Design of Microwave Gain-Standard Horns

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Reprinted from ELECTRONICS, July 1955

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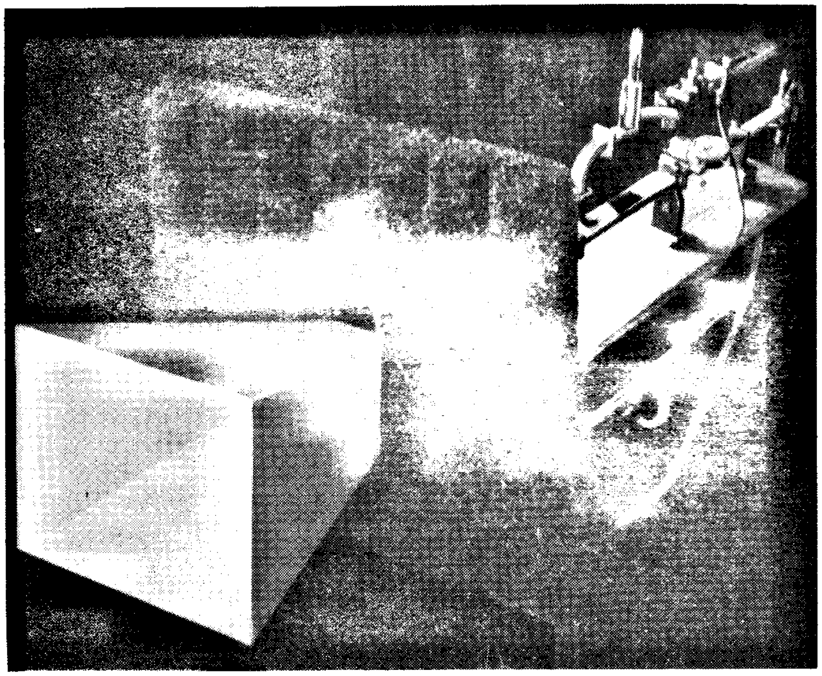
Design of Microwave

SUMMARY —— Electromagnetic horns for the microwave region from 0.77 cm to 31.5 cm have been built and calibration techniques perfected. Resulting designs are easily and accurately duplicated and have been adopted as standards by the Inter-Service Antenna Group



Horn and transmitter on adjustable mount. Microwave absorbent material reduces wave reflections inside horn

SOME time ago a program was initiated at the Naval Research Laboratory to design and calibrate a series of gain-standards covering the microwave region from a wavelength of 0.77 cm to 31.5 cm. The present paper is based on an NRL report.

The series of gain-standards consists of eleven broadband horns having gains ranging from 24.7 db to 13.7 db. The horns can be easily and accurately duplicated.

Criteria

Electromagnetic horns were considered well suited as gain-standard antennas because they are broadband, rugged and easily duplicated. However, previous attempts to obtain accurate horn calibrations had shown marked discrepancies in the measured gain obtained at various horn-separation distances.

The usual criterion for minimum horn-separation distance had been $2D^2/\lambda$ where D is the larger aperture dimension of the horn and λ is the wavelength. This criterion was shown to be invalid. A new criterion was developed[2] which resolved previous inconsistencies and formed the basis for a set of curves correcting for finite separation between horns.

Three general requirements were considered of prime importance in the design: a useful gain figure; a simple construction; and accuracy of calibration. Because of size and weight considerations, the horns were not scaled from band to band throughout the range. Instead, five basic designs were used and the horns for each of the other bands were scaled from one of these.

Design

A nearly optimum horn was desirable to obtain the maximum gain consistent with size limitations. An optimum horn has aperture dimensions chosen to give maximum gain for a fixed slant height. This is the case when $a^2 \cong 3.18\ \lambda l_H$ and $b^2 \cong 2.08\ \lambda l_E$ where a, b, l_H and l_E refer to dimensions shown in Fig. 1. Approximately equal half-power beamwidths for the radiation patterns in the two planes was another desirable characteristic. The theoretical criterion for equal beamwidths is that $a = 1.35b$. This assumes an in-phase aperture with the electric field intensity constant in the E-plane and varying cosinusoidally in the H-plane.

Schelkunoff's gain curves[3,4] were used in determining the horn dimensions for the desired gain, equal beamwidth and optimum horn requirements. A final determination of the calculated gain was obtained by using the formulas from which the Schelkunoff curves were plotted.

The fabricated type of pyramidal horn shown in Fig. 1 was chosen as the best means of satisfying the requirements. For simplicity a simple butt-joint between horn and waveguide was adopted. Most of the horns are made of flat brass sheets. Exceptions are the 8-mm electroformed horn and the 15, 23, and 30-cm horns which are made of welded aluminum sheets.

A typical horn construction drawing is shown in Fig. 2. Design and

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construction data are given in Table 1.

Calibration

Using the setup shown in Fig. 3, experimental primary gain measurements were made to check the accuracy of the calculated gain. The formula for the experimental determination of gain is

$$G = \frac{4\pi R}{\lambda}\sqrt{\frac{P_R}{P_T}}$$

where R is the separation distance between horns, λ is the wavelength and P_R/P_T is the ratio of power received to power transmitted. Two identical matched horns separated by a distance R were used, one acting as the transmitting antenna and the other as the receiving antenna.

The r-f source was a reflex klystron with 1,000 cycle square-wave modulation. Attached to the receiving horn at point A' in Fig. 3, was a matched bolometer-detector which delivered the detected voltage to a linear amplifier connected to a vacuum-tube voltmeter.

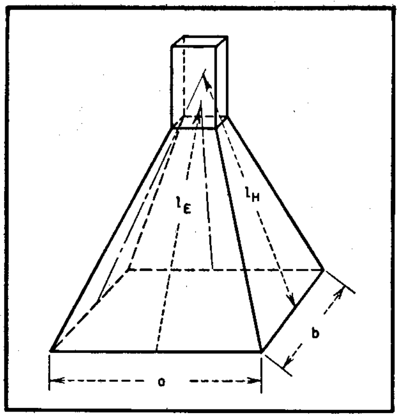

FIG. 1—Physical dimensions of horn used for calculating gain. Butt joint is used between horn and waveguide

The horn and associated r-f components at both the transmitting and receiving ends were mounted on tripods so that each horn could be peaked in azimuth and elevation for maximum received power.

The voltmeter reading was proportional to the received power P_R, for this measurement since a bolometer-detector is a square-law device. To obtain a voltage reading proportional to the transmitted power P_T, the transmitting horn was removed and the receiving detector connected at A in Fig. 3.

Unusual care was necessary in making these measurements. The separation distance R was varied frequently and the measuring procedure was repeated several times at each new distance. The horns and the bolometer were carefully matched at each frequency.

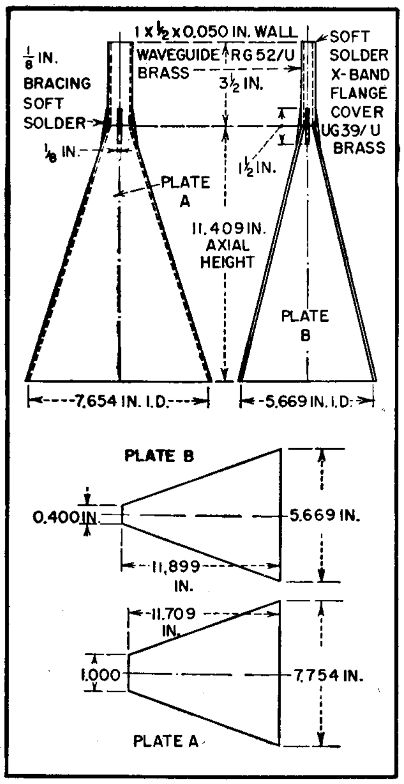

FIG. 2—Typical construction drawing for a gain-standard horn. Plates are made from 0.50 in. sheet brass

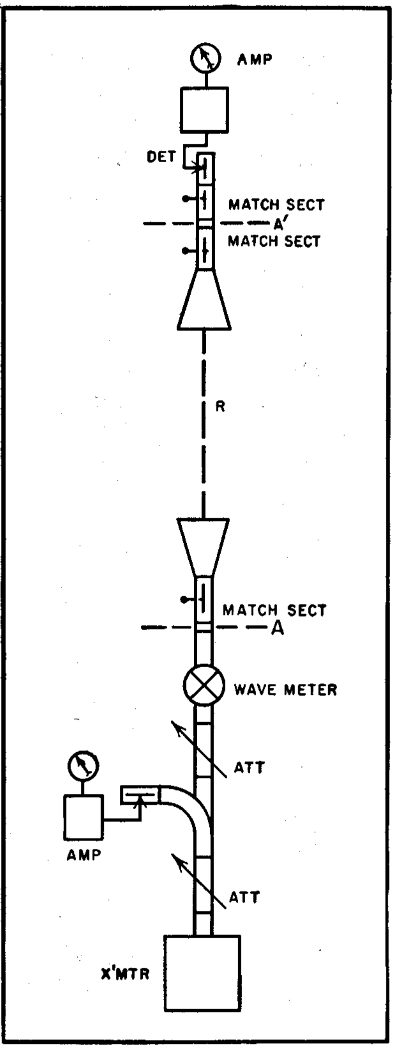

FIG. 3—Experimental setup for gain measurements

Microwave absorbent material[5], shown in the photograph, was used to minimize the reflections. At longer wavelengths difficulties were encountered because of reflections and the large separation distances required. True Fraunhofer field (far-field) conditions which are assumed in deriving the gain formula, do not exist until a horn-separation-distance of many times the magnitude of $2D^2/\lambda$ is attained[8].

The effectiveness of the absorbent material is a function of wavelength, the absorbing power diminishing as the wavelength is increased. At wavelengths longer than in the 6-cm band there is sufficient reflection to virtually preclude making accurate gain measurements. The absorption is still adequate for most other purposes at considerably longer wavelengths.

Because of the difficulties mentioned, experimental gain measurements at 10 cm and longer wavelengths were abandoned. The 10-cm horn calibration was obtained from that of the 3.95-cm and 6-cm horns. The latter were scaled from the 10-cm horn to obtain reliable measurements at the shorter wavelengths.

Measurements were made over the range of the band for the 1.8-cm, 3.2-cm and 6-cm horns, since these represent the three basic horn designs from 8 mm to 10 cm inclusive (see Table 1). Several measurements were also made at the 3.95-cm band, taking advantage of the scaling to get a cross-check on the 6-cm horn calibration. Similarly, a measurement was made at 1.25 cm as a check on the 1.8-cm horn at the scaled wavelength of 1.87 cm. These comparisons of the measured gain for horns scaled from one band to another showed good agreement (see Fig. 4 and 5).

Accuracy

At any one wavelength the measured points showed a dispersion of less than 0.1 db. As a function of wavelength, the gain curve is not monotonic as would be predicted from the theory, but shows small periodic variations, as in Fig. 5. After exhaustive checking it is felt that these variations, of the order of ±0.1 to 0.2 db, are actually present and not due to experimental difficulties. This effect can probably be attributed to higher modes in the aperture, and currents on the outside of the horn, both of which are neglected in the theory. Taking into account all possible deviations from the true gain over each band, the maximum possible error was less than ±0.3 db up to and including the 10-cm horns.

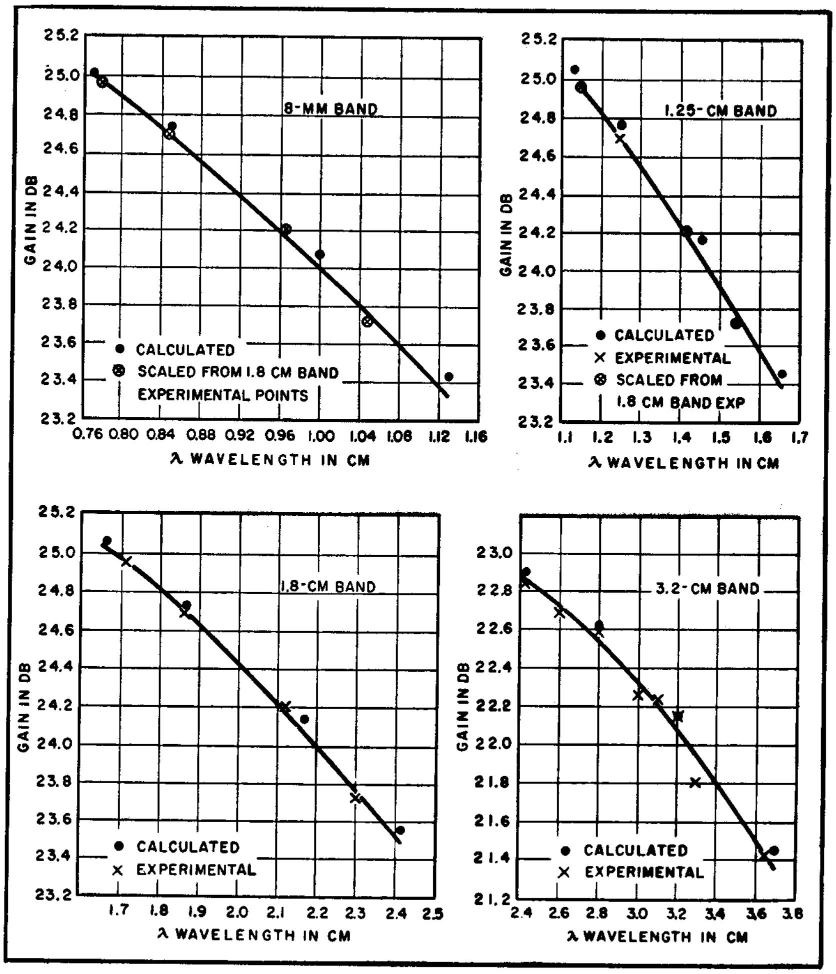

FIG. 4—Gain curves for gain-standard horns in the 8-mm, 1.25-cm, 1.8-cm and 3.2-cm bands. Comparisons of measured gain for hours scaled from one band to another show good agreement

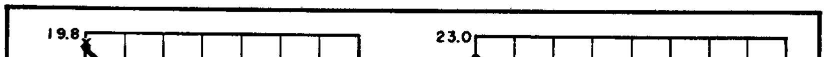

FIG. 5—Gain curves for gain-standard horns in the 3.95-cm, 4.75-cm, 6-cm and 10-cm bands. Variations in curves are not due to experimental difficulties

At wavelengths longer than 10 cm, where no experimental measurements have been feasible, the gain has been calculated by means of Schelkunoff's formula. Below 10 cm the greatest discrepancy between the average measured gain (using Braun's correction curves for near-field conditions) and the gain calculated from Schelkunoff's formula was of the order of 0.2 db. In general the difference was much less. Because of the infeasibility of making experimental checks a maximum tolerance of ±0.5 db is reasonable for all horns above the 10-cm band (see Fig. 6).

VSWR

The greatest voltage-standing wave ratio encountered in horn measurements made over the band at four representative bands was 1.25. In any event the vswr should be measured at the wavelength used. For accurate measurements the horns should either be carefully matched or allowance should be made for any mismatch. In either case the bolometer must be well-matched.

Error Sources

Obtaining an accurate gain measurement requires that a number of precautions be observed. Instability is one of the greatest problems. The r-f source should be carefully selected for stability of both frequency and power output. The bolometer amplifiers and vacuum-tube voltmeters must also be very stable. Rigid waveguide, rather than flexible cables, should be used in the r-f transmission line. Adjustable bolometer holders and variable attenuators should have a stable adjustment.

Flange-to-flange connections rather than choke-to-flange, should be used, since chokes may introduce considerable mismatch at some wavelengths. The bolometer amplifiers should be checked for linearity throughout the range used and both the amplifiers and the voltmeters should be accurately calibrated.

Power Level

The power level was kept low enough to maintain amplifier linearity. This restriction limited the maximum horn-separation distance, so that measurements were made at distances of three or four times D^2/λ. Corrections were required be-

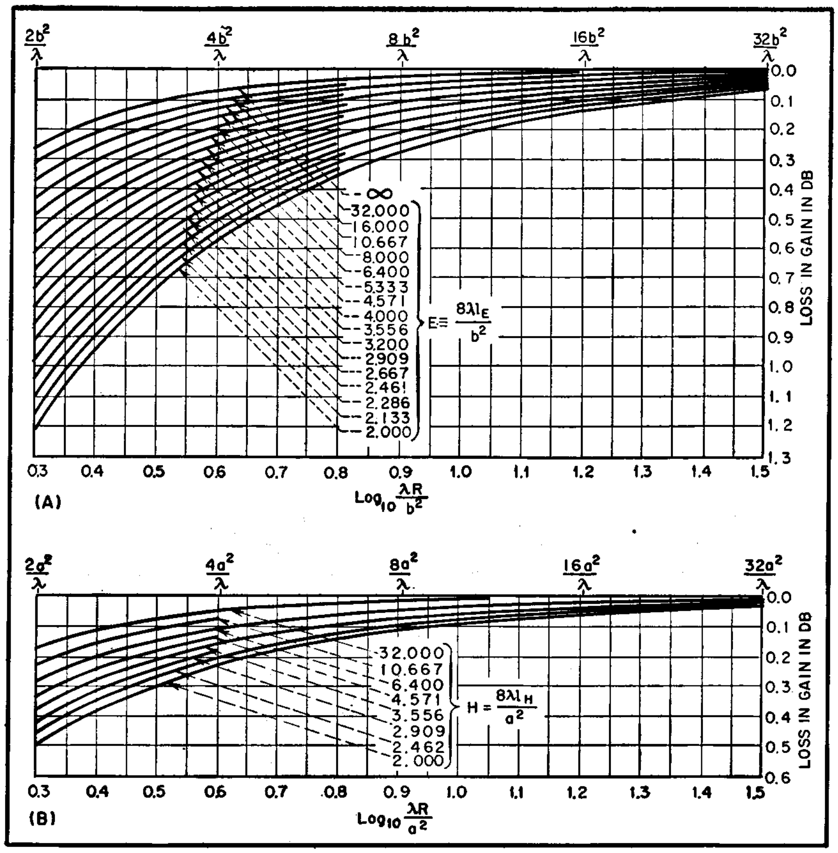

FIG. 7—Braun's E- and H-plane correction curves

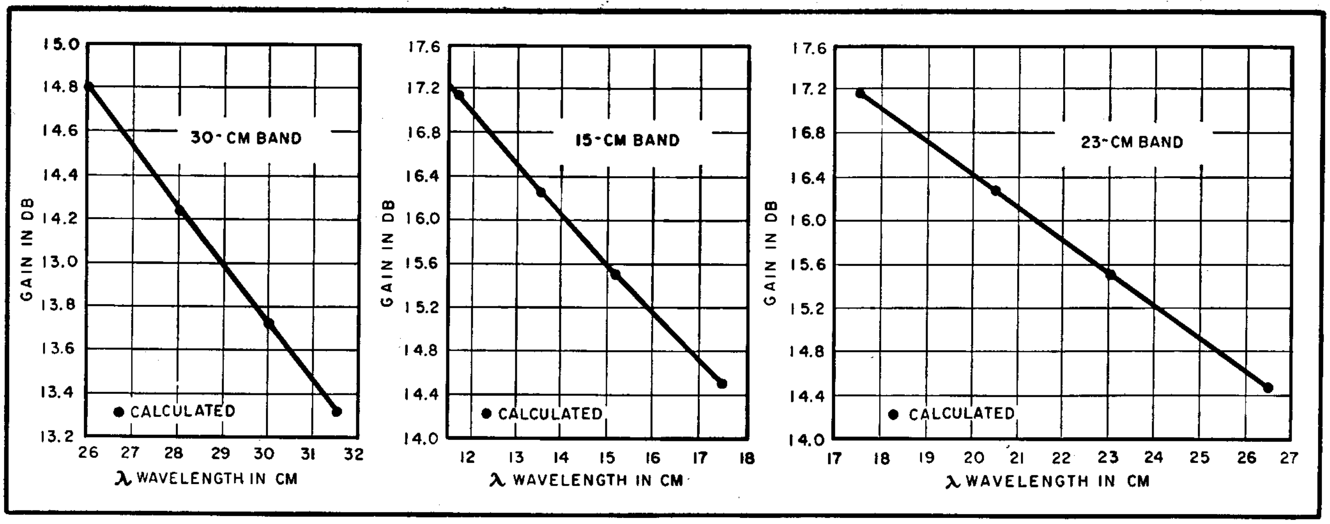

FIG. 6—Gain curves for gain-standard horns in the 15-cm, 23-cm and 30-cm bands

Table I—Summary of Gain-Standard Horn Data

Band	Dimensions (I. D.) See Fig. 1	Plate Data					Waveguide		Axial Length to Wave-guide	Over-all Length	Design Point Frequency	Gain at Design Point (db)
		Plate	Large End	Small End	Length	Material	Size (O.D.)	Flange				
8 mm	$a = 2.720$ $b = 2.231$	......	....	....	....	....	0.360×0.220	UG-381/U	....	6.46	0.85 cm	24.7
	$l_H = 6.513$ $l_E = 6.197$	Electroformed; details not shown					RG-96/U				35,290 mc	
1.25 cm	$a = 4.000$ $b = 3.281$	A	4.080	0.500	8.641	0.040	0.500×0.250	UG-117/U	8.500	11.2	1.25 cm	24.7
	$l_H = 9.706$ $l_E = 9.113$	B	3.281	0.170	8.688	Brass	RG-53/U				24,000 mc	
1.8 cm	$a = 5.984$ $b = 4.908$	A	6.064	0.702	12.769	0.040	0.702×0.391	UG-420/U	12.560	15.6	1.87 cm	24.7
	$l_H = 14.333$ $l_E = 13.633$	B	4.908	0.311	12.843	Brass	RG-91/U				16,040 mc	
3.2 cm	$a = 7.654$ $b = 5.669$	A	7.754	1.000	11.709	0.050	1.000×0.500	UG-39/U	11.409	14.9	3.20 cm	22.1
	$l_H = 13.484$ $l_E = 12.598$	B	5.669	0.400	11.899	Brass	RG-52/U				9,375 mc	
4.75 cm	$a = 11.360$ $b = 8.415$	A	11.485	1.497	17.318	1/16	1.500×0.750	UG-344/U	16.874	20.4	4.75 cm	22.1
	$l_H = 20.014$ $l_E = 18.700$	B	8.415	0.622	17.597	Brass	RG-50/U				6,315 mc	
3.95 cm	$a = 5.041$ $b = 3.733$	A	5.166	1.247	5.682	1/16	1.250×0.625	UG-51/U	5.447	9.45	3.95 cm	18.0
	$l_H = 7.447$ $l_E = 6.555$	B	3.733	0.497	5.789	Brass	RG-51/U				7,595 mc	
6 cm	$a = 8.507$ $b = 6.300$	A	8.632	1.997	9.531	1/16	2.000×1.000	UG-149A/U	9.136	13.1	6.67 cm	18.0
	$l_H = 12.462$ $l_E = 11.062$	B	6.300	0.872	9.720	Brass	RG-49/U				4,500 mc	
10 cm	$a = 12.760$ $b = 9.450$	A	12.95	3.00	14.24	3/32	3.000×1.500	UG-214/U	13.65	20.7	10.00 cm	18.0
	$l_H = 18.682$ $l_E = 16.593$	B	9.45	1.34	14.52	Brass	RG-48/U				3,000 mc	
15 cm	$a = 14.508$ $b = 10.747$	A	14.508	4.300	11.285	3/32	4.460×2.310	UG-437/U	10.43	14.4	15.22 cm	15.5
	$l_H = 16.508$ $l_E = 14.107$	B	10.747	2.150	11.616	Alum.	RG-105/U				1,970 mc	
23 cm	$a = 21.931$ $b = 16.245$	A	21.931	6.500	17.059	1/8	6.660×3.410	UG-418/U	15.77	21.8	23.00 cm	15.5
	$l_H = 24.955$ $l_E = 21.325$	B	16.245	3.250	17.559	Alum.	RG-103/U				1,300 mc	
30 cm	$a = 21.931$ $b = 16.245$	A	21.931	7.700	18.312	1/8	7.950×4.100	10"x6"x3/8"	17.23	23.2	30.00 cm	13.7
	$l_H = 28.730$ $l_E = 24.000$	B	16.245	3.850	18.643	Alum.	RETMA WR-770				1,000 mc	

Horns in each bracket have essentially same design in terms of wavelengths

Plate tolerances

1.25–6 cm: ±0.005 in.
10–30 cm: ±0.015 in.

All dimensions in inches

cause of the near-field conditions.

The procedure for determining the true Fraunhofer (far-field) gain from the primary gain test data, using Braun's near-field correction curves, Fig. 7A and B is shown in the following example: See Fig. 1 and Table I

3.2-cm band horn dimensions:

$a = 7.654$ in. $\quad l_H = 13.484$ in.
$b = 5.669$ in. $\quad l_E = 12.598$ in.

Parameters for using the gain formula:

$$\lambda = 3.20 \text{ cm} = 1.2598 \text{ in.}$$

$$R(\text{distance between horns}) = 140.25 \text{ in.}$$

$$\frac{4\pi R}{\lambda} = \frac{(12.566)(140.25)}{1.2598} = 1398.94$$

From test data:

$$\frac{P_T}{P_R} = \frac{11.3}{0.123} = 91.87; \quad \sqrt{\frac{P_T}{P_R}} = 9.585$$

$$\text{Uncorrected Gain} = \frac{4\pi R}{\lambda} \Big/ \sqrt{\frac{P_T}{P_R}} = \frac{1398.94}{9.585} = 145.95$$

$$10 \log 145.95 = 21.64 \text{ db}$$

Parameters for using the correction curves:

E-plane, Fig. 7A

$$\frac{8l_E}{b^2} = \frac{(8)(12.598)}{32.1376} = 3.1360$$

$$\left.\begin{aligned} E &= \left(\frac{8l_E}{b^2}\right)\lambda \\ &= (3.1360)(1.2598) \\ &= 3.951 \\ \log\frac{\lambda R}{b^2} &= \log\frac{(1.2598)(140.25)}{32.1376} \\ &= \log 5.498 = 0.740 \end{aligned}\right\} \text{0.22 db correction}$$

H-plane (Fig. 7B):

$$\frac{8l_H}{a^2} = \frac{(8)(13.484)}{58.5837} = 1.8413$$

$$\left.\begin{aligned} H &= \left(\frac{8l_H}{a^2}\right)\lambda \\ &= (1.8413)(1.2598) \\ &= 2.320 \\ \log\frac{\lambda R}{a^2} &= \log\frac{(1.2598)(140.25)}{58.5837} \\ &= \log 3.016 = 0.479 \end{aligned}\right\} \text{0.28 db correction}$$

Reading from the correction curves as detailed above:

E-plane correction	0.22 db
H-plane correction	0.28 db
Total correction	0.50 db
Uncorrected gain	21.64 db
Corrected gain	22.14 db

The calculated gain, using Schelkunoff's gain formula, in this case was the same. Note that the separation distance R, was approximately $3D^2/\lambda$, and the required correction at this distance was not small.

Consistently good agreement was obtained between measurements made at different distances using the correction curves.

A series of microwave gain-standard horns has now been built which incorporates the following desired characteristics: a useful value of gain; broad-band coverage; accurate calibration; reasonable size; ease of duplication.

Improved techniques have resulted in an accuracy of gain measurement which was not possible previously.

The author wishes to express his appreciation to E. H. Braun for his advice and cooperation and to F. W. Lashway for his suggestions and drawings

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