yielding accuracies of the order of ±0.1 dB for routine calibrations and ±0.05 dB or better in special situations. Axial ratio uncertainties obtained are approximately ±0.05 dB/dB of axial ratio.

The extrapolation technique is useful for antennas and ranges where multipath signals from ground reflections or other scattering objects are small. If such reflections become significant, either because the antennas in use are broad-beam or because the range has a small height-to-length ratio, the extrapolated value may be significantly biased. An extension to the extrapolation method has recently been reported which removes these biases and yields accuracies comparable to those obtained using the standard technique [9]. The technique requires the measurement of phase as well as amplitude in order to eliminate the contribution of the reflected wave.

IV. SWEPT-FREQUENCY MEASUREMENT TECHNIQUES

Careful measurements of gain versus frequency of standard gain horns exhibit small periodic amplitude oscillations of the order of 0.1 to 0.2 dB superimposed on a smooth monotonic gain function. These oscillations are attributed to multiple reflections between the mouth and throat of the horn [2]. For highest accuracy, the gain must be determined at closely spaced frequencies and swept-frequency techniques may be employed to advantage. The parameters are measured as a function of frequency and the values are adjusted at specific frequencies to agree with the more accurate but time-consuming extrapolation measurements. The accuracy obtainable over the band will typically be of the order of ±0.15 dB.

Fig. 2 illustrates a comparison between a theoretically obtained gain curve for an *X*-band pyramidal horn as predicted by theory [1] and data obtained using the three-antenna method applied to swept-frequency data.

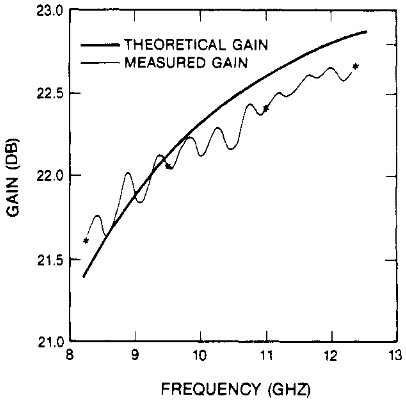

Fig. 2. Comparison between theoretical gain and gain measured by the swept-frequency technique for an *X*-band pyramidal horn. Gain values indicated by the * were obtained by extrapolation and used to "calibrate" the swept results.

V. NEAR-FIELD SCANNING TECHNIQUES

When a transfer standard is required with a gain greater than about 25 dB, both the type of antenna and the calibration technique are different than discussed above. The pyramidal horn is not used because it would be too large and difficult to handle. Instead, paraboloidal reflector antennas with either focal point or Cassegrain feeds are used.

It is generally not possible to calculate the gains of such reflectors to the accuracy required for reference standards, and they must therefore be calibrated at each frequency of interest. The extrapolation technique is not used because the range length and height and data requirements become prohibitive. The most reliable approach for such calibrations is near-field scanning [10], [11], in which a calibrated probe antenna is moved over a well-defined surface within a few wavelengths of the antenna under test (AUT). The amplitude and phase of the probe output signal are recorded as a function of the probe position on the measurement surface. These data are then computer processed to obtain the far-field gain, pattern, and polarization of the AUT. Currently, three measurement surfaces are used—planar [12], cylindrical [13], [14], and spherical [15], [16]. These differ in the details of the mechanical system used to accomplish the probe scanning relative to the AUT. and in the mathematics employed to calculate the far-field parameters. The electronic systems and the measurement procedures are very similar for the three surfaces.

The planar technique is generally used for the calibration of large gain standards since it is best applied to narrow-beam antennas. The first step in the measurement process is to calibrate a probe since the probe serves as the gain standard. The probe gain is normally determined using the three-antenna method and extrapolation technique. For best accuracy, the probe is chosen to have the same polarization and a gain approximately 25–30 dB below that of the AUT. Open-ended waveguides and small pyramidal or conical horns satisfy these requirements and are the most commonly used probes. The probe's relative receiving pattern must also be known, and this is usually obtained in an anechoic chamber.

In the second step, near-field data are obtained as the probe is translated over a rectangular lattice. At points of the measurement lattice spaced δ_x and δ_y apart the relative probe output, $B'_0(x, y) = b'_0(x, y)/b'_0(x_0, y_0)$, is measured and recorded. $B'_0(x, y)$ is a complex quantity with amplitude and phase measured relative to a reference point (x_0, y_0) generally near the maximum amplitude point. Data are obtained over an area slightly larger than the physical aperture of the AUT. The third and final step consists of placing the probe at the reference point and measuring the ratio between the AUT input a_0 and probe output $b'_0(x_0, y_0)$.

