NRL Report 4433

DESIGN AND CALIBRATION OF MICROWAVE ANTENNA GAIN STANDARDS

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November 9, 1954

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Washington, D.C.

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ABSTRACT

A set of antenna gain-standard horns covering the microwave range from 0.77 cm to 31.5 cm has been designed and carefully calibrated. The horn fabrication is simple and can be duplicated accurately from the drawings supplied. A simple method of extending and improving the accuracy of Schelkunoff's gain curves is also described.

PROBLEM STATUS

This is a final report on this phase of the problem; work on the problem is continuing.

AUTHORIZATION

NRL Problem R09-03
Project NR 689-030

Manuscript submitted September 2, 1954

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INTRODUCTION

The need for accurate and practical microwave antenna gain standards has led to the design and calibration of a series of pyramidal horns covering the microwave bands from 0.77 cm to 31.5 cm. The series consists of eleven broadband horns having gains ranging from 24.7 db to 13.7 db. There is a horn for each waveguide size in the range. The horns can be easily and accurately duplicated from drawings supplied in this report.

DESIGN

Three requirements were considered of prime importance in the design: a useful gain figure, simplicity of construction, and accuracy of calibration. The fabricated type of horn (Fig. 1), with flat metal sheets forming the sides, was decided upon as the best means of satisfying the construction requirements. For simplicity, the horns were designed so that the E- and H-plane flares meet the waveguide in a common plane.

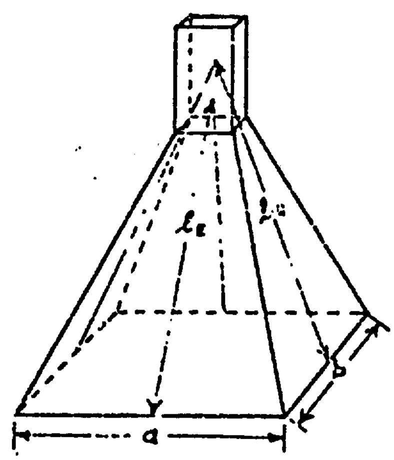

Fig. 1 - Physical dimensions for calculating the gain

Another consideration was the over-all size and weight. It was impractical to scale the horns from one band to another throughout the range, since the horns at the longer wavelengths would be too large and those at the shorter wavelengths too small. Accordingly, there are five different designs; each of the other six horns was scaled from one of these.

The 8-mm and 1.8-cm horns were scaled from the 1.25-cm horn; the 4.75-cm horn from the 3.2-cm horn; the 3.95-cm and 6-cm horns from the 10-cm horn; and the 15-cm horn from the 23-cm horn. In scaling, the values of ℓ_H had to be altered slightly in order to make a simple junction at the waveguide. This was necessary because, with one or two exceptions, the inside dimensions of the waveguides are not scaled from one band to another. The adjustment made only a very slight change in the calculated gain (about 0.02 to 0.03 db).

The 3.95-cm horn represents an overlapping of the 3.2-cm band and the 4.75-cm band. However, it was decided to include this horn in the series because it fits a standard waveguide size (1.250 x 0.625 in. O.D.) and it provided an opportunity to make experimental checks on the 10-cm horn from which it is scaled.

The basic design data including the dimensions, operating range, and design-point gain for all the horns are summarized in Table A-2.*

Readers who are interested in a detailed design procedure are referred to the Appendix, where a simple means of extending the range of Schelkunoff's gain curves and improving the accuracy of the gain figure obtainable from them is described. This method eliminates the necessity for long computations involving Fresnel integrals, and yields very close agreement with the detailed calculations.

CONSTRUCTION

As mentioned previously, the fabricated type of horn using flat metal sheets was decided upon as most suitable. The one exception is the 8-mm design, where electroforming was considered necessary because of the small size and close tolerances. Horns for the bands from 1.25 cm to 10 cm were made of brass sheets. At the 15-, 23-, and 30-cm bands, horns were fabricated from sheet aluminum using helium gas to facilitate welding the joints (heliarc process). This construction reduced the weight considerably and was found to be satisfactory for producing accurate, uniform, and rugged horns.

Dimensions for each set of horns are given in Figs. A-6 through A-17.

CALIBRATION

Experimental primary gain measurements (Fig. 2) were made in order to check the accuracy of the calculated gain.† Great care was taken in making these measurements. Both the horns and the bolometer detectors were carefully matched and the bolometer amplifier and output meter (VTVM) were calibrated accurately. The bolometer amplifier was found to be linear throughout the range used. The use of r-f coaxial cables was avoided because of instability, waveguide being used instead. Microwave absorbent material (1) was used to minimize reflections. Even so, difficulties were encountered at the longer wavelengths because of reflections and the large separation distances required. As Braun has shown (2), true Fraunhofer field conditions do not exist until a separation distance between horns of many times $2d^2/\lambda$ is attained, d being the larger aperture dimension. Because of these difficulties, experimental gain measurements at 10 cm and above were abandoned. It was decided to scale the 3.95-cm and 6-cm horns from the 10-cm horn in order to obtain reliable measurements at the shorter wavelengths. Figure 3 shows the anechoic test site. An example of the method used in evaluating the experimental data is given in the Appendix.

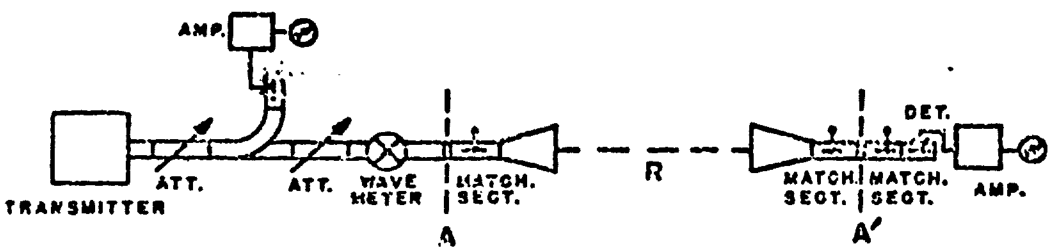

Fig. 2 - Experimental setup for gain measurements

*With the exception of Fig. A-1, all figures and tables bearing the letter A are grouped at the end of the Appendix, and are listed on page 6.

†For a general description of the methods used in making such measurements see Footnote 2, p. 7 of the Appendix, ref. pp. 582-586. The remarks in this reference about the minimum separation distance for the horns should be re-evaluated in the light of Ref. 2.

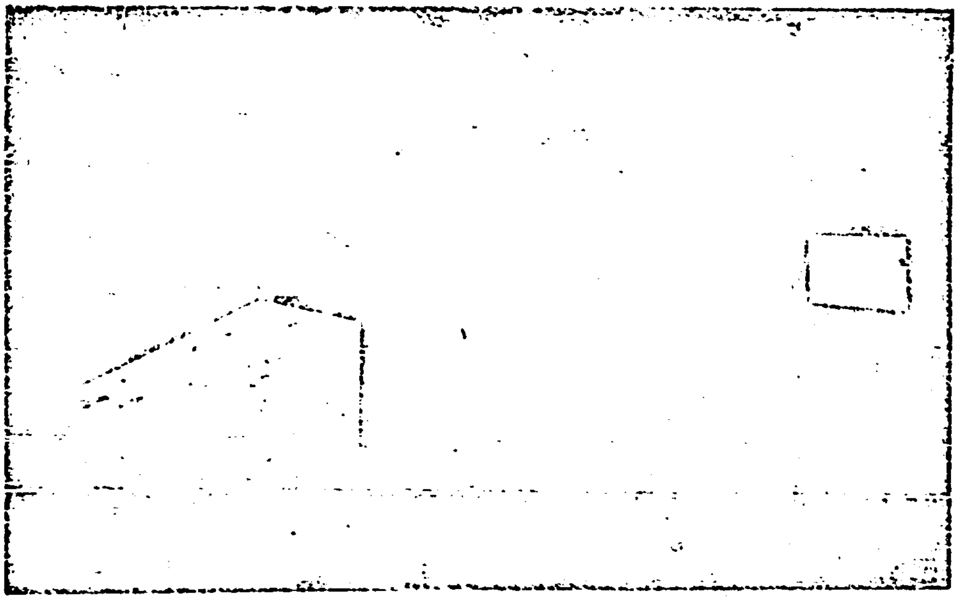

Fig. 3 - Anechoic test site

Measurements were made at several separation distances in each case, and were repeated many times, changing such variables as the power level and the peaking of the horns. See Figs. 3 and 4.

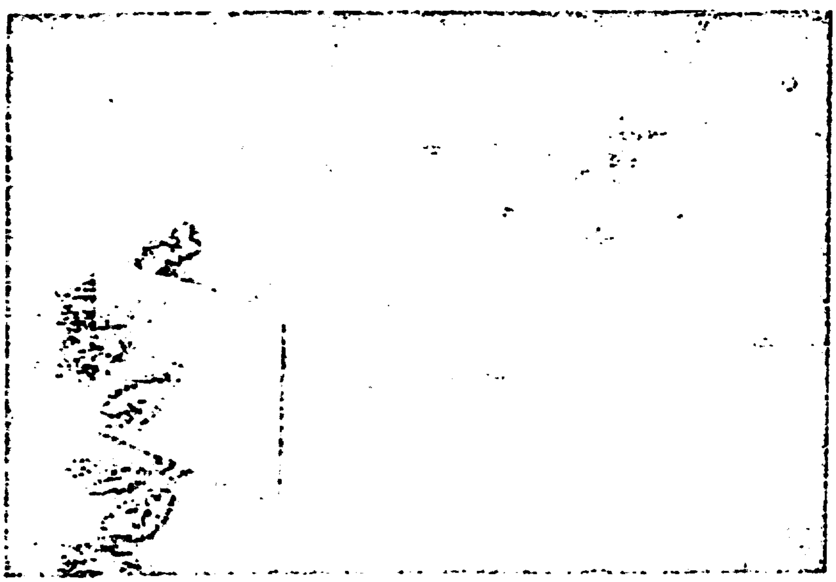

Fig. 4 - Horn and transmitter on adjustable mount

Gain curves for each band are shown in Fig. A-5 (a, b, c). Figures A-4 (a-f) show the field patterns for three basic horn designs.

REMARKS

Horns representing four basic designs were measured for mismatch over their bands. The greatest VSWR's encountered in the various bands are as follows:

Band	Max VSWR
1.8 cm	1.10
3.2 cm	1.20
6 cm	1.25
23 cm	1.20

The horns for the other bands should have a VSWR close to that of the horns from which they were scaled.

In any event, when the horns are used in gain measurements, the VSWR should be measured at the wavelength used, and for accurate measurements the horns should be carefully matched, or allowance should be made for any mismatch. In either case the bolometer must be well-matched. The use of flange-to-flange connections rather than chokes, is recommended whenever operating at a wavelength differing from that for which the chokes were designed, since at some wavelengths choke-to-flange joints may introduce considerable mismatch.

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, though definite, periodic wiggles (see Fig. A-5 (b)). After exhaustive checking it is felt that these wiggles 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. However, since the wiggles are small, and since a tremendous amount of additional data would have to be taken to reproduce the wiggles accurately, a curve drawn through the average of the measured points was used. Taking into account all possible deviations from the true gain over each band, it was decided that the maximum possible error would be less than ±0.3 db up to and including the 10-cm horns.

At wavelengths longer than 10 cm, where no direct experimental checks have been feasible, the gain has been calculated by means of Schelkunoff's formula. To arrive at a reasonable tolerance at these wavelengths, it was noted that below 10 cm the greatest discrepancy between the average measured gain (using Braun's correction curves[2] for near field effects) and the calculated gain at the same wavelength was of the order of 0.2 db. In general the difference was much less than this figure. Therefore it is felt that a tolerance of ±0.5 db is reasonable for all horns above the 10-cm band. In all probability, the actual errors are considerably less than the maximum possible tolerances quoted.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to E. H. Braun for his advice and cooperation and to F. W. Lashway for his suggestions in connection with the construction of the horns.

