A Precise Measurement of the Gain of a Large Horn-Reflector Antenna

By D. C. HOGG and R. W. WILSON

(Manuscript received March 24, 1965)

The gain of a horn-reflector antenna with an aperture area of about 400 square feet has been measured with a probable error of 2 per cent at a frequency of 4080 mc. *Errors and fluctuations normally introduced into gain measurements by terrain and other environment were obviated by mounting the source on a helicopter which maintained a position about 2500 ft. above ground at a distance of one mile from the antenna under test. It is concluded that high precision can be obtained in measurement of gain of large antennas using such methods.*

I. INTRODUCTION

The gains of horn-reflector antennas have been measured many times in the past at Bell Telephone Laboratories, usually with the result that the effective area is about 1.5 db below full area. In other words, the measured aperture efficiencies run between seventy and seventy-five per cent.*

Traditionally, such gain measurements employ a source located in the Fraunhoffer region of the antenna to be measured. The field radiated by the source is then sampled at the antenna by taking "height runs" with a standard (or reference) horn. A thorough job involves several height runs at various lateral positions to examine the field over the entire area occupied by the aperture of the antenna. Inevitably, due to the presence of the ground and other environment, variations exist in the field that illuminate the antenna under test. If the measurement is made over the flat ground of an antenna test range, it is possible to apply corrections to the measured gain. However, when large, high-gain antennas are involved, it is difficult to find a sufficiently long range over flat ground. Antenna sites are often surrounded by terrain covered with vegetation, and the radiation from the source located on a tower

* A precise measurement of a horn-reflector antenna recently was made elsewhere.[1]

a mile or so away, being in part scattered from such environment, results in a spatially rough and time-varying field at the antenna under test. The time-varying effect is usually more evident in the relatively small reference (standard) horn because its beamwidth is much larger than that of the antenna under test.

Many of these objectionable features are overcome if the source can be located at an elevation angle of about 20°. Thus, neither the main lobe of the reference horn nor that of the antenna under test intercept the environment, and the measurement proceeds under more or less "free-space" conditions as it must do if one wishes to evaluate the absolute gain with confidence.

For the measurement to be discussed here, a source mounted on a helicopter was used to measure the gain of the 20-foot horn reflector[2] on Crawford Hill, Holmdel, N. J., at the frequency 4080 mc. The principle reason for making this measurement was to provide a reliable value of the effective area which could be used, in turn, for absolute measurement of the flux of extra terrestrial radio sources. Once the flux is known such sources can be used as radiators of known power for evaluating the effective areas of other large antennas at four kmc.

The measurement has resulted in a determination of the gain to within a probable error of 2 per cent. The measured gains for transverse and longitudinal polarization (the principal polarizations of the antenna) are 47.73 and 47.57 db while the calculated full area gain, assuming uniform amplitude and phase over the aperture, is 49.27 db at 4080 mc. Thus, the measured gains are 1.54 and 1.70 db below full area gain for transverse and longitudinal polarization, respectively.

II. DESCRIPTION OF THE METHOD

A block diagram of the equipment used in the measurement is shown in Fig. 1. The 4080-mc source shown schematically in the figure was flown on a helicopter. Two observers, with the aid of a TV camera mounted and boresighted along the beam of the horn-reflector antenna, accurately tracked the source antenna. A reference (standard) horn mounted on the horn reflector, was of course, also automatically beamed toward the source. When the tracking was precise (within ±.05°), the receiver was switched from the horn reflector to the reference horn and the difference in the received levels was read on an output meter. When this result was combined with the measured constants of the system, the gain of the horn-reflector relative to that of the standard horn was obtained.

The 4080-mc signal source consisted of a battery operated crystal controlled 1 mw transmitter in the cab of the helicopter connected by a length of waveguide to a special low-back-lobe radiator suspended in front of the aircraft. The surface of the helicopter nearest the radiator was covered with hair flex absorber so that any backward radiation from the source antenna would not be reflected to interfere with the forward radiation; this effect would result in a ripple in the pattern of the source

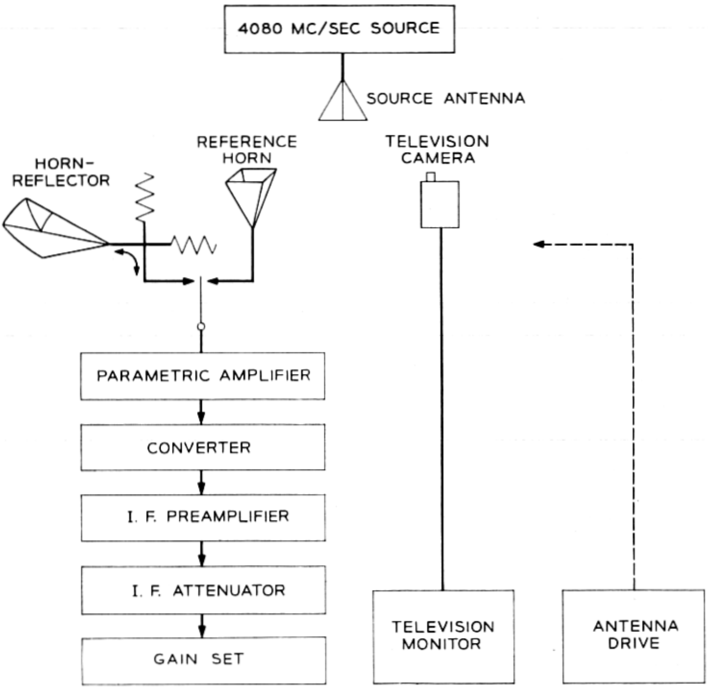

Fig. 1 — Block diagram of measuring system.

horn. The source "horn" consisted of an open ended waveguide near the apex of a pyramidal wooden horn lined with absorbent material and covered on the outside with a fine mesh brass screen. This "lossy horn" was moved along the waveguide to a position which produced the flattest pattern over the central portion of the main beam.* In a test (before installation on the aircraft), four by four-foot sheets of metal placed anywhere behind the lossy horn arrangement were found to produce total changes of only 0.2 db in its gain.

* A helicopter can not maintain an absolutely steady orientation; thus it is necessary to have an essentially flat source pattern.

The reference horn attached to the horn-reflector antenna was a (nominally) 20-db gain pyramidal horn; its performance is described in detail in Ref. 3. The reference horn was connected by a long run of waveguide to a waveguide switch inside the cab and could be mounted to receive either of the two polarizations used for the measurement. The output of the horn reflector was also connected to the waveguide switch through appropriate waveguide including a 31-db directional coupler used as an attenuator. The output of the switch was connected to the receiver by cable. The loss of the various waveguide runs was obtained by measuring the VSWR with a short circuit at the end of the line; the attenuation of the directional coupler was measured carefully by several substitution methods.

The receiver used a 2-stage parametric amplifier for its front end which provided a signal to noise ratio of more than 20 db. The paramp was followed by a converter and IF amplifier which fed through an IF attenuator into a measuring set. One 3-db step of this IF attenuator was carefully calibrated with precision attenuators. By switching in this attenuator at the same time that the input to the receiver was switched from the horn reflector to the reference horn, the signal level at the gain set remained essentially constant, and the difference could be read on the expanded scale of an output meter to within 0.01 db; it was recorded as the nearest tenth db.

III. RESULTS

The distributions of measured level differences between the signals received by the horn-reflector and the reference horn are shown in Fig. 2 for both planes of polarization. A measurement with a higher level for the horn reflector is plotted with a positive abscissa, R. The meaning of the terms "transverse polarization" and "longitudinal polarization" is given in Fig. 3.

The medians of both distributions have been found as well as the range which has a 99 per cent chance of including the true value. These results are given in Table I.

To convert the numbers in Table I to the corresponding gains of the horn reflector we need the following additional constants of the system, given in decibels in Table II. (For an explanation of the last two columns, see the next section, which discusses accuracy and corrections.) From the equation:

$$G_{HR} = G_{RH} + L_{HR} + L_{DC} - L_{RH} - L_{IF} + \bar{R} - C_{SNR} + C_{NF}$$

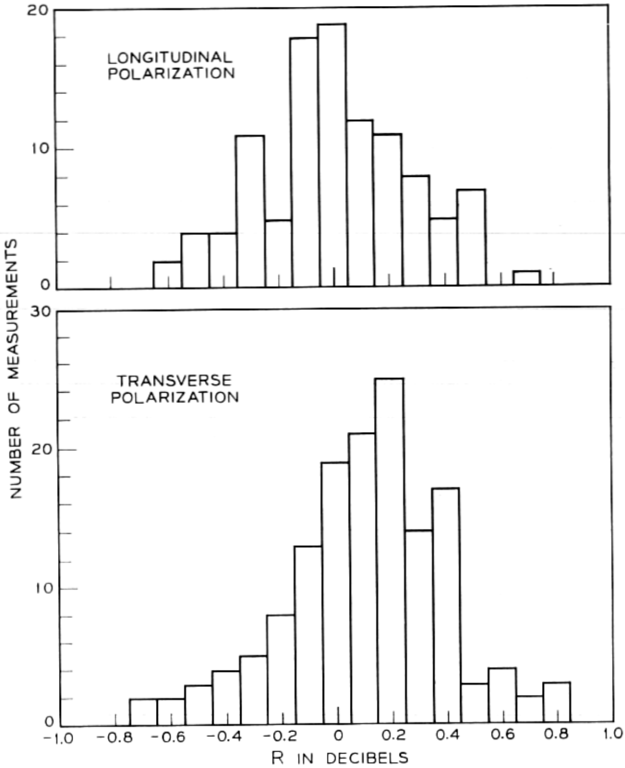

Fig. 2 — Distribution of measured data.

where all quantities are in db and $\bar{R}$ is the median value given in Table I, the measured gain of the horn-reflector is obtained:

$$\text{Longitudinal Pol.} \quad G_{HR} = 47.57 \text{ db}$$

$$\text{Transverse Pol.} \quad G_{HR} = 47.73 \text{ db}$$

IV. ACCURACY OF RESULTS AND CORRECTIONS

The known sources of error in the gain measurement are listed in Table III along with the corresponding maximum error for each.

The first three errors are lumped together in this list because their combined effect gives the scatter in the observed data (Fig. 3). The maximum error given in Table III is the average of the deviations of the 99 per cent confidence limits from their corresponding median as given in Table I.

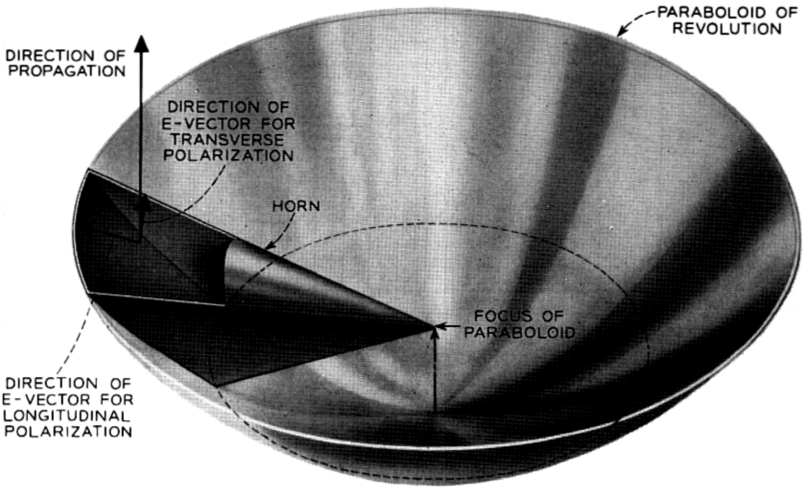

Fig. 3 — Directions of the two planes of polarization for a horn-reflector antenna.

The gain measurements were made with the helicopter at a slant range of about 5000 feet or 3 D^2/λ, D being the aperture dimension. The unusual shape and illumination of the aperture of the 20-foot horn-reflector make the usual calculations of the effect of phase error inapplicable, so the gain reduction at this range was calculated using formulas similar to those used in Ref. 2. This reduction amounts to 0.037 db in longitudinal polarization and 0.036 db in transverse. These corrections have been entered as C_{NF} in the calculation of gain above, and the uncertainty in the values due to changes in distance of the helicopter, and phase errors in the antenna is shown in Table III.

During the gain measurement the signal to noise ratio when the receiver was switched to the horn reflector was about 20 db. In this condition the noise of the parametric amplifier ($\approx$1.7 db noise figure including the input cable) was increased by the noise from the room temperature load (300°K) in the 31-db directional coupler (Fig. 1) used to approximately equalize the received signal levels. When switched to

Table I

Polarization	Number of Measurements	Median	99% Confidence Limits	
			Upper	Lower
Longitudinal	107	0.00 db	+0.092 db	−0.078 db
Transverse	145	+0.129 db	+0.206 db	+0.040 db

TABLE II

Polarization	Gain of Ref Horn G_{RH} (db)	Trans. Line & Switch Loss Horn Refl. L_{HR} (db)	Directional Coupler in Horn Refl. Line L_{DC} (db)	Trans. Line & Switch Loss Ref. Horn L_{RH} (db)	I.F. Attenuation Used While Switched to Reference Horn L_{IF} (db)	Median Level Difference $\overline{R}$ (db)	Correction for Change in Signal to Noise Ratio C_{SNR} (db)	Near Field Correction C_{NF} (db)
Longitudinal	20.11	0.11	31.10	0.75	3.00	0.00	0.04	0.04
Transverse	20.11	0.15	31.10	0.76	3.00	0.129	0.04	0.04

the reference horn, however, the noise added to that of the parametric amplifier was only 120°K, rather than 300°K, since that horn looks toward the cool sky. In addition the signal from the reference horn was about 3 db stronger than the signal from the horn reflector. These considerations result in a 0.04 db correction to the measured gain (C_{SNR}) with an uncertainty as listed in Table III.

The directional coupler used to equalize the signals from the two antennas was measured at Bell Telephone Laboratories by the Calibration Service of the National Bureau of Standards and by Weinschel Engineering Co. The results were 31.17 ± 0.1 db, 35.10 ± 0.3 db, and 35.04 ± 0.03 db respectively. In all cases the ranges given are "limit of error". The mean of 31.10 will be used with a limit error of ±2 per cent.

Line and switch losses (L_{HR} and L_{RH}) were obtained by measuring the standing wave ratio with a short circuit at the end of the line. The uncertainty quoted in Table III allows for errors in the calibration of the IF attenuator used in making the SWR measurements and random errors in the measurement.

TABLE III

Maximum Error	Source of Error
1.9%	Reading Meter Re-orientation of source during measurement Inaccurate pointing of the horn-reflector
1.0%	Uncertainty in near field correction
1.0%	Signal to noise ratio uncertainty
	Uncertainty in the attenuation of components
2.0%	Directional Coupler
0.7%	Line and switch losses
0.5%	IF attenuator
0.7%	Uncertainty in gain of reference horn
2.8%	Mismatch of parametric amplifier

The IF attenuator has been compared with standard attenuators and the error listed in Table III is the uncertainty in the standards.

The measurement of the gain of the reference horn is discussed in Ref. 3. The pertinent error is made up of two parts: random errors and the error in a standard attenuator. This same attenuator was used in the Bell Telephone Laboratories measurement of the 31-db directional coupler. Therefore a correlation between the error in the standard horn measurement and the error in the Bell Telephone Laboratories value of the attenuation of the directional coupler used in the horn-reflector gain measurement is expected. The correlation, however, is in the sense of reducing the total error, so by treating the errors as random we are being conservative.

The question of correlation of errors might be asked in relation to all of our attenuation measurements since, except for the directional coupler, they are based entirely on Bell Laboratories attenuation standards which may have common origins of error of which the present authors are unaware. We therefore show in Table IV the effect of a 1 per cent error in attenuation scale for each of the terms involved in measurement of the gain of the horn reflector. However, it is not suggested that such large errors exist. What is shown in the table is measured gain minus true gain and the error assumed is in the sense that a standard attenuator labeled 20 db would actually have 20.2-db attenuation. It is seen from the table that the errors tend to cancel and it is acceptable to treat them as independent.

The last source of error shown in Table III is an unknown interaction of the mismatch of the reference horn with the input impedance of the receiver. The magnitude of this effect was not realized until after the measurement had been made and it was not possible to correct for it precisely. The maximum error of 2.8 per cent is derived from measurements made on the parametric amplifier just prior to the antenna gain measurement, taking into consideration the impedance of its connection to the switch and the impedance of the reference horn. The match of the components in the horn-reflector line was good enough that no significant uncertainty was introduced by them.

Taking the square root of the sum of the squares of all but the last error in Table III, one obtains a total (99 per cent confidence) limit

Table IV

Transmission Lines	Directional Coupler	IF Atten.	Reference Horn
−.013	−0.31	+0.03	+0.05

error of 3.3 per cent. Adding 2.8 per cent for the mismatch error we have a total (maximum) uncertainty in the gain of 6.1 per cent which corresponds to a probable error of about 2 per cent.

V. COMPARISON OF THE MEASUREMENT WITH THEORY AND EVALUATION OF SPILLOVER LOSS

The gain of the horn-reflector antenna at 4080 mc, when calculated by the method discussed in Ref. 2, results in gains of 48.16 db and 48.23 db for longitudinal and transverse polarization respectively. This calculation assumes that the dominant mode in the feed waveguide is preserved in the horn and is based on the projection of that mode into the aperture plane, i.e. the gain degradation due to spillover (significant only in longitudinal polarization) is neglected.

The calculated gain values can be corrected for the loss of energy in the spillover lobe (discussed in Ref. 2). Consider the equation for conservation of energy in an antenna pattern. If $G(\theta,\varphi)$ is the gain of the antenna in the direction specified by the angles θ,φ and $d\Omega$ is the differential of solid angle:

$$\iint_{\text{sphere}} G(\theta,\varphi)\, d\Omega = 1$$

Since the main-lobe region of the antenna pattern is distinct from the spillover region for horn-reflector antennas, this integral can be broken into two parts:

$$\iint_{\substack{\text{main-lobe}\\ \text{region}}} G(\theta,\varphi)\, d\Omega = 1 - \iint_{\substack{\text{spillover}\\ \text{region}}} G(\theta,\varphi)\, d\Omega$$

Because of the geometry of the antenna, the shape of the pattern in the region of the main lobe is essentially undisturbed by the presence of spillover, so the maximum gain will be reduced by the factor

$$1 - \iint G(\theta,\varphi)\, d\Omega$$

In order to make this correction to the calculated gain, the antenna pattern (longitudinal polarization) was measured in the spillover region. A source was mounted on a tower about 2 miles away ($\approx 6D^2/\lambda$) and the antenna was swept in azimuth at constant elevations. Ten unequally spaced scans were made covering 35° in elevation. On each scan the response was averaged over a degree or two and a contour map was drawn from the scans (Fig. 4). The lower elevation scans were

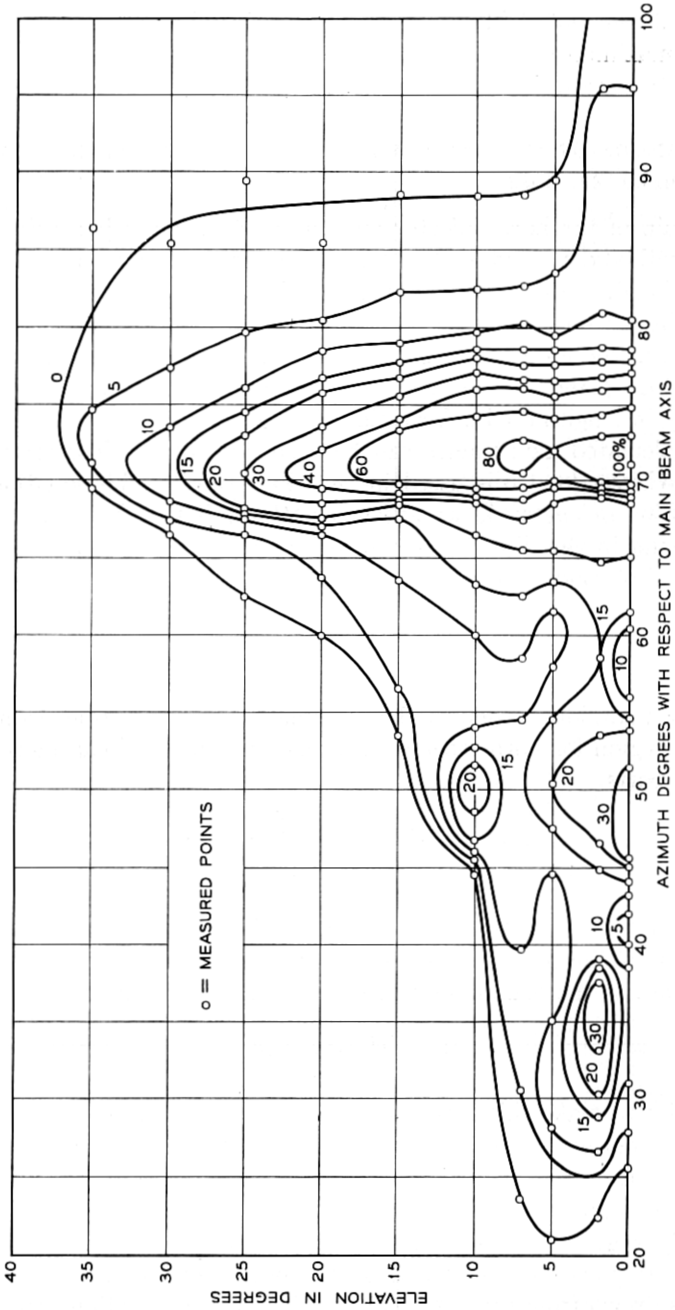

Fig. 4 — Contour map of spillover region.

checked for reflections from the environment into the main beam by inverting the antenna (which orients the main beam in a different direction) and repeating the scan through the same section of the spillover region; no significant difference was found.

The contour map was then divided into elevation zones and integrated with a planimeter. The resultant value of the integral over the full spillover lobe was 5.4 per cent of total power; this corresponds to a 0.23-db decrease in gain in longitudinal polarization.*

These results are summarized in Table V.

VI. REMARKS

A method of measuring the gain of a moderately large antenna (dimension $\approx 80\lambda$) at 4 gc, using a source mounted on a helicopter in order to minimize environmental effects, has proven accurate to within a probable error of 2 per cent ($\approx$0.09 db) and, with knowledge gained from this experience, could now be repeated with a probable error of about 1 per cent. The method would, however, be expected to prove somewhat less accurate for much larger antennas due to the increased altitude required and resultant instability of the aircraft under such conditions. Specifically, the gain of the 20-foot horn-reflector antenna has been found to be 1.70 and 1.54 db below full area gain (efficiencies 68 and 70 per cent) for longitudinal and transverse polarizations respectively. Recent measurements on radio sources (Ref. 4) have resulted in a value of 0.21 db for the difference in gain for the two polarizations; this compares favorably with the 0.16 db obtained using the aircraft-borne source.

Table V

	Longitudinal	Transverse
Full area gain	49.27	49.27
Computed gain	48.23	48.16
Spillover correction	0.23	0.00
Theoretical gain	48.00	48.16
Measured gain	47.57	47.73
Difference	0.43	0.43

VII. ACKNOWLEDGMENT

We thank the numerous people who actively participated in the design, calibration and operation of the experiment.

* In transverse polarization the spillover lobe is found to be negligible.

REFERENCES

1. Jull, E. V., and Deloli, E. P., IEEE Trans., *AP-12*, July, 1964, p. 439.
2. Crawford, A. B., Hogg, D. C., and Hunt, L. E., B.S.T.J., *40*, July, 1961, p. 1095.
3. Chu, T. S., and Semplak, R. A., B.S.T.J., *44*, March, 1965, p. 527.
4. Penzias, A. A., and Wilson, R. W., The Astrophysical Journal, to be published.