For the case when the main beam of the AUT is normal to the measurement plane and the probe is polarization matched to the AUT in that direction, the gain equation reduces to the simple form

$$G_A(0) = \left(\frac{4\pi\delta_x\delta_y}{\lambda^2}\right)^2 M \left|\frac{b'_0(x_0, y_0)}{a_0}\right|^2 \frac{|\Sigma B'_0(x, y)|^2}{G_p}. \quad (3)$$

In (3), $G_A(0)$ is the gain of the AUT in the direction normal to the measurement plane, λ is the operating wavelength, M is an impedance mismatch factor, and G_P is the gain of the probe. The main sources of error are uncertainties in the gain of the probe and power ratio measurement $|b'_0(x_0, y_0)/a_0|^2$, and amplitude nonlinearities in the measurement of $B'_0(x, y)$. These three errors are generally independent and uncorrelated and the total uncertainty in $G_A(0)$ is usually of the order of ±0.15 to ±0.25 dB.

Gain measurements using cylindrical and spherical surfaces are similar and involve the same steps. However, the gain calculations for cylindrical and spherical scanning have not been reduced to a single simple equation, and involve more complex calculations.

In addition to gain, detailed and complete far-field patterns are also obtained from the near-field measurements as shown in Fig. 3. If a second near-field scan is performed with a probe having polarization nominally orthogonal to the first, corresponding cross-polarized patterns are also obtained.

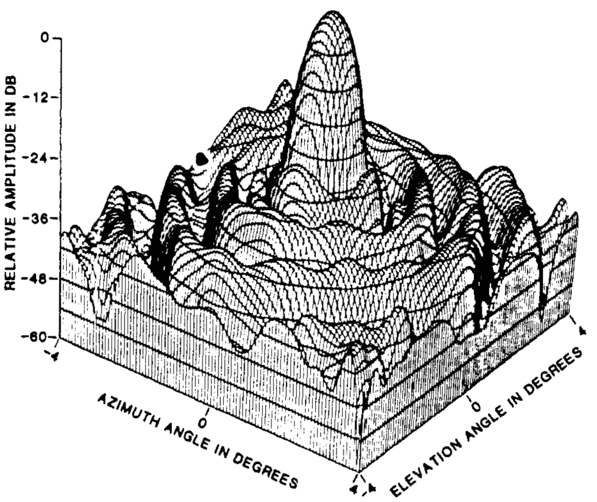

Fig. 3. Far-field pattern for a 2.5-m paraboloidal reflector antenna illustrating detailed pattern information obtained from near-field scanning techniques. Contours are every 6 dB with reference to peak of main beam.

There are other approaches which do not use the probe as the gain standard. A comparison near-field gain measurement is possible when another antenna serves as the gain standard and relative near-field measurements are performed on both the AUT and the standard. The power ratio measurement in this case compares the probe output at the reference point (x_0, y_0) when first the AUT and then the standard are being measured. The spherical technique has also been used to calibrate pyramidal horns by using a horn nominally identical to the AUT as the probe [17]. Neither the pattern nor the gain of either horn is initially known, but from the relative near-field data, a power ratio measurement, and an iteration of the data processing in which the description of the "probe" is successively improved, the gain of the AUT is obtained.

VI. CONCLUSIONS

A variety of precision techniques for calibrating antenna gain standards have been reviewed. Antennas having gains between 6 and 60 dB in the frequency range from 1 to 100 GHz may be calibrated using one or more of these techniques with uncertainties ranging from 0.05 to 0.25 dB.

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Frequency and Time—National Standards

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Invited Paper

The design and performance of the national standards of time and frequency are outlined for countries which maintain primary cesium beam devices. Typical accuracies now attainable are of the order of 10^{-13}, and new developments may improve these significantly within the next few years. Current work is directed toward optical pumping techniques of state selection and to studies of different atoms as the atomic reference.

I. INTRODUCTION

In 1967, the Thirteenth General Conference of Weights and Measures formally defined the second, the unit of time in the International System of Units, as "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the cesium 133 atom." This decision was based on over a decade of increasingly successful and promising results obtained from comparisons between cesium frequency and time standards located in national laboratories of the United States, the United Kingdom, Switzerland, and Canada. These standards fell into two main categories, the large laboratory devices designed to operate intermittently as frequency references with accuracies of the order of a part in 10^{12}, and smaller, commercially produced, less accurate, continuously operating clocks manufactured by two companies in the United States, the National Company of Malden, MA, and the Hewlett-Packard Company of Palo Alto, CA. The four primary standards were located at the National Physical Laboratory in the United Kingdom, the Laboratoire Suisse de Recherches Horlogères in Switzerland, the National Bureau of Standards in the United States, and the National Research Council in Canada.

For some time prior to the formal adoption of the cesium second, these and certain other laboratories had compared their standards by simultaneous measurement of the low- and very-low-frequency transmissions radiated by a number of nationally operated transmitters used primarily in electronic navigation systems. Use of these comparisons, and later, those provided through the Loran-C navigation system, by the Bureau International de l'Heure in Paris, France, then led to the generation of a mean Atomic Time Scale, formally known as TAI (Temps Atomique International). A derived scale, UTC (Universal Time Coordinated), closely approximating the astronomical scale UTI, was, by international agreement, the time scale transmitted by all national standard frequency and time transmitters and used for the comparisons.

Today, 18 years after the adoption of the atomic second, there are a total of 58 laboratories in almost as many countries which operate one or more cesium clocks as their national time standard and contribute to the generation of

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