* * *

REFERENCES

1. Simmons, A. J., and Emerson, W. H., "An Anechoic Chamber Making Use of a New Broadband Absorbing Material," NRL Report 4193, 7 July 1953

2. Braun, E. H., "Gain of Electromagnetic Horns," Proc. I.R.E., Vol. 41, No. 1, pp. 109-115, Jan. 1953

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LIST OF APPENDIX ILLUSTRATIONS

APPENDIX
Methods for Determining Horn Dimensions and Gain

BACKGROUND

Schelkunoff's gain curves in various forms[1,2,3] were used for determining the tentative dimensions of the horns and for obtaining a first approximation to the gain. After the aperture dimensions had been chosen and a reasonable value for ℓ_E (the E-plane slant height) had been set, the H-plane slant height, ℓ_H, was uniquely determined by the requirement that the flared sides of the horn meet the waveguide in the same plane (Fig. 1, p. 1). For the purpose of calculating the expected gain, this value of ℓ_H was approximated by the relation

$$\ell_{H_{approx.}} = \frac{1 - \frac{w_E}{b}}{1 - \frac{w_H}{a}} \ell_E \qquad (1)$$

where a = H-plane aperture dimension

b = E-plane aperture dimension

w_E = E-plane inside dimension of the waveguide

w_H = H-plane inside dimension of the waveguide.

After the tentative gain had been determined, the exact value of ℓ_H was obtained from the formula

$$\ell_H = \frac{a}{a - w_H} \sqrt{\left[\left(\ell_E\right)^2 - \left(\frac{b}{2}\right)^2\right] \left[\left(1 - \frac{w_E}{b}\right)^2\right] + \left[\frac{a - w_H}{2}\right]^2} . \qquad (2)$$

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[1]Schelkunoff, S. A., "Electromagnetic Waves," D. Van Nostrand, Inc., New York, pp. 363-365, 1943

[2]Silver, S., "Microwave Antenna Theory & Design," McGraw-Hill Book Co., Inc., New York, pp. 588-589, 1949

[3]Schelkunoff, S. A., and Friis, H. T., "Antennas - Theory and Practice," John Wiley and Sons, Inc., New York, pp. 528-529, 1952

In using Schelkunoff's gain curves, it was found that no one family of curves in the references mentioned covered a range great enough to include all the desired sizes of horns. Furthermore, certain parts of the curves were found to be less accurate than others. To overcome these difficulties a new procedure has been devised.[4] A brief review of the relationship of the curves to the gain formula will help to clarify the procedure. The notation is substantially that used in the recent book by Schelkunoff and Friis,[3] and by Silver.[2]

The Schelkunoff curves give the directive gain for horns flared in either of the two principal planes; g_E is the directive gain of a sectoral horn flared in the E-plane, and g_H is the directive gain of a sectoral horn flared in the H-plane. The two sectoral gain curves are obtained from the following formulas, expressed in terms of the tabulated Fresnel integrals $C(X)$ and $S(X)$:

$$\frac{\lambda}{b} g_H = \frac{4\pi \ell_H}{a}\left[\left\{C(u) - C(v)\right\}^2 + \left\{S(u) - S(v)\right\}^2\right] \tag{3}$$

$$\frac{\lambda}{a} g_E = \frac{64\ell_E}{\pi b}\left[C^2(w) + S^2(w)\right], \tag{4}$$

where

$$u = \frac{1}{\sqrt{2}}\left(\frac{\sqrt{\lambda \ell_H}}{a} + \frac{a}{\sqrt{\lambda \ell_H}}\right)$$

$$v = \frac{1}{\sqrt{2}}\left(\frac{\sqrt{\lambda \ell_H}}{a} - \frac{a}{\sqrt{\lambda \ell_H}}\right)$$

$$w = \frac{b}{\sqrt{2\lambda \ell_E}}$$

λ = wavelength.

The gain of a pyramidal horn is

$$g = \frac{8\pi \ell_E \ell_H}{ab}\left[C^2(w) + S^2(w)\right]\left[\left\{C(u) - C(v)\right\}^2 + \left\{S(u) - S(v)\right\}^2\right]$$

This result can easily be obtained from the two sectoral curves by multiplying together $(\lambda/a)g_E$ and $(\lambda/b)g_H$, and dividing the result by $32/\pi = 10.1859$, yielding the convenient formula

$$g = \frac{\left(\frac{\lambda}{a} g_E\right)\left(\frac{\lambda}{b} g_H\right)}{\frac{32}{\pi}} \tag{5}$$

where $\frac{\lambda}{a} g_E$ and $\frac{\lambda}{b} g_H$ are read directly from the curves.

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[4] Braun, E. H., "Calculation of the Gain of Small Horns," Proc. I.R.E., Vol. 41, No. 12, pp. 1785-6, Dec. 1953

EXTENSION AