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5.2 Three Nominally Linearly Polarized Antennas

It is assumed that the axial ratio for all three antennas is at least 20 dB and that each antenna is oriented such that its principal component is approximately along the y-axis. Equation (25) for the linear components upon substituting eq (22) is then approximately

$$Y_1 \cong -i \sqrt{\frac{D'_{12}D'_{13}}{D'_{23}}}, \qquad X_1 \cong \frac{-Y_1}{2}\left(\frac{D''_{12}}{D'_{12}} + \frac{D''_{13}}{D'_{13}} - \frac{D''_{23}}{D'_{23}}\right) = \frac{-Y_1\Delta_1}{2}, \tag{42}$$

where Δ_1 is the quantity within the brackets of eq (42). The gain, polarization ratio, axial ratio, and tilt angle are then

$$G_1 = \frac{4\pi k^2}{1 - |S_{00}|^2} \left\{\left|\frac{D'_{23}D'_{13}}{D'_{23}}\right| \left(1 + \frac{|\Delta_1|^2}{4}\right)\right\} \tag{43}$$

and

$$\rho_\ell = -\frac{\Delta_1}{2} \qquad A_1 \cong -2/\mathrm{Im}(\Delta_1) \qquad \tau_1 \cong \frac{\mathrm{Re}(\Delta_1)}{2}. \tag{44}$$

For nearly linearly polarized antennas, Δ_1 will have little effect on the gain, and the error in G will be primarily due to the errors in the $|D'_{nm}|$s. If we let ε_{mn} be the error in decibels for each of the measured quantities, then the resulting error in the gain will be

$$\varepsilon_g = \varepsilon_{12} + \varepsilon_{13} - \varepsilon_{23}.$$

For the case of three antennas with approximately equal gains, the systematic error in each ε_{mn} will be very nearly the same. If we denote the systematic component by ε_s and the random component by ε_r, then for this case

$$\varepsilon_g = \varepsilon_s + \sqrt{3}\,\varepsilon_r.$$

For the axial ratio and tilt angle, errors in Δ_1 have the major effect. If we denote the amplitude and phase of the ratios in Δ_1 as

$$\frac{D''_{nm}}{D'_{nm}} = a_{nm}\, e^{i\theta_{nm}}, \tag{45}$$

then the errors in A and τ will be given by

$$dA_1 \cong -\frac{A_1^2}{2}\,(a_{12}\cos\theta_{12}d\theta_{12} + a_{13}\cos\theta_{13}d\theta_{13} - a_{23}\cos\theta_{23}d\theta_{23} + \sin\theta_{12}da_{12} + \sin\theta_{13}da_{13} - \sin\theta_{23}da_{23}) \tag{46}$$

and

$$d\tau \cong a_{12}\sin\theta_{12}d\theta_{12} + a_{13}\sin\theta_{13}d\theta_{13} - a_{23}\sin\theta_{23}d\theta_{23} - \cos\theta_{12}da_{12} - \cos\theta_{13}da_{13} + \cos\theta_{23}da_{23}. \tag{47}$$

5.3 Two Nominally Linearly and One Nominally Circularly Polarized Antenna Combination

The linearly polarized antennas are again oriented with their principal components approximately along the y-axis, and we assume that antenna number 3 is nearly left circularly polarized. When either antenna 1 or 2 is used with number 3, the 90 deg rotation about the z-axis will result in a very small amplitude change, and approximately 90 deg phase change. Therefore,

$$\frac{D''_{12}}{D'_{12}} = \delta_{12}, \quad \frac{D''_{13}}{D'_{13}} = -i + \delta_{13}, \quad \frac{D''_{23}}{D'_{23}} = -i + \delta_{23}, \tag{48}$$

where the δ's represent the small deviation from exactly linear and circular polarization. An analysis similar to that in the previous section shows that the left and right components of $S_{10}(0)$ are given approximately by

$$L_3 \cong \pm\frac{4\,D'_{13}D'_{23}}{D'_{12}}, \quad R_3 \cong \pm\frac{L_3}{2}\sqrt{-\delta_{13}\delta_{23}}, \tag{49}$$

and that the gain, circular polarization ratio, axial ratio, and tilt angle are approximately

$$G_3 \cong \frac{4\pi k^2}{1 - |S_{00}|^2}\;\frac{(|D'_{13}| + |D''_{13}|)(|D'_{23}| + |D''_{23}|)}{2\,|D'_{12}|} \tag{50}$$

and

$$\rho_c \cong \frac{\sqrt{-\delta_{13}\delta_{23}}}{2} \qquad A \cong -\left(1 + \left|\sqrt{\delta_{13}\delta_{23}}\right|\right) \qquad \tau = \frac{\pi + \phi_{13} + \phi_{23}}{4},$$

where ϕ_{13} and ϕ_{23} are the phase angles of δ_{13} and δ_{23}.

The gain calculation here is similar to the previous case, where only the large quantities were significant. There is once again some cancellation of the systematic error components for this case, but since five rather than three quantities are involved, the effect of random error is larger. The gain error is given by $\varepsilon_g = \varepsilon_s + \sqrt{5}\,\varepsilon_r$ where ε_s and ε_r are the systematic and random errors in each of the D_{nm}'s.

If two similar linear antennas are used, then $\delta_{13} \cong \delta_{23}$ and for this case the error in the axial ratio is

$$dA \cong (2a_{13} + 2\sin\theta_{13})\,da_{13} + 2a_{13}\cos\theta_{13}d\theta_{13}. \tag{51}$$

Since $\theta_{13} \cong -90^0$ and $a_{13} \cong 1$, errors ($da_{13} \approx 0$) in the measured quantities do not strongly affect the calculated axial ratio.

The accuracy of tilt angle is very dependent on experimental errors, especially for highly circular polarization. The angles θ_{13} and θ_{23} are related to the measured ratios by

$$\phi_{13} = \tan^{-1}\left(\frac{1 + a_{13}\sin\theta_{13}}{a_{13}\cos\theta_{13}}\right) \qquad \phi_{23} = \tan^{-1}\left(\frac{1 + a_{23}\sin\theta_{23}}{a_{23}\cos\theta_{23}}\right), \tag{52}$$

and the error in ϕ_{13} is

$$d\phi_{13} = \frac{-\cos\theta_{13}da_{13} + (a_{13}^2 + a_{13}\sin\theta_{13})d\theta_{13}}{1 + a_{13}^2 + 2a_{13}\sin\theta_{13}}. \tag{53}$$

The tilt angle error is given by

$$d\tau \cong \frac{d\phi_{13} + d\phi_{23}}{4} \tag{54}$$

and can be quite large for nearly circular polarization when θ_{13} and θ_{23} are close to -90 deg and a_{13} and a_{23} are nearly 1.

6. Measurement Examples

The extrapolation technique has been used on a number of antennas at frequencies from 1 to 65 GHz. For some of these, gain measurements have been made using different techniques and the results have always agreed to within ±0.15 dB. In one comparison, the gain of a multimode X-band horn was measured by NBS using both the extrapolation technique and a near-field scanning technique. The Jet Propulsion Labs also determined the gain of the horn [25] from far-field pattern measurements. The results of all three measurements were within ±0.10 dB of each other.

For some measurements on pyramidal horns, the proximity corrections obtained from the extrapolation measurements had been compared with theoretical expressions based on the geometry of the horn and assumed field distributions. There has been fairly good agreement with the results of Chu and Semplak [26] for a limited number of comparison.

The results of measurements on two different antenna sets will now be described. These will illustrate the present accuracy capabilities for antenna gain and polarization measurements.

6.1 X-Band Standard Gain Horns

This antenna set consisted of two commercial standard gain horns with nearly linear polarization and one horn with nominally circular polarization. The measurement frequency was 7.250 GHz, and a^2/λ for the circularly polarized horn was about 1.33 m. Measurements were made over a distance range from 1.2 to 2.8 m for the three antenna combinations and the extrapolation procedure carried out to give the results shown in table 1 which also includes the 3σ error estimates. The error estimates for atmospheric loss uncertainty are obtained from reference [27]. The measured data and error estimates then result in the following calculated quantities for the circularly polarized horn:

Gain = 21.32 dB ± 0.11 dB
Axial ratio = 1.34 dB ± 0.05 dB
Tilt angle = - 59.3° ± 2.5°

Table 1. Data and errors for X-band antennas.

		Linear #1 and C.P.	Linear #2 and C.P.	Linear #1 and #2
D'_{nm}	Amp. (dB)	3.60	3.69	3.29
	Phase (deg)	0.0	0.0	0.0
D''_{nm}	Amp. (dB)	3.28	3.37	-2.30
	Phase (deg)	262.1	262.5	275.0

Source of Error	Error in D_{nm}(dB)
Impedance mismatch	0.01
Attenuator calibration	0.01
System drift and receiver nonlinearity	0.05
Atmospheric loss uncertainty	0.00
Antenna alignment	0.01
Distance nonlinearity	0.04
Quadrature sum systematic errors	0.06
Random errors	0.03

6.2 V-Band Reflector Antennas

These were linearly polarized, 45 cm diameter reflector antennas. Antennas 1 and 2 were equipped with focal point feeds and #3 has a Cassegrain feed. At the test frequency of 57.5 GHz, a^2/λ was 40 m. Extrapolation data was taken over a range from 10 to 60 m on the NBS outdoor range with the results shown in table 2.

From these data the antenna parameters and error estimates were determined to be

Antenna	#1	#2	#3
Gain (dB)	46.61 ± 0.23	46.59 ± 0.23	46.26 ± 0.23
Axial ratio (dB)	35.1 ± 2.4	43.7 ± 3.3	26.7 ± 1.2
Tilt angle (deg)	87.6 ± 0.2	88.6 ± 0.1	-89.0 ± 0.5

Table 2. Data and errors for mm-wave antennas.

		#1 and #2	#2 and #3	#1 and #3
D'_{nm}	Amp. (dB)	-26.06	-26.23	-26.21
	Phase (deg)	0.0	0.0	0.0
D''_{nm}	Amp. (dB)	-37.56	-40.19	-40.49
	Phase (deg)	20.0	280.0	310.0

Source of Error	Error in D_{nm}(dB)
Impedance mismatch	0.01
Attenuator calibration	0.006
System drift and receiver nonlinearity	0.05
Atmospheric loss uncertainty	0.10
Antenna alignment	0.03
Distance nonlinearity	0.04
Quadrature sum systematic errors	0.12
Random errors	0.07

7. Improved Polarization Measurements

Absolute polarization parameters have been obtained in the previous sections using a three-antenna measurement technique [12,13,28]. By a modification of this approach [29], the accuracy of the results are significantly increased, and the measurements are easier to perform. Using this technique, it is possible to accurately calibrate polarization standards which have axial ratios greater than 40 dB. These standards are an important factor in the measurement of antenna systems which require high polarization purity. This work demonstrates the power and utility of using complex rather than real polarization parameters in formulating polarization problems.

As we did before and repeat here for convenience, let us define three coordinate systems, one fixed to each of two antennas and one fixed in space and referenced to the test range. Each antenna system is defined with the boresight direction along the z-axis and the y-axis nominally along the major

axis of the polarization ellipse. The exact location of axes is not critical but it is important that they be clearly defined. The reference, or space, coordinate system has its x-axis horizontal, its y-axis vertical, and its z-axis along the center of the test range. Now place the source antenna on the test range so that its axes are coincident with the reference system. The receiving antenna has its boresight (+z-axis) along the reference -z-direction, and is rotated about the reference z-axis into two orientations where measurements are performed (fig. 15). In the first orientation the +y-axes of the antennas are in the same direction, and in the second the -x of the receiving antenna is in the same direction as the +y of the source antenna. The coupling equations for these two orientations [eq (21)] are respectively

$$X_1X_2-Y_1Y_2 = D'_{12}, \tag{55}$$

$$X_1Y_2+X_2Y_1 = D''_{12} \tag{56}$$

where the D's are proportional to the complex received signals, and X_1 and Y_1 are the x- and y-components of the plane-wave spectrum transmitting characteristic $\underline{S}_{10}(\theta,\phi)$ of the source antenna in the direction $\theta = \phi = 0$. X_2 and Y_2 are similar quantities for the receiving antenna. $\underline{S}_{10}(\theta,\phi)$ is simply related to the far-electric field $\underline{E}$, [eq (9)] and since we will only be concerned here with ratios of the components, the formulation can be thought of as being in terms of either $\underline{E}$ or $\underline{S}$.

In eqs (55) and (56) we have assumed that the receiving antenna is reciprocal and expressed all antenna parameters in terms of transmitting properties. This is not necessary to the technique, but it makes the notation more concise and consistent with previous material [13].

The approach in the three-antenna measurement is to repeat this procedure for all three antenna pairs, measure the D_{nm}'s and solve the resulting six equations for the linear components X_n and Y_n, the right and left circular components R_n and L_n, and obtain gain, complex linear polarization ratio ρ_ℓ, complex circular polarization ratio ρ_c, axial ratio A, and the tilt angle τ. These polarization parameters are related by the equations [eqs (13) through (18)]

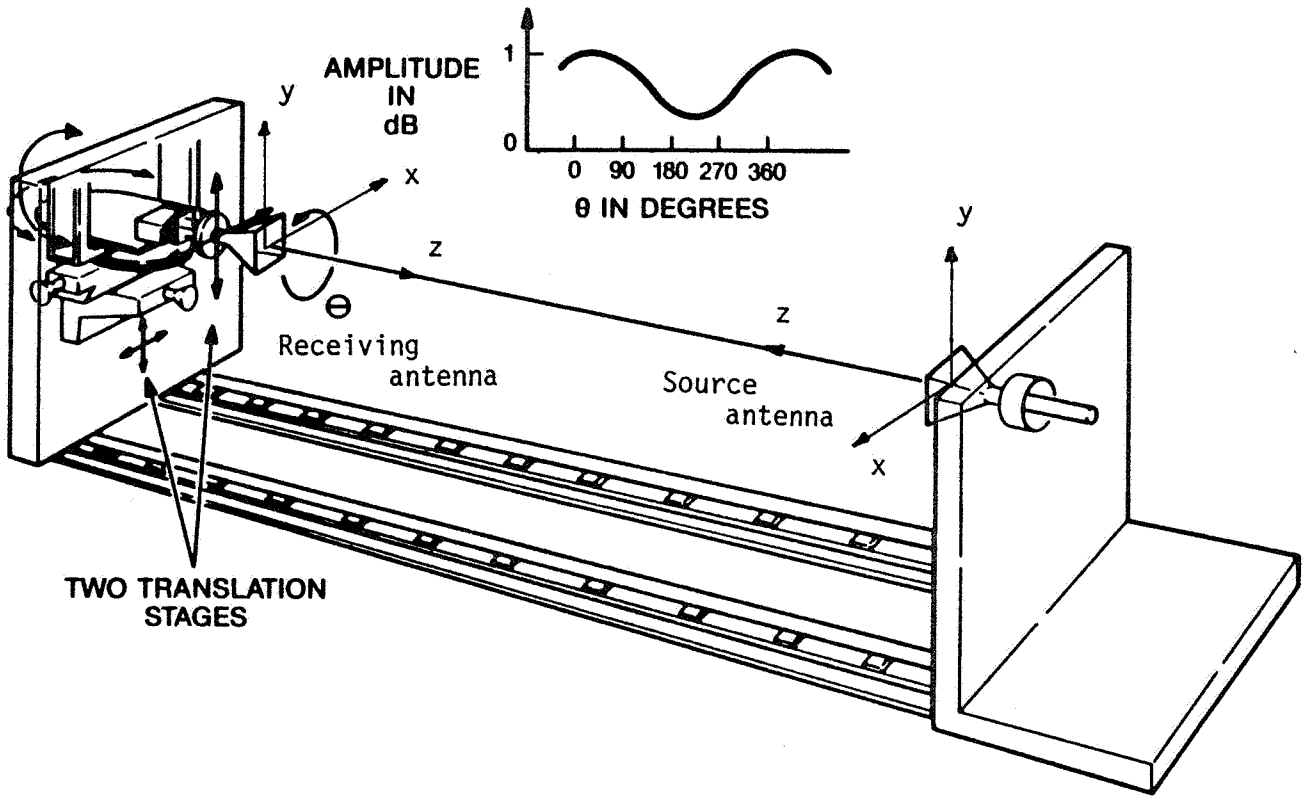

Figure 15. Polarization measurements.

$$R = \frac{X-iY}{\sqrt{2}} \ , \ L = \frac{X+iY}{\sqrt{2}} \ , \ X = \frac{R+L}{\sqrt{2}} \ , \ Y = \frac{i(R-L)}{\sqrt{2}} \ , \tag{57}$$

$$\rho_\ell = \frac{X}{Y} \ , \ \rho_c = \frac{L}{R} \ , \ A = \frac{|R|+|L|}{|R|-|L|} \ , \ \tau = \frac{\arg(\rho_c)}{2} \ . \tag{58}$$

All four of the vector components are, in general, complex quantities, and X and Y do not represent real and imaginary parts. Also the measured linear components are those for the reference coordinate system and all of the quantities in eqs (39) and (40) except A will change if the initial orientation of the antennas is changed.

For polarization measurements, only the ratios of the components and the received signals are necessary and we can combine eqs (56) and (57) and express the result for the general case of antennas m and n in terms of linear and circular polarization ratios.

$$\frac{\rho_{\ell m} + \rho_{\ell n}}{\rho_{\ell m}\rho_{\ell n} - 1} = Q_{nm} = \frac{D''_{nm}}{D'_{nm}}, \tag{59}$$

$$\rho_{cm}\rho_{cn} = \frac{1 + iQ_{nm}}{1 - iQ_{nm}} = \frac{1 - iP_{mn}}{1 + iP_{mn}} \ . \tag{60}$$

In the above equation, P_{nm} is the ratio of D''_{nm}/D'_{nm} if the receiving antenna is rotated in the opposite direction for the second orientation, placing its +x-axis coincident with the source antenna's +y-axis. The major source of error in the polarization parameters obtained from these measurements is the uncertainty in the phase of Q_{nm}. For two nearly linearly polarized antennas, the magnitude of Q_{nm} may be -30 to -60 dB and at these levels, multipath signals, depolarization of scattered signals, and leakage make accurate phase measurements difficult. The phase will also change very rapidly as the 90 deg rotation is approached; this makes it necessary to measure the rotation angle quite accurately. The uncertainty in the phase of the Q's can be reduced essentially to zero by the following modification of the measurement.

We first note from eq (57) and the definition of τ that $\tau = \pm\pi/2$, if and only if ρ_c is negative and real, arg $(\rho_\ell) = \pm\pi/2$, and the major axis of the polarization ellipse is exactly along the y-axis of the reference coordinates.

We can further show that $|Q_{mn}|$ will be a minimum if the major axes are initially coincident, and under this condition, the phase of Q_{nm} must be precisely $\pm\pi/2$. If we can initially align the antennas so that their major axes are parallel, the phase measurement will reduce to one of determining the sign of the phase. The initial alignment can be accomplished quite easily by rotating the source antenna about the reference z-axis for a minimum received signal and then rotating back 90 deg from that orientation.

The sign of the phase change can be determined by observing the direction of phase change as the receiving antenna is rotated towards 90 deg. It can be shown using eq (55) expressed in terms of circular components that for the previously assumed conditions, the phase change of D'_{nm} denoted by ψ, for any rotation angle ϕ, is

$$\psi(\phi) = \tan^{-1} \left[\frac{|\rho_{cn}\rho_{cm}| - 1}{|\rho_{cn}\rho_{cm}| + 1} \tan\phi \right]. \tag{61}$$

Therefore, if the argument of Q_{nm} is $+\pi/2$, the phase change will be positive for all angles between 0 and 90 deg and the converse will be true for a $-\pi/2$ argument.

In summary, the measurement procedure is to initially align the antennas with their chosen y-axes parallel, set the angle encoders to 0 deg for this orientation, and rotate the receiving antenna in the proper direction about the z-axis until a minimum is found, and then rotate 90 deg in the opposite direction. In this orientation the amplitude is set to 1.0, the phase to 0 deg, and the rotation angle $\Delta\phi_{nm}$ is recorded. The receiving antenna is again rotated to the minimum, the direction of phase change during rotation is noted, and the amplitude at the minimum, α_{nm} is recorded. Q_{nm} is then equal to $\pm\, i\alpha_{nm}$ where the correct sign is equal to the direction of phase change. This procedure is repeated for the other two antenna pairs, and eq (60) solved for the polarization ratios.

By aligning the antennas so that their electrical axes are parallel we have essentially redefined the reference coordinate system to be coincident with the electrical axes of the source antenna. With this redefinition, $A = 1/|\rho_\ell|$ for both antennas.

The tilt angle with respect to the antenna axes is determined from the measured rotation angles $\Delta\phi_{nm}$ by the equation,

$$\tau_k = 90° + \frac{\Delta\phi_{km} + \Delta\phi_{kn} - \Delta\phi_{mn}}{2}. \tag{62}$$

This technique is especially useful in the calibration of linear polarization standards with very small cross polarization. In this case, the magnitude of the denominator of eq (59) is very nearly 1 and a quick calculation yields the linear polarization ratios. For instance,

$$\rho_{\ell 1} \simeq - (Q_{12} + Q_{13} - Q_{23})/2. \tag{63}$$

This technique was used on a set of four Ku-band standard gain horns where all combinations were measured to give three sets of data from which each antenna's polarization could be computed. The consistency of the results shown in table 3 indicates the accuracy of the technique.

We have discussed the case where the polarization is measured in the boresight directions (along the antenna z-axis), but the same procedure can be used for any direction. By rotating one or both of the antennas so that a direction other than boresight is along the space z-axis, the spherical components in that direction will be determined. Rotation of the receiving antenna in the measurement of Q_{nm} must be about the space z-axis which may not be the antenna z-axis in this case.

Table 3. Results of polarization measurements.

Antenna combinations	A_1 (dB)	τ_1 (deg)	A_2 (dB)	τ_2 (deg)	A_3 (dB)	τ_3 (deg)	A_4 (dB)	τ_4 (deg)
1,2,3	67.7	89.62	54.8	89.84	47.1	89.83		
1,2,4	73.9	89.60	53.9	89.86			60.0	89.86
1,3,4	70.3	89.68			46.8	89.79	61.0	89.80
2,3,4			54.4	89.80	47.3	89.77	59.1	89.82

The accuracy of the results are primarily dependent on the measurement of the magnitude of the Q's. If care is taken to average the effect of multipath by moving one antenna a small distance in the z-direction, the errors in A are on the order of ± 0.05 dB/dB of axial ratio, and about ± 0.2 deg in τ.

8. 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 [7]. For highest accuracy, the gain must be determined at closely spaced frequencies and swept frequency techniques may be used. 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 resulting gains as a function of frequency are fully corrected for mismatch, near-zone effects and multiple reflections between antennas. The accuracy obtainable over the band will typically be of the order of ±0.15 dB.

As implied earlier, the extrapolation method is used as the basis for accurate swept (stepped) frequency gain calibrations (fig. 16). To accomplish this, fixed frequency extrapolation measurements are usually performed at the end and mid-points of a waveguide band. Next, swept measurements of the pertinent reflection coefficients (both amplitude and phase) are taken looking into (1) generator port, (2) transmitting antenna, (3) receiving antenna, and (4) load port. Examples are given in figures 17 through 20. From these values, the mismatch correction is calculated as a function of frequency (fig. 21).

The next step in taking swept frequency measurements is to determine the z-distance at which the measurements will be taken. This is done by examining the extrapolation data and determining the distance where the insertion loss is approximately -10 to -12 dB. This usually assures that the distance is about 1 to 2 a^2/λ, which is sufficient for currently specified error uncertainties. This distance also ensures that there is a measurable signal across the band. It is at this distance that the near-zone correction is obtained

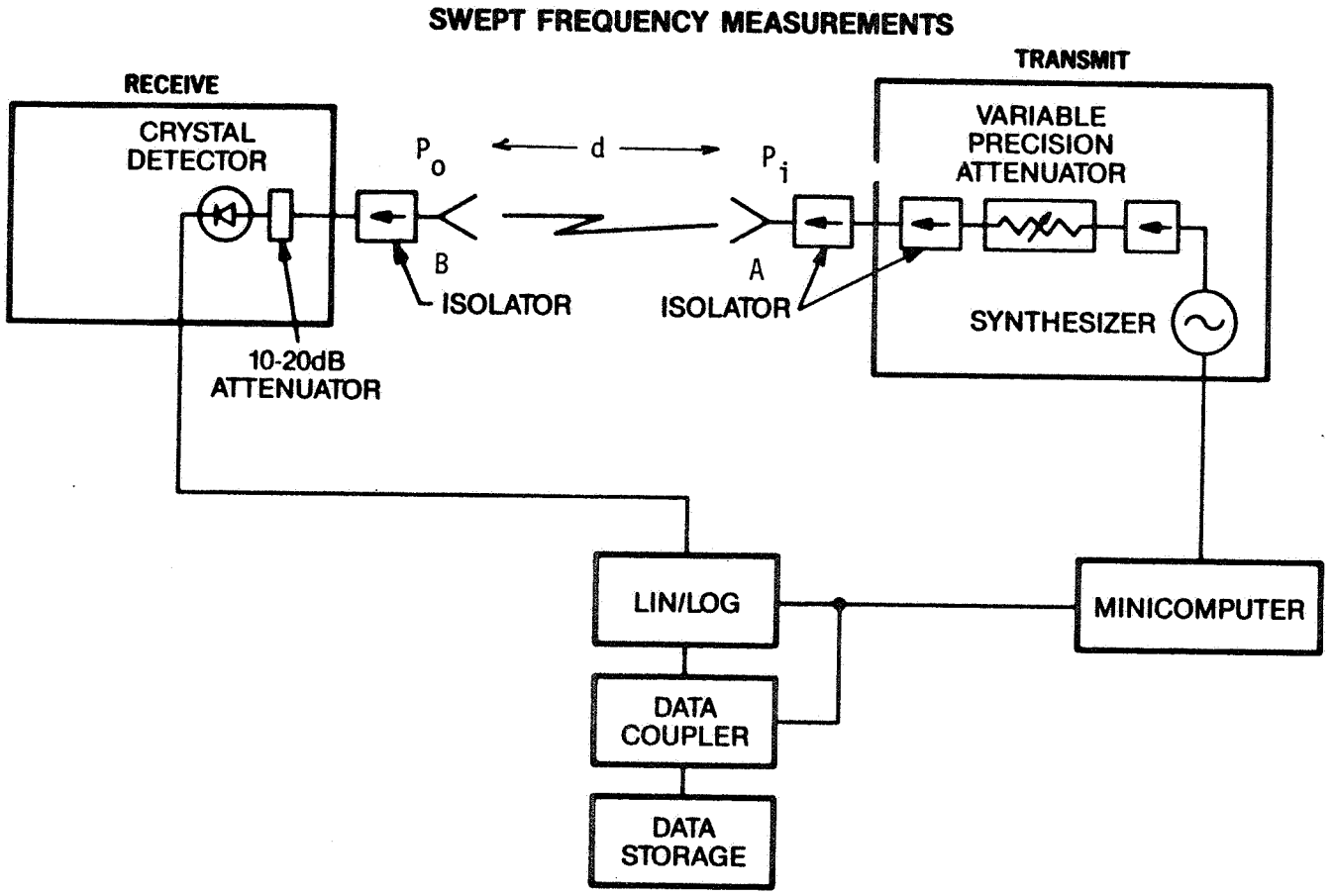

Figure 16. Swept frequency measurements.

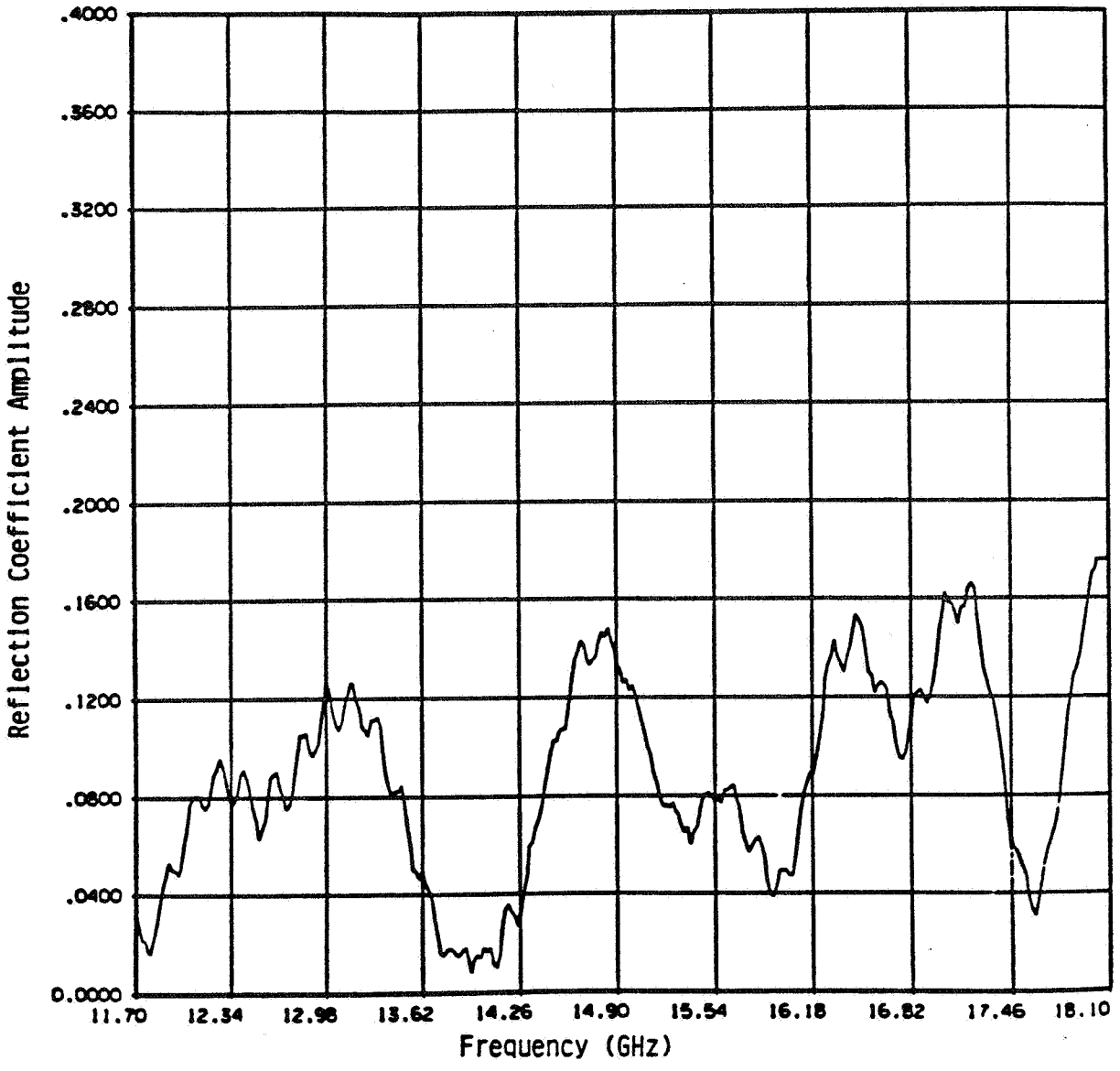

Figure 17. Swept frequency, reflection coefficient measurement (amplitude) for generator port.

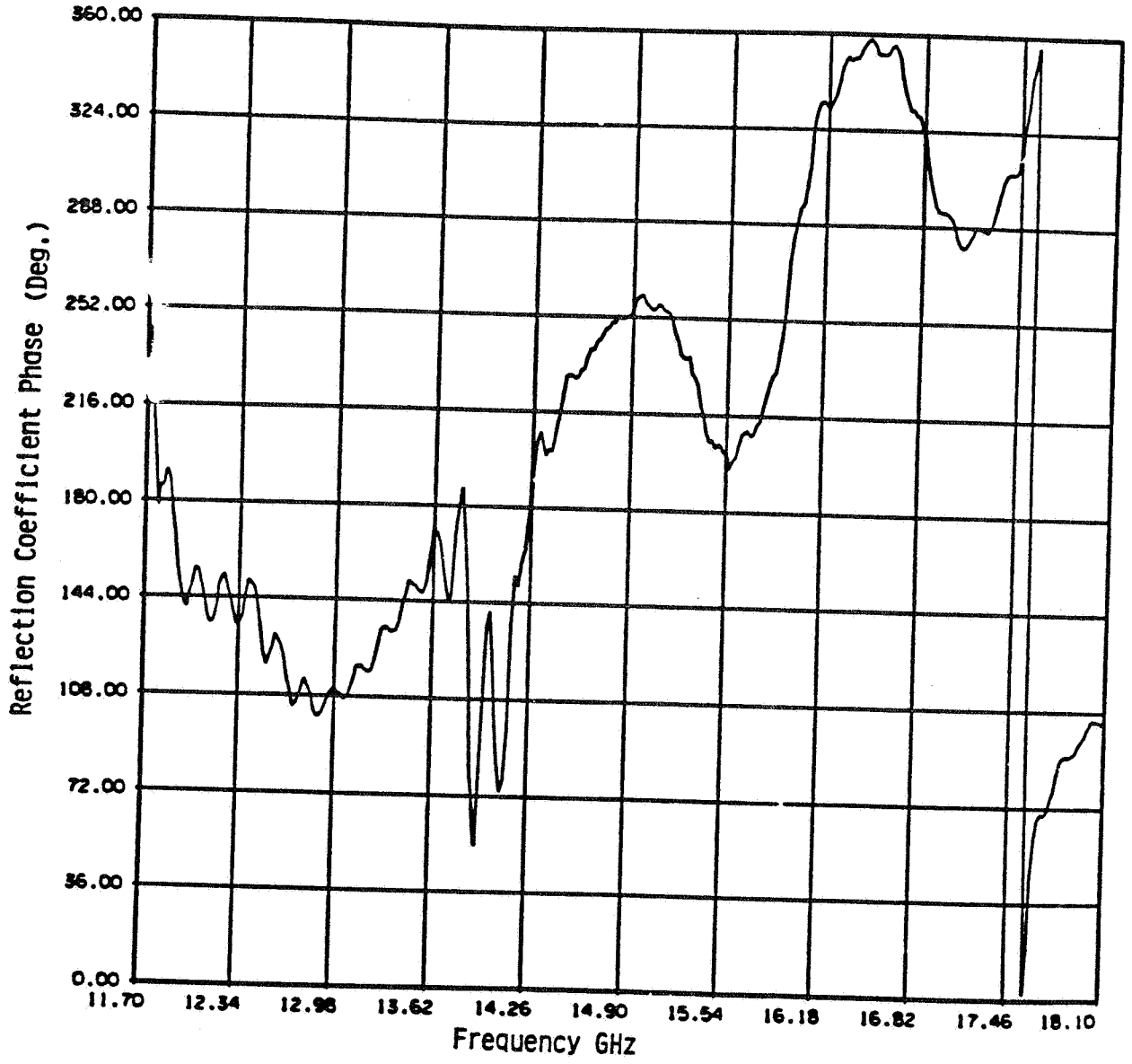

Figure 18. Swept frequency, reflection coefficient measurement (phase) for generator port.

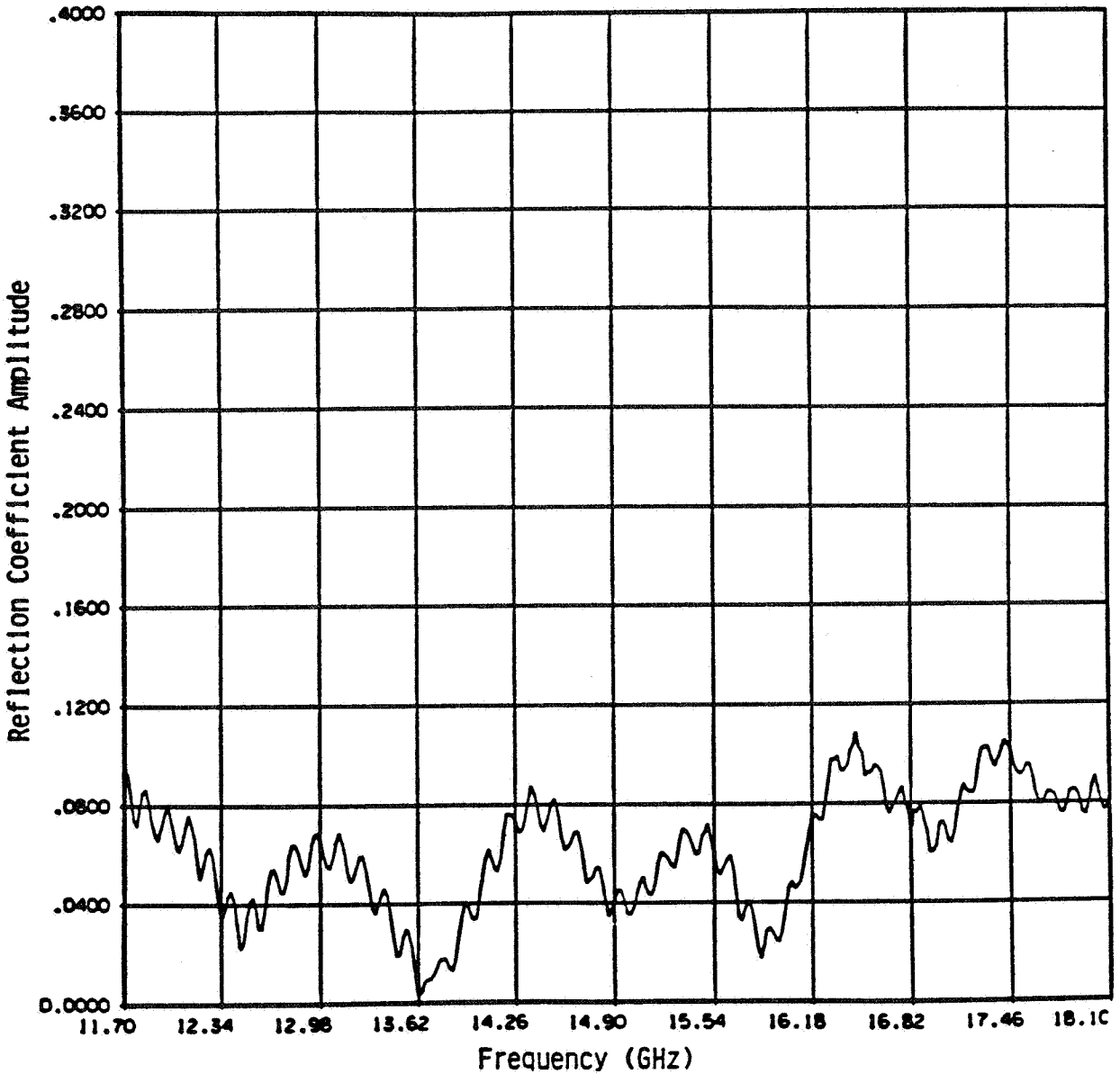

Figure 19. Swept frequency, reflection coefficient measurement (amplitude) for a long pyramidal horn.

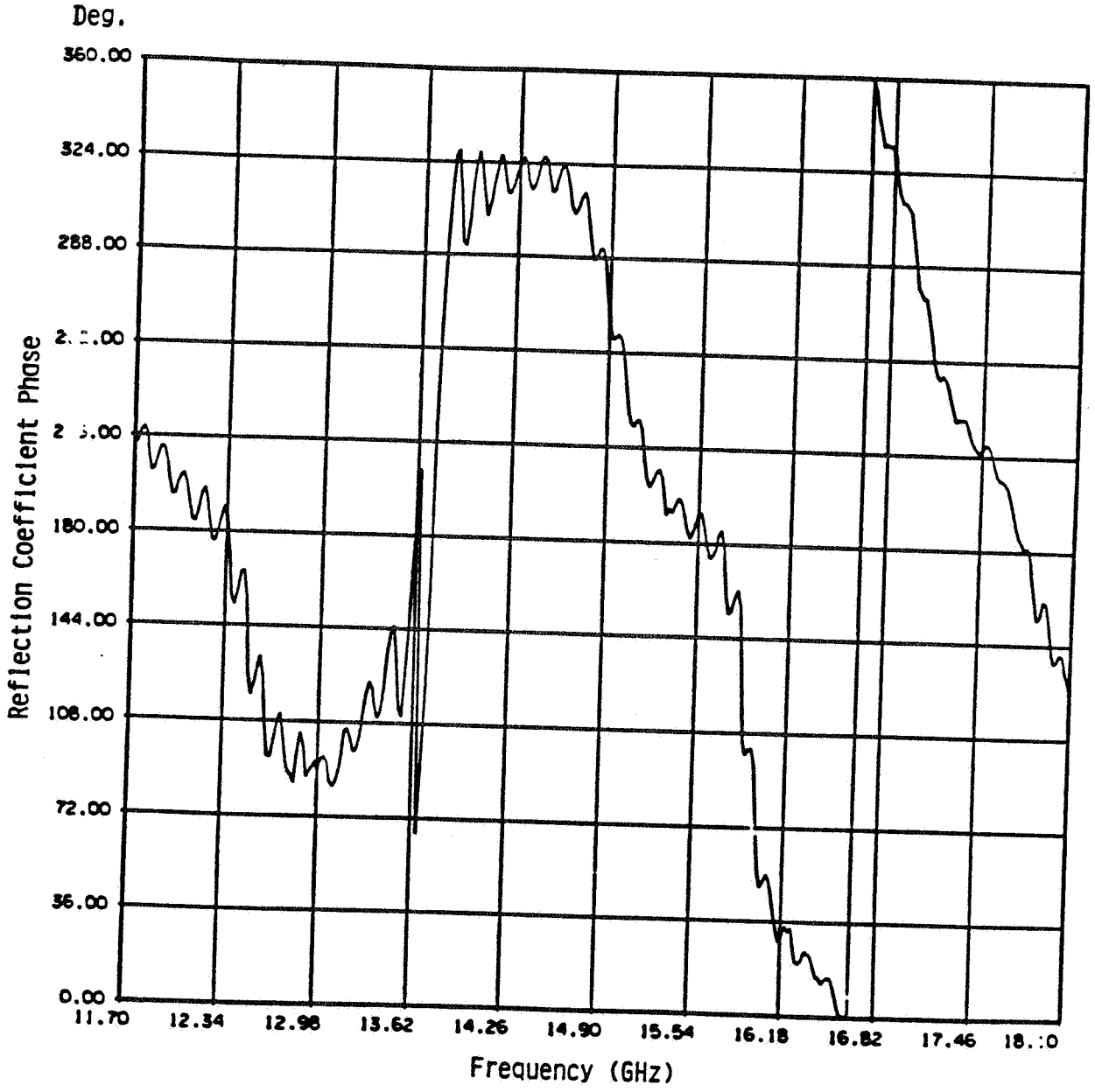

Figure 20. Swept frequency, reflection coefficient measurement (phase) for a long pyramidal horn.

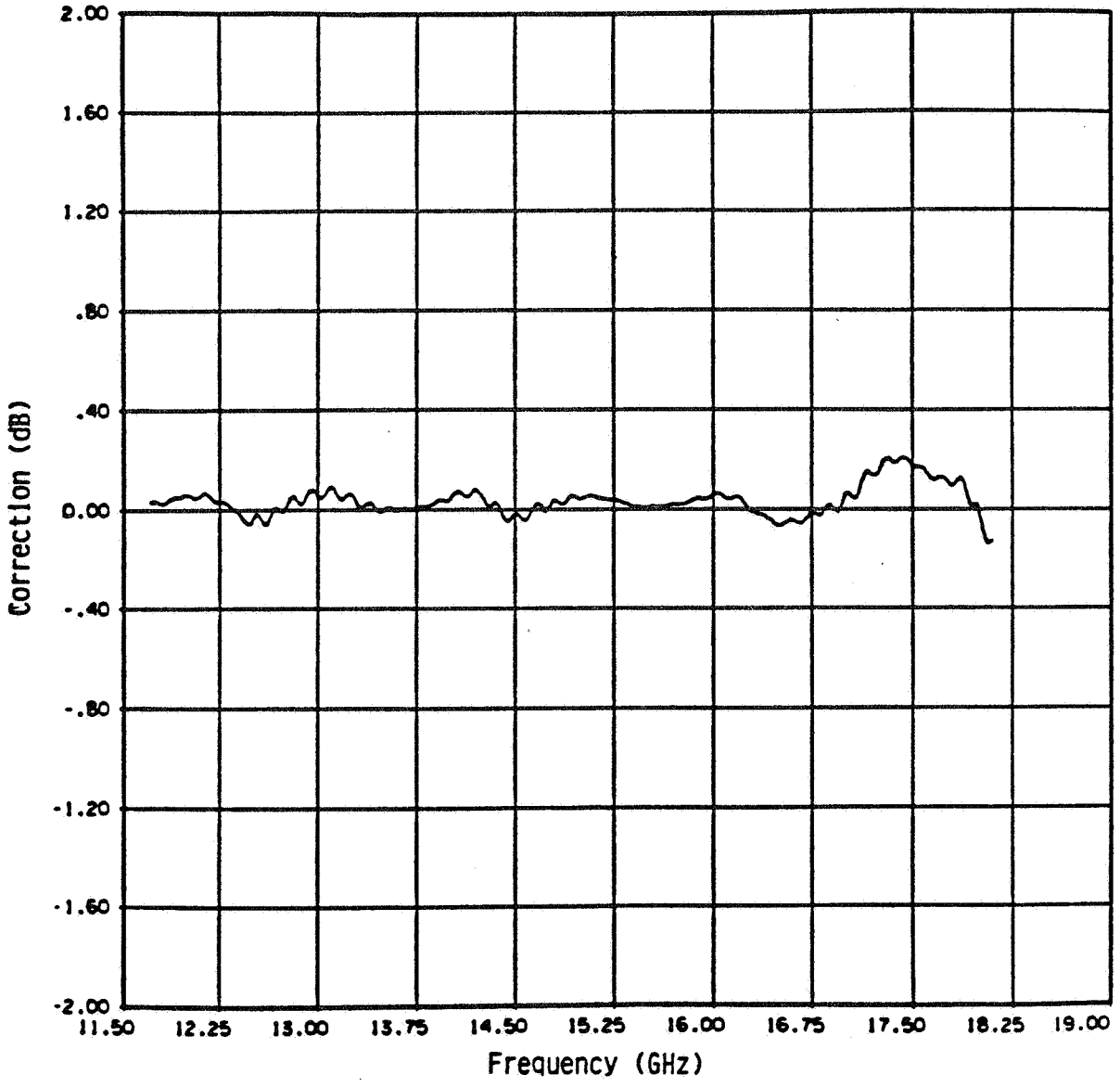

Figure 21. Mismatch correction calculated from measured reflection-coefficient data.

from the fixed-frequency extrapolation measurements (fig. 22). The receiving system is then initialized by requiring that the receiver is operating in its linear range and that the analog-to-digital amplitude meter is within its operating range (0 to -20 dB). The computer is then programmed to step (sweep) the signal source from f_{min} to f_{max} in steps small enough to assure that small variations in antenna gain are measured. Usually, f_{min} and f_{max} are chosen to be the lowest and highest frequencies at which extrapolation range gain measurements at fixed frequencies were taken. Frequency and amplitude data are then recorded (fig. 23).

The towers are then brought together and a generator-load connection is made. A recorded offset has been inserted on the precision rotary vane attenuator (RVA) to reduce the power level and again insure proper receiver system operation. Frequency and amplitude data for this hookup are then recorded (fig. 24).

After this procedure is checked out, the measurement is redone at least twice for each pair of antennas. The sequence becomes first to measure the generator-load connection, followed by reinstalling the horns, removing the RVA offset, moving the towers to the appropriate distance and then recording the frequency and amplitude measurements.

We now have sufficient information to determine the gain as a function of frequency, fully corrected for mismatch, near zone, and multiple reflection effects between antennas. Figure 25 shows a typical insertion loss result including mismatch and near-zone corrections for a pair of Ku band horns. This insertion loss is the difference between the generator-load reference curve and the insertion loss curve with the antennas in place, both mentioned above. The high frequency oscillations are due to multiple reflections between the antennas. The effects can be either averaged out or filtered out as shown in figure 26. The average gain for the pair of antennas is then determined as shown in figure 27. After processing the average gains obtained from the measurement of the three antenna pairs, the final gain values for the standard gain horns are determined. Some final results are shown in figures 28 and 29. The oscillations about the nominal values are approximately ±0.04 dB, ±0.1 dB, respectively, and are due to mismatches or multiple reflections at the throat and aperture of the horns.

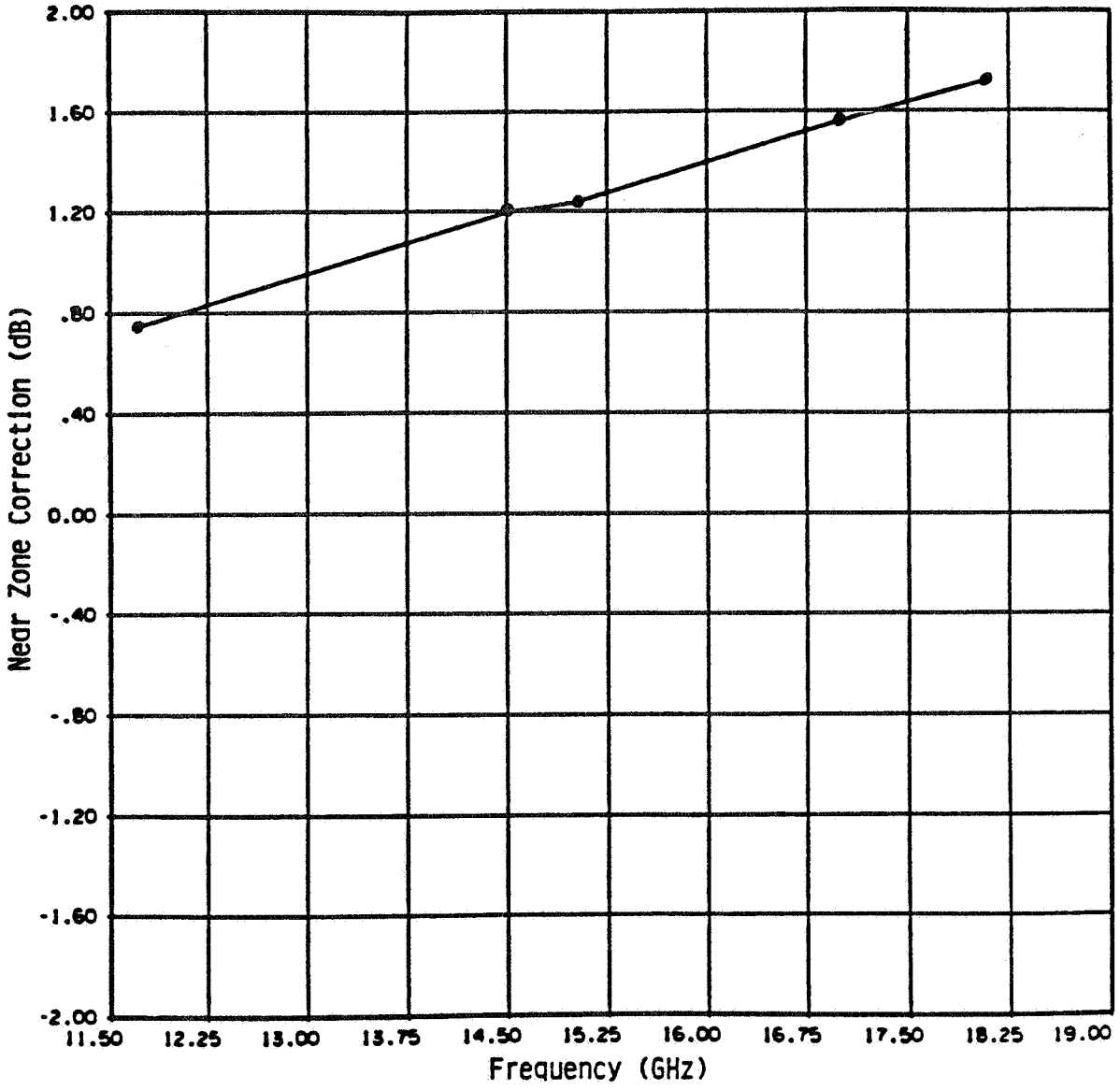

Figure 22. Near-zone correction obtained from extrapolation method for fixed-frequency measurements at 11.7, 14.5, 15.0, 17.0, and 18.1 GHz.

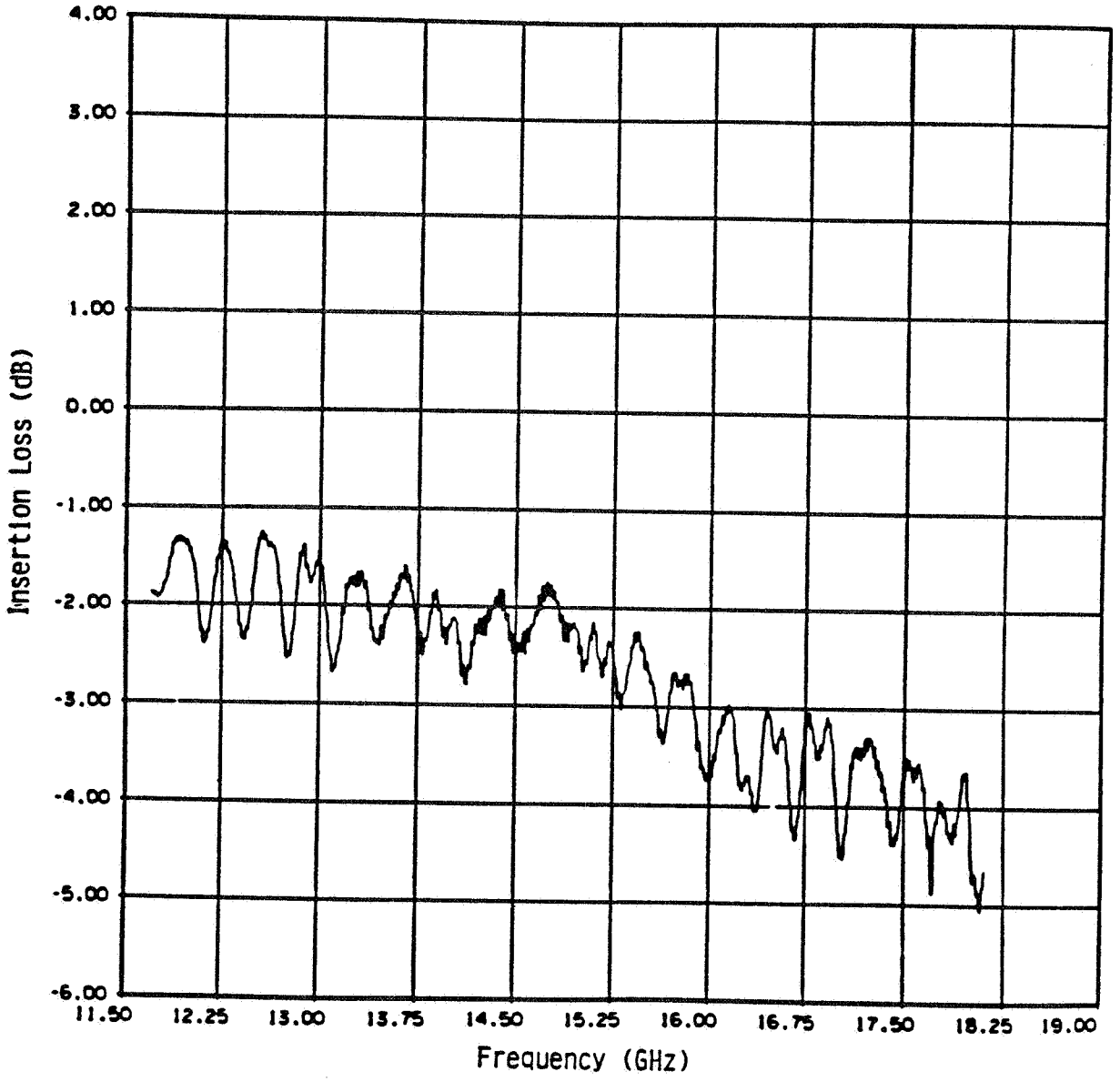

Figure 23. Swept frequency amplitude measurement with antennas in place at fixed distance of about a^2/λ.

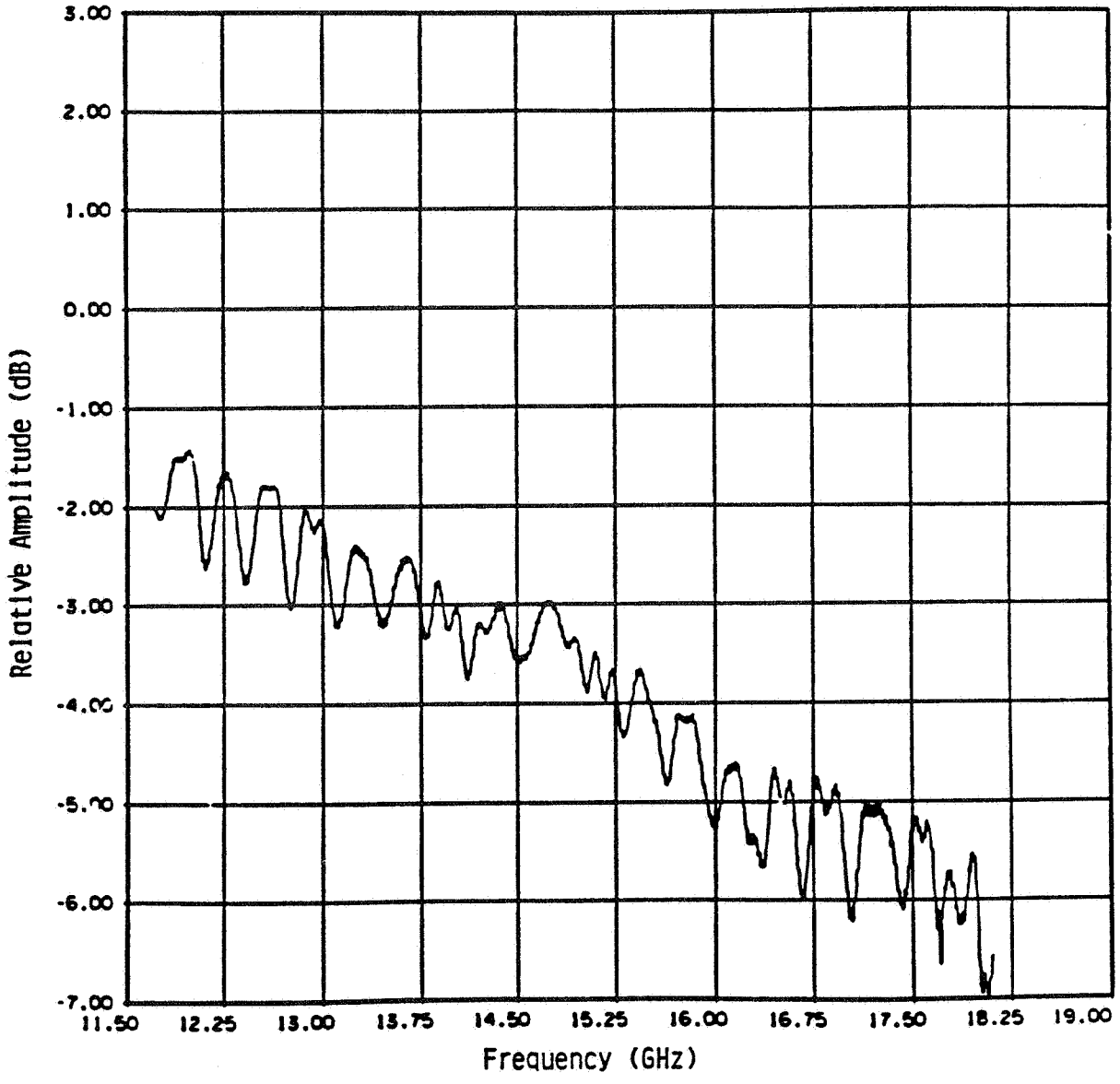

Figure 24. Swept frequency reference amplitude curve obtained with generator and load ports connected directly together.

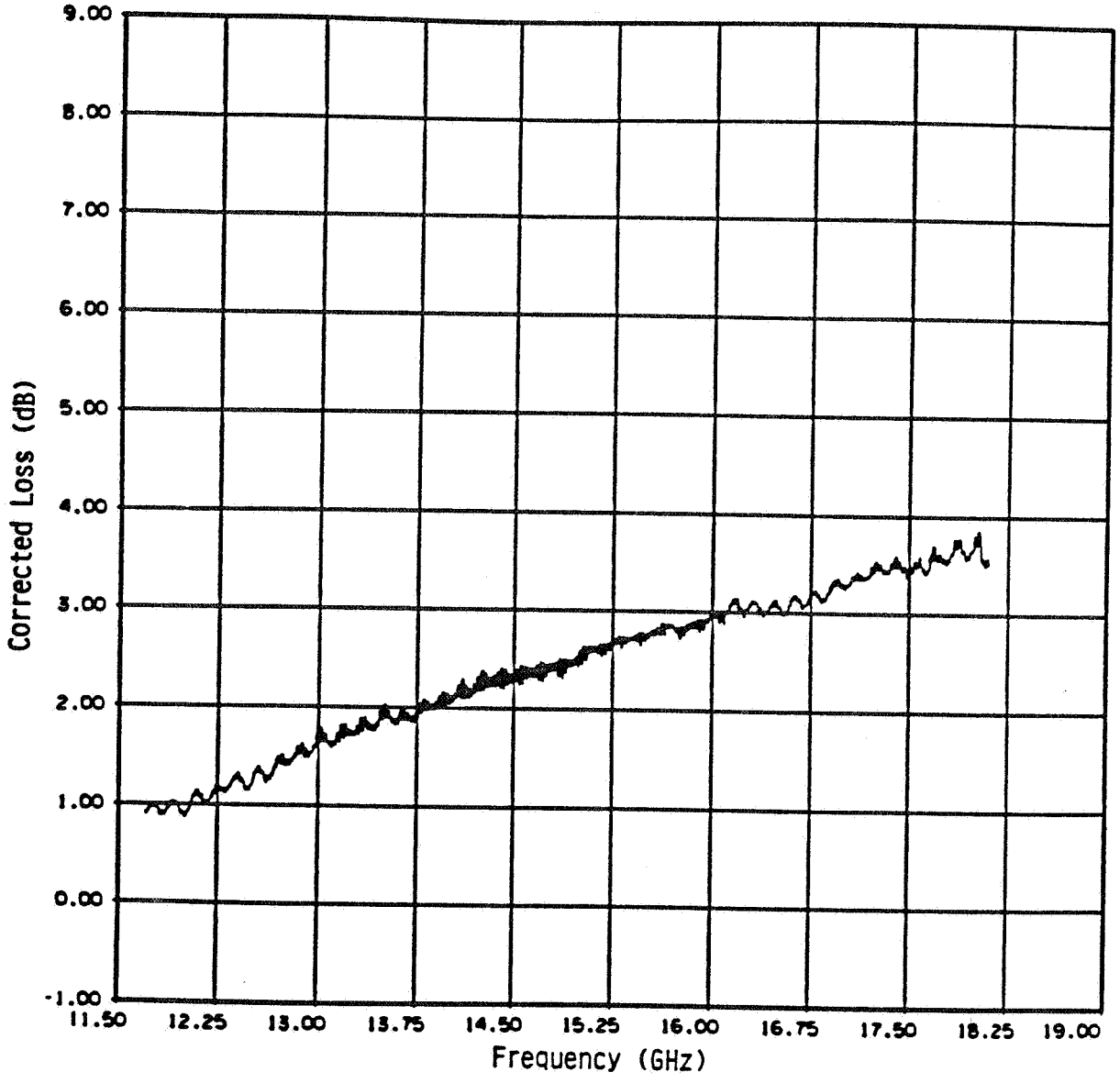

Figure 25. Insertion loss including mismatch and near-zone corrections. This is the difference between the reference curve and amplitude curve with antennas in place. The high-frequency oscillations are due to multiple reflections between the antennas.

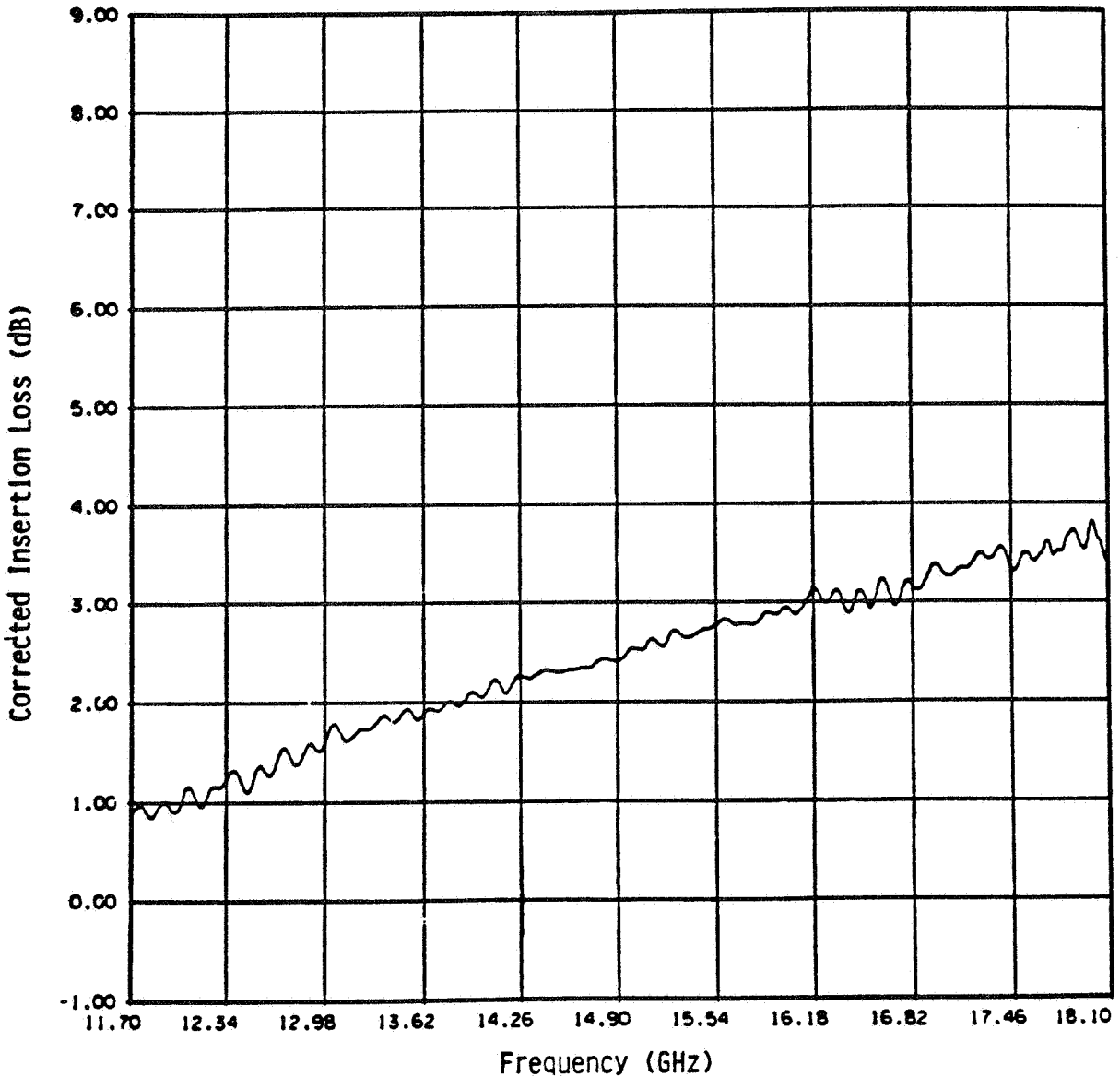

Figure 26. Insertion loss with multiple reflections averaged out.

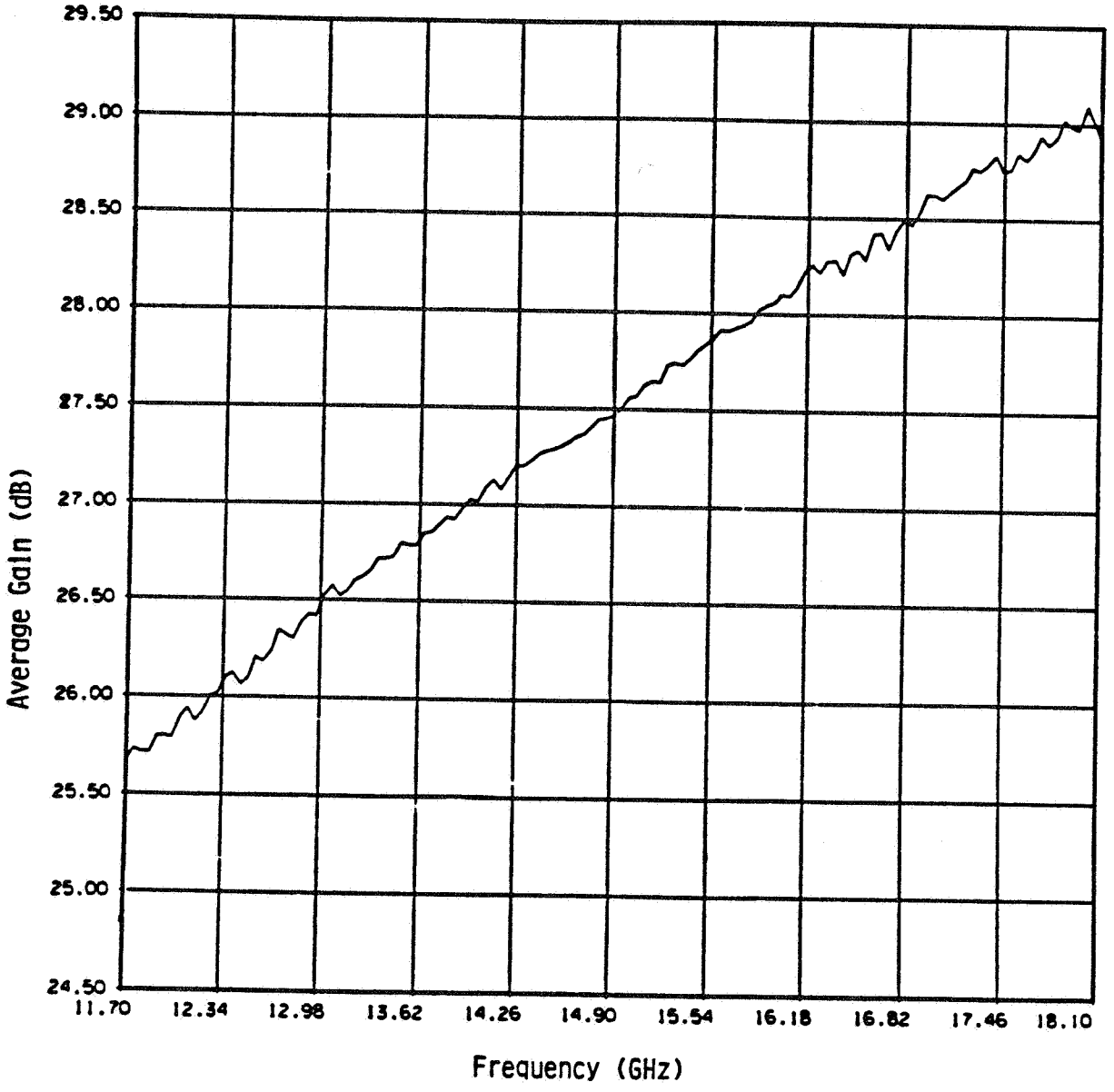

Figure 27. Average gain for a pair of antennas.

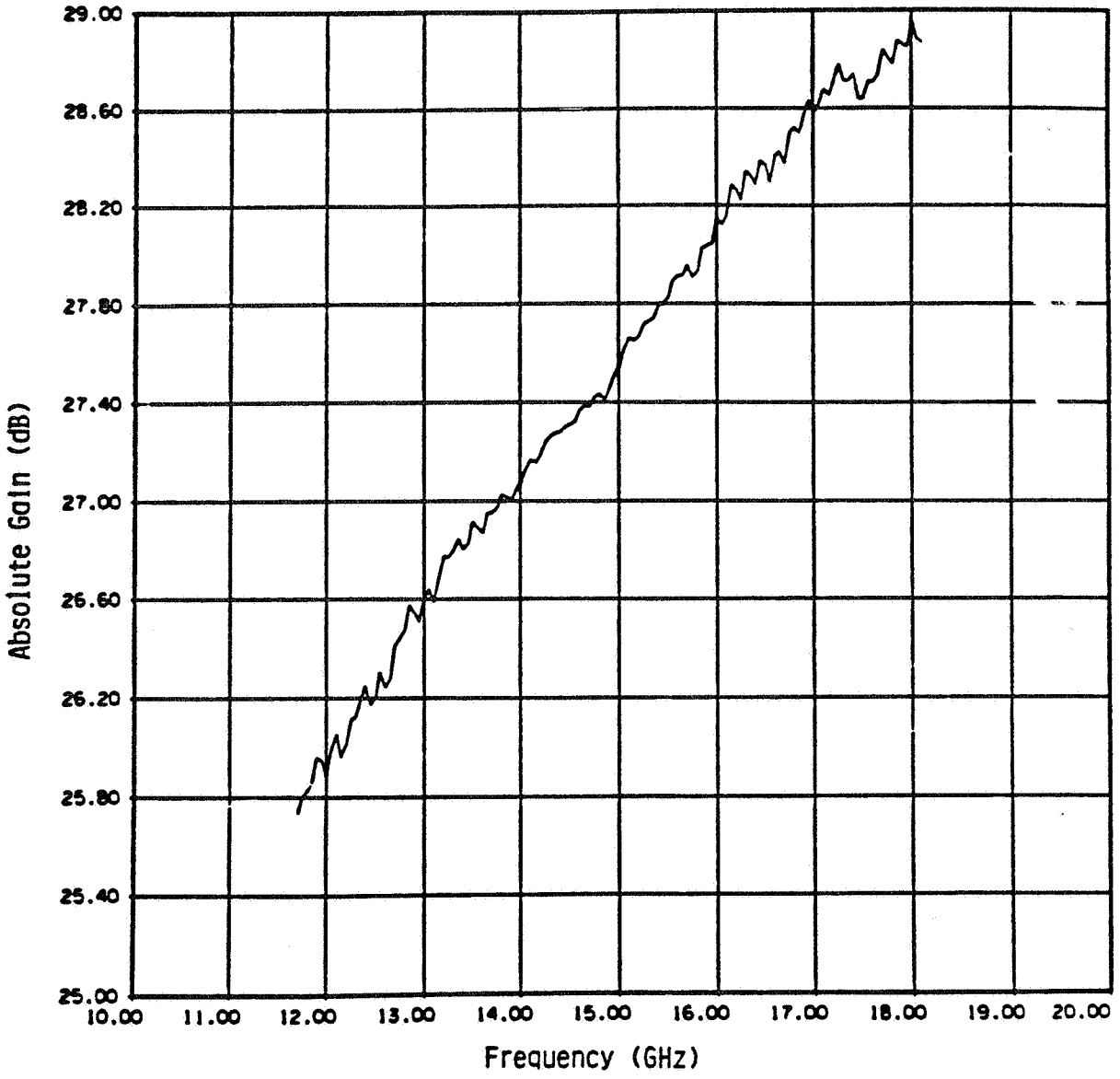

Figure 28. Final gain values for a long Ku-band horn. The oscillations about the nominal values are approximately ±0.04 dB and are due to mismatches at the throat and aperture of the horn.

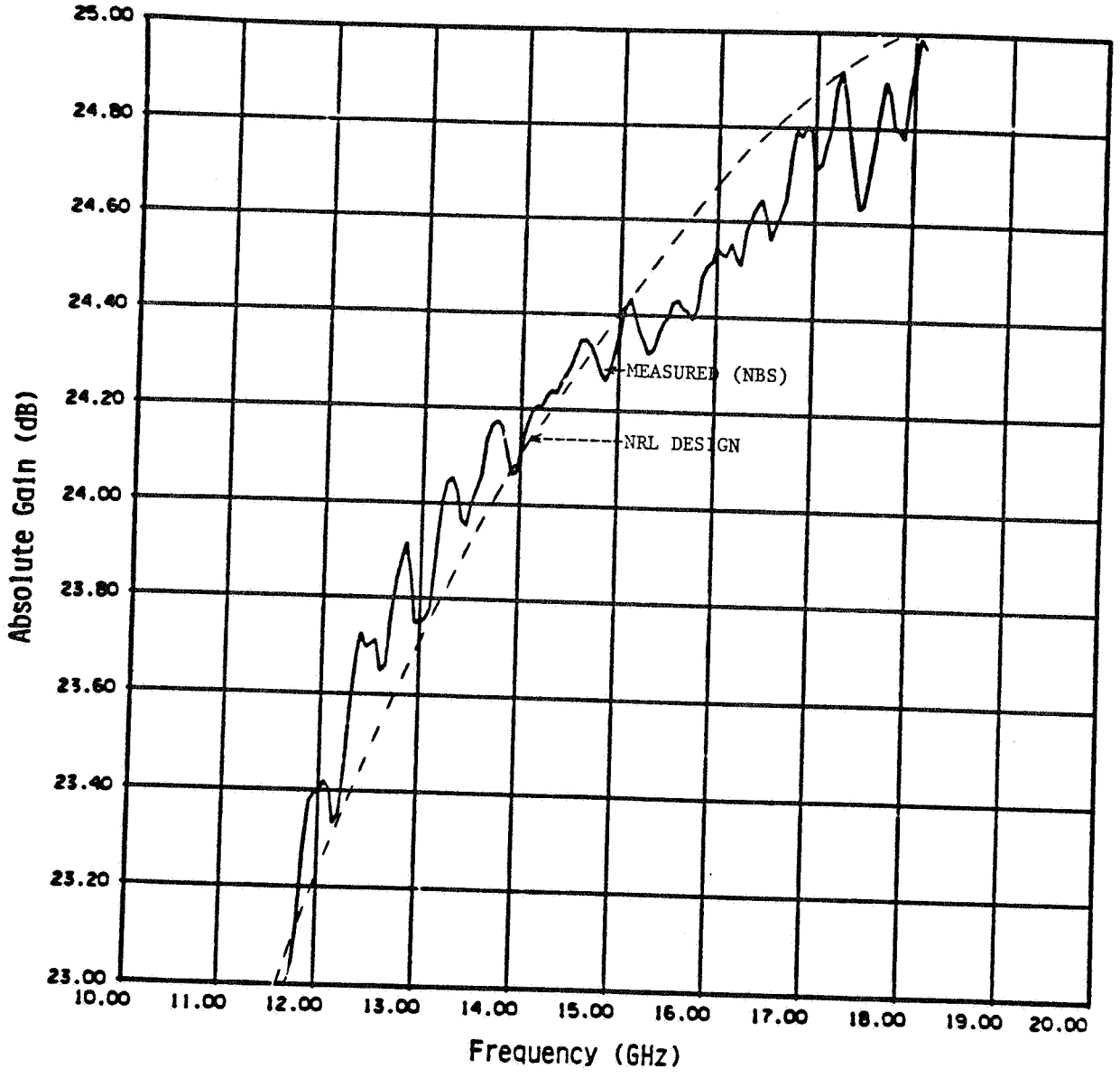

Figure 29. Final gain values for a standard gain horn. The oscillations about the nominal values are approximately ±0.1 dB and are due to mismatches at the throat and aperture of the horn.

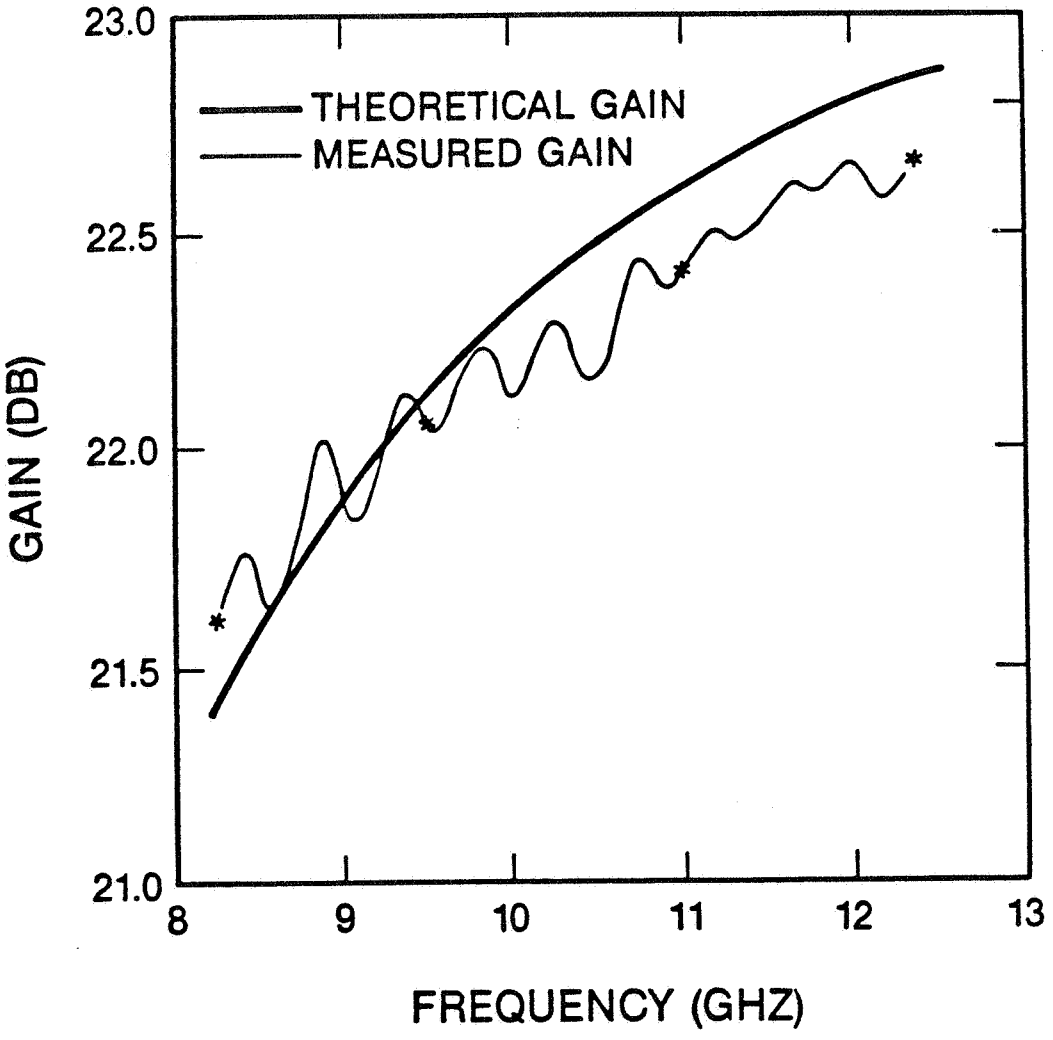

Figure 30. Comparison between theoretical gain and gain measured by the swept-frequency technique for an X-band pyramidal horn. Gain values indicated by the * were obtained by the extrapolation method.

As another example, figure 30 illustrates a comparison between a theoretically obtained gain curve for an X-band pyramidal horn as predicted by theory [6] and data obtained using the three-antenna method applied to swept frequency data.

9. Summary

The extrapolation range measurement technique has been described for determining the power gain and polarization of antennas at reduced distances. It is used extensively by the National Bureau of Standards, Boulder, Colorado to calibrate antenna gain standards for industry and other agencies. A modification in the approach that significantly increases the accuracy of the polarization parameters has also been described and should be of particular interest to the reader.

Two extensions of the extrapolation method have also been presented. The first extension applies to swept frequency measurements where it has been demonstrated that accuracies over an entire band of frequencies can be achieved typically to within ±0.15 dB. Swept frequency measurements continue to be of interest to the measurement community as they can determine whether "holes" exist in an antenna's frequency response.

The second extension of the extrapolation method given as an appendix corrects for the effects of ground reflections in absolute gain measurements. This is particularly significant for broadbeam antennas such as those encountered below 1 GHz, where ground reflections may produce unwanted oscillations in the amplitude-versus-distance data.

In summary, the main purpose of this technical note is to describe the extrapolation measurement method, its improvements and its extensions, and its errors in detail. Through this exposition, it is hoped that managers, engineers, and technicians involved in antenna measurements will understand the deliberate steps necessary to ensure calibrations of the highest accuracy.

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Appendix A.

Extension of Extrapolation Technique to Correct for Effects of Ground Reflections

Antenna Gain Measurements by an Extended Version of the NBS Extrapolation Method

ANDREW G. REPJAR, SENIOR MEMBER, IEEE, ALLEN C. NEWELL, MEMBER, IEEE, AND RAMON C. BAIRD, SENIOR MEMBER, IEEE

Abstract—**A General Extrapolation Technique which corrects for the effects of ground reflections in absolute gain measurements is described. It utilizes the Extrapolation Method developed at NBS which, in its present form, utilizes only amplitude versus distance data. However, for broadbeam antennas such as those encountered below 1 GHz, ground reflections may produce unwanted oscillations in the amplitude versus distance data. Hence the data are not amenable to the curve-fitting procedure of the Extrapolation Method. This problem can be overcome by including phase versus distance information to reduce the effects of ground reflections.**

INTRODUCTION

A SPECIFIC OBJECTIVE of the Antenna Systems Metrology Group at NBS is to develop the required techniques and standards for accurately determining antenna characteristics. One existing NBS measurement service is the accurate calibration of transfer standard antennas (on-axis gain and polarization) by the Extrapolation Method. The theoretical basis of this method was developed by Wacker [1] and its application to accurate antenna measurements has been described briefly by Newell and Kerns [2] and more fully, in an experimentally oriented paper, by Newell *et al.* [3]. The method utilizes a generalized three-antenna approach which does not require quantitative *a priori* knowledge of the antennas.

The main advantages of the Extrapolation Method, which presently utilizes amplitude versus distance data only, are its accuracy and generality, and there is essentially no upper frequency limit. It can, in principle, be applied to any type of antenna although some directivity is desirable to reduce multipath interference. Above 1 GHz, uncertainties between ±0.08 and ±0.10 dB in gain are achieved routinely. The maximum gain values that can be measured depend on the range dimensions since a maximum separation of approximately $2D^2/\lambda$ is desirable. With the present NBS facilities, the maximum gain ranges from about 45 dB at 75 GHz down to about 25 dB at 1 GHz.

At frequencies below 1 GHz and for the purposes of this paper, in the VHF-UHF region, a transfer standard is often broadbeam and produces ground reflections which cause oscillations in the amplitude data as a function of distance. These oscillations have longer periods than those due to the multiple reflections between antennas which are routinely averaged out in the Extrapolation Method. For this reason, below 1 GHz and for gains less than about 15 dB, the antenna might not be calibratable by the usual Extrapolation Method which uses a curve-fitting procedure to determine gain. The purpose of this paper is to demonstrate that by utilizing both amplitude *and* phase data as a function of distance, one can obtain an amplitude versus distance curve which is corrected for the effects of ground reflections. This curve can then be processed by the Extrapolation Method to determine gain.

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The authors are with the Antenna Systems Metrology Section, Electromagnetic Fields Division, National Bureau of Standards, Boulder, CO 80303.

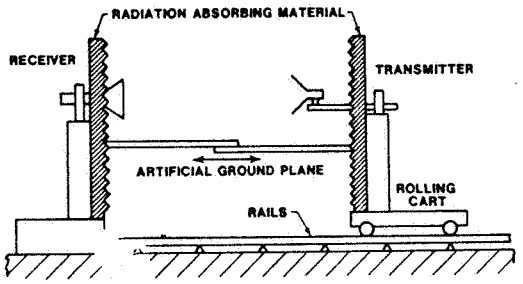

Fig. 1. Schematic agram showing the NBS indoor extrapolation range modified to fun on as a scaled model of the larger outdoor range.

DISCUSSION OF MEASUREMENT PROCEDURE

Recently at NBS, it was determined that a VHF-UHF scalar horn can be designed to meet the requirements of a transfer standard for 240-400 MHz [4]. This fact was demonstrated by designing and constructing a *C*-band model of the VHF-UHF antenna and extensively measuring the critical performance parameters and comparing them with theoretical results. The expected calibration accuracy of the VHF-UHF horn was then determined by performing measurements of the scaled model on the NBS indoor extrapolation range. Measurements were conducted both with and without ground reflections so that we could determine how well we could correct for the multipath effects in our calibration technique. Ultimately, the full-scale horn will be measured on the NBS outdoor extrapolation range. Fig. 1 is an illustration of how we can use the scaled model horn on the indoor range to simulate the situation that will exist at 240-400 MHz on the outdoor range.

EXTRAPOLATION METHOD

The first step in the measurement process is to connect the generator and load ports together to obtain a reference signal. The antennas are then installed and the received signal is re-

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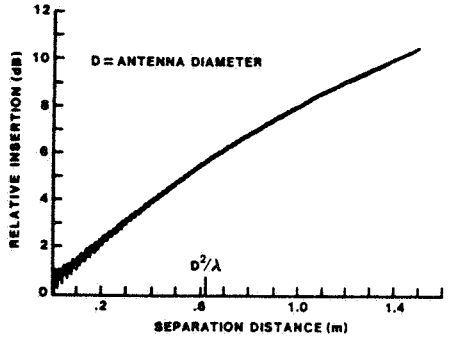

Fig. 2. Extrapolation data for scalar horn showing the insertion loss plotted as a function of separation distance (meters).

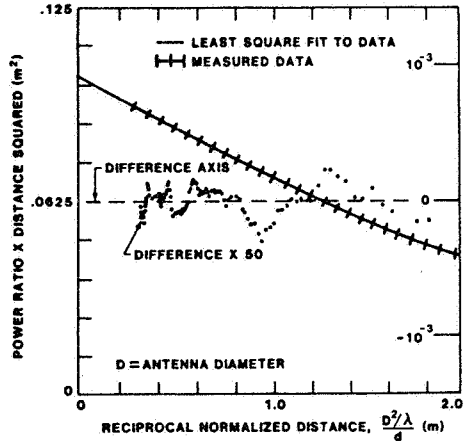

Fig. 3. Measured data without ground plane, four-term polynomial fit, and differences for scalar horn.

corded as a function of the separation distance. Fig. 2 displays some typical data for the case where no ground reflections are present. The oscillations are due to multiple reflections between the antennas. In the curve-fitting process to determine gain, the effects of these multiple transits are eliminated by locally averaging the relative insertion-loss values. The averaged curve is then fitted with a polynomial in $1/d$ (ordinarily, four or five terms will suffice). This procedure determines the coefficient, A_{00}, of the $1/d$ term of the series (see [3], eq (27)] which determines the gain of the antenna under test. With the artificial ground plane removed and, hence, with no ground reflections present, the results obtained by the curve-fitting procedure are given in Fig. 3, which shows the averaged curve obtained from the measured data for the scalar horn and the curve obtained by fitting with a four-term polynomial. The greatly magnified differences between the measured and fitted curve qualitatively indicate the goodness of fit. The absolute gain of this horn was determined to be 13.32 dB at 4.0 GHz, which simulates 240 MHz in the VHF-UHF range. It should be noted that the abscissa in Fig. 3, and subsequently in Figs. 4 and 6, is the inverse of the normalized separation distance, a natural means of analyzing curve fitting with a polynomial in $1/d$.

ANALYSIS

With the artificial ground plane in place, the averaged curve, i.e., the curve obtained after applying the local averaging process discussed above, as a function of antenna separation

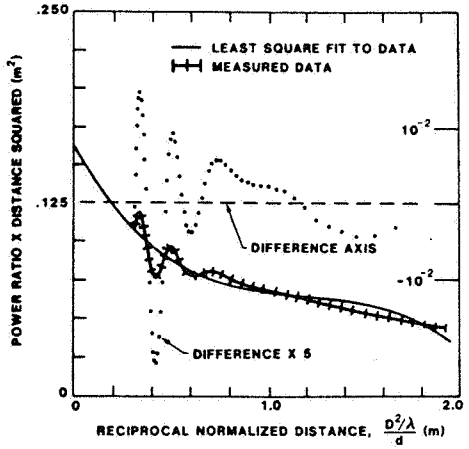

Fig. 4. Measured data with ground plane, four-term polynomial fit, and differences for scalar horn.

is given in Fig. 4. Note the region of oscillatory behavior due to ground reflections. Fitting this curve with four-term polynomial in $1/d$, which is also shown in Fig. 4, results in a calculated gain of 14.29 dB, 0.97 dB higher than it. calibrated value obtained without the ground plane! In addition, it is evident from this figure that the differences between averaged curve and the fitted curve are pronounced.

Denoting ϕ_t as the measured phase and ϕ_d as the phase of the direct wave, one can see that when the ground plane is removed, i.e., no ground effects present, the measured phase minus the phase of the direct wave should be zero plus an arbitrary constant in the far field. This is important in our analysis because the only *assumption* made in obtaining an amplitude versus distance plot that is free of multipath effects is that the direct wave phase can be represented in the far field as

$$\phi_d = 360\, d/\lambda \text{ degrees} \tag{1}$$

where d is the separation distance and λ is the wavelength.

Using a laser interferometer to accurately measure the separation distance, the phase was measured without the ground plane to test the above assumption. (Since (1) is being used to calculate the phase of the direct wave, the measured separation distance must be accurate to about 1/360 of a wavelength. For this reason, at *C*-band, a laser interferometer was used to measure the separation distances. For measurements of the full-scale UHF-VHF horn, other means may be adequate.) The dashed line in Fig. 5 shows the results, demonstrating that for large distances, $\phi_t - \phi_d$ is in fact extremely close to being constant. It should be noted that where the separation distance is small, the variation of $\phi_t - \phi_d$ is due to the near-zone effect, i.e., the antennas are still in the near field of each other. (A correction for this effect is routinely obtained in the standard extrapolation method.)

An analysis of the interaction between the direct wave and the ground wave shows that at the local peaks of the $\phi_t - \phi_d$ curve

$$\rho \equiv \frac{|V_g|}{|V_d|} = \sin(\phi_t - \phi_d) \tag{2}$$

where $|V_g|$ and $|V_d|$ are the amplitudes of the ground and direct waves, respectively. In addition, it can be shown that

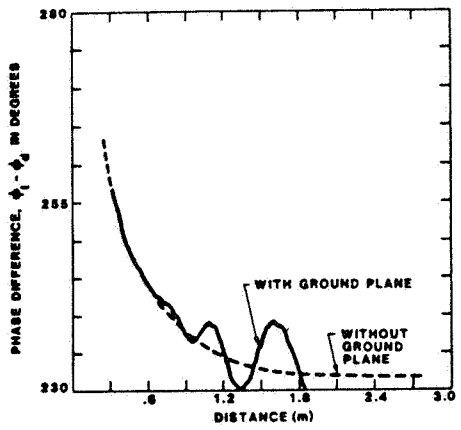

Fig. 5. Phase difference between measured wave and direct wave with and without ground plane.

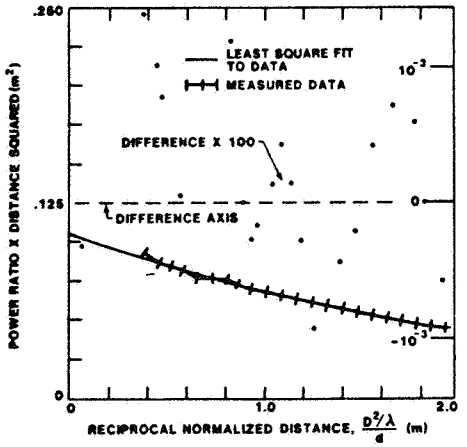

Fig. 6. Measured data points with ground plane and $|V_t| = |V_d|$, four-term polynomial fit, and differences for scalar horn.

$$\frac{\phi_t - \phi_d}{2} = \sin^{-1}(\rho/2), \qquad \text{when } |V_t| = |V_d| \qquad (3)$$

where $|V_t|$ is the amplitude of the total wave resulting from the combination of the direct and ground waves. It is $|V_t|$ that is measured as a function of distance in the extrapolation method. Since $|V_t|_{max}$ and $|V_t|_{min}$ occur when the ground wave adds in and out of phase, respectively, with the direct wave, the distances at which $\phi_t - \phi_d = 0$ are also determined. From these preceding results, the points on the insertion-loss curve where $|V_t| = |V_d|$ can be determined. For example, when the phase differences, $\phi_t - \phi_d$, are small, the condition $|V_t| = |V_d|$ occurs at those distances where the $\phi_t - \phi_d$ curve has local maxima and minima. Using only these points as data in the region where ground reflection effects are dominant, one can then use the extrapolation method to determine gain.

The solid line in Fig. 5 displays the measured $\phi_t - \phi_d$ data obtained with the ground plane in place. Through the above procedure, the points where $|V_t| = |V_d|$ were determined, and the curve obtained using these points in the region where ground effects are dominant is shown in Fig. 6. After fitting this curve with a four-term polynomial, also shown in Fig. 6, the gain of the antenna was calculated to be 13.27 dB, only 0.05 dB lower than the value obtained in the absence of ground reflections! In addition, in this figure, the differences between the curve and the fitted curve indicate the goodness of fit.

TABLE I
MEASURED GAIN IN dB OF THE SCALAR HORN MODEL
(Principal component horizontally oriented.)

Frequency in GHz	Without ground plane	With ground plane	With ground plane and back-structure
4.0	13.32	13.27	13.25
4.83	14.10	14.11	14.15
5.5	14.52	14.41	14.41
6.8	12.15	12.17	12.22

TABLE II
MEASURED GAIN IN dB OF SCALAR HORN MODEL
(Principal component vertically oriented.)

Frequency in GHz	Without ground plane	With ground plane	With ground plane and back-structure
4.0	13.23	13.31	13.31
4.83	14.09	14.02	14.03
5.5	14.41	14.50	14.54
6.8	12.17	12.26	12.29

RESULTS

In order to further test the use of the extended version of the extrapolation method, the gain of the scaled-model antenna was determined at four frequencies across the band. The amplitude versus distance data obtained *without* the ground plane present were processed by the *extrapolation method* to determine the gain of the antenna at these frequencies. Next, the amplitude versus distance data obtained *with* the ground plane present were processed by the *extended version* of the extrapolation method to determine the gain. Comparisons were then made. In addition, the gain of the antenna was obtained with its principal component first horizontally and then vertically oriented. (The phase of the field reflected by the ground plane depends on the polarization of the field incident on the ground plane. This results in different, i.e., shifted, positions for the oscillations in the amplitude versus distance data. To be useful, the *extended* version of the extrapolation method must give the correct gain for all orientations.) Finally, the structures of the towers on which antennas are mounted on the outdoor range were simulated to determine their effect on the gain measurements. The results of all these measurements are summarized in Tables I and II.

Upon examination of the data in Tables I and II, the rms difference between the gain values obtained with and without the ground plane are 0.07 and 0.09 dB for the principal component horizontally and vertically oriented, respectively. Also, the rms difference between the gain values obtained without the ground plane for the horizontal and vertical orientations is 0.07 dB. These values are within ±0.10 dB, the bounds nominally expected by the error analysis discussed in [3]. It should be again noted that *without* the extended version of the extrapolation method to account for ground reflections, errors in gain could be in the order of ±1 to 2 dB.

CONCLUSIONS

A technique has been described to determine the gain of antennas operating at frequencies below 1 GHz. Under simulated conditions, it was determined that phase versus distance measurements can be used to determine an amplitude versus distance curve which is corrected for ground reflection effects. This curve can then be processed by the extrapolation method which uses amplitude data only to determine gain. Measure-

ments on the full-scale VHF-UHF horn on the NBS outdoor extrapolation range are planned for the future.

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Appendix B.

Standard NBS Calibration Report

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
NATIONAL ENGINEERING LABORATORY
Boulder, Colorado 80303

REPORT OF CALIBRATION

STANDARD GAIN HORN
National Bureau of Standards
X-Band Horn, Serial No. 485
calibrated against
National Bureau of Standards
International Comparison Standard, Serial No. 1
and
National Bureau of Standards
International Comparison Standard, Serial No. 2

Submitted by:

National Bureau of Standards
Antenna Systems Metrology Group
Boul , Colorado 80303

The on-axis power gain and polarizat on parameters of the antenna were measured by a generalized three antenna measuremer technique [1]. An extrapolation measurement technique was used to evaluate and correct for near-zone and multipath effects in the measured data. The two other antennas which were used in the measurement were pyramidal type horns with nominal linear polarization. The antennas were not assumed to be perfectly linearly polarized, and their actual cross polarization was accounted for in the measurements and calculations.

The axis of measurement was in the direction of maximum power gain for all antennas, and their 'E' field was in the horizontal direction.

The results of the measurements are summarized in the following table.

Frequency (GHz)	Power Gain (dB)	Axial Ratio (dB)	Sense of Polarization	Tilt Angle (degrees)	Reflection Coefficient Amplitude	Reflection Coefficient Phase (degrees)
8.00	21.60 ± 0.1	48 ± 2	Right	90.3 ± 0.5	0.049	105.9
10.00	22.37 ± 0.1	44 ± 2	Right	90.1 ± 0.5	0.043	-59.6
12.00	22.78 ± 0.1	43 ± 2	Right	90.3 ± 0.5	0.025	-147.9

In addition to the gain measurements at the fixed frequencies, swept gain measurements were also obtained. The results of these measurements are shown in figure 1.

[1] Newell, A. C.; Baird, R. C.; Wacker, P. F. Accurate measurement of antenna gain and polarization at reduced distances by an extrapolation technique. IEEE Trans. Antennas and Propagation, Vol. AP-21:418-431; 1973 July.

Date of Calibration: July 1982

Standard Gain Horn
National Bureau of Standards
X-Band Horn, Serial No. 485
calibrated against
National Bureau of Standards
International Comparison Standard, Serial No. 1
and National Bureau of Standards
International Comparison Standard, Serial No. 2

The error estimates are the result of a quadrature (RSS) sum of the individual error components listed in the following tables. Each error component is a worst case or 3 sigma value, and the errors are independent and uncorrelated. The confidence level for the resulting combination is, therefore, equivalent to that associated with 3 sigma.

Errors in Gain Measurement

Source of Error	Resultant Error in Gain (dB)
System Drift and Receiver Nonlinearity	0.05
Attenuator Calibration	0.04
Impedance Mismatch	0.01
Antenna Alignment	0.05
Distance Nonlinearity	0.02
Flange Loss and Reproducibility	0.05
Residual Multipath	0.03
Random Errors	0.03
Quadrature Sum	±0.11

Errors in Polarization Measurements

Source of Error	Resultant Error	
	Axial ratio (dB)	Tilt angle (deg.)
Antenna Alignment	1.0	0.5
Residual Multipath	1.0	0.1
Rotation Angle for Maximum and Minimum	1.5	0.15
	±2.0	±0.5

The estimated uncertainty in the swept gain measurement is 0.15 dB.

For the Director,
National Engineering Laboratory

Allen C. Newell

Allen C. Newell, Leader
Antenna Systems Metrology Group
Electromagnetic Fields Division

Page 2 of 2
Date of Calibration: July 1982

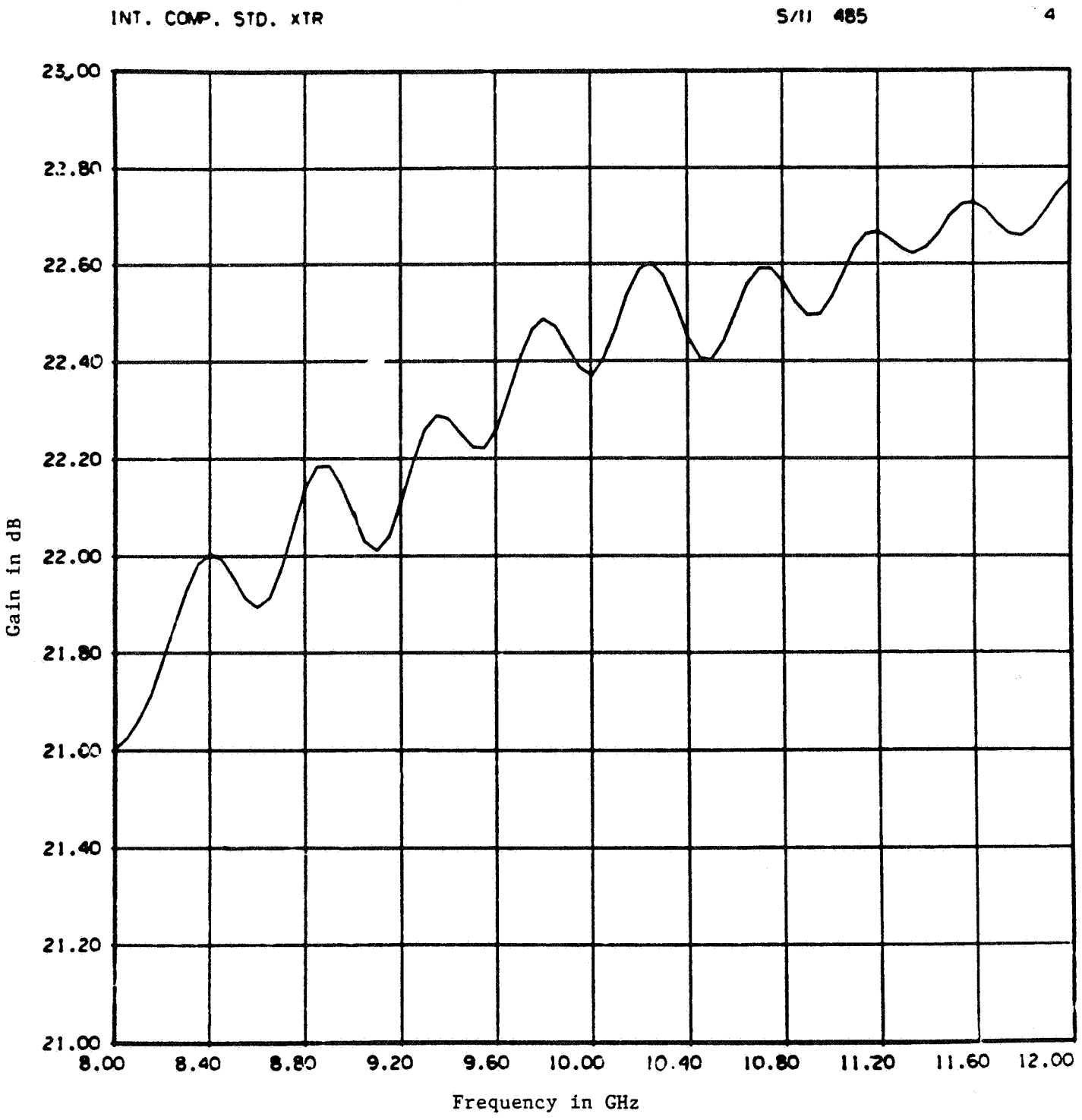

Figure 1. NBS X-Band Horn, Serial No. 485.

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** (See instructions)	1. PUBLICATION OR REPORT NO. NBS/TN-1311	2. Performing Organ. Report No.	3. Publication Date August 1988

4. TITLE AND SUBTITLE

Extrapolation Range Measurements for Determining Antenna Gain and Polarization

5. AUTHOR(S)

Andrew G. Repjar, Allen C. Newell, and Douglas T. Tamura

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The extrapolation range measurement technique for determining the power gain and polarization of antennas at reduced range distances is described. It is based on a generalized three-antenna approach and does not require quantitative a priori knowledge of the antennas. During the past decade, it has been extensively used by the National Bureau of Standards, Boulder, Colorado, to calibrate antenna gain standards for industry and other agencies within ±0.1 dB. To help one understand how calibrations of this accuracy are achieved, the extrapolation range description includes discussions on the required theory, the measurement procedures, the range configuration and instrumentation, the errors, and some measurement examples. Recent extensions of the extrapolation method required for swept/stepped frequency gain calibrations and for corrections to reduce ground reflection effects, are also presented.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

antenna measurements; antenna ranges; antennas; near-field measurements; probe antennas; standard gain horns; swept frequency measurements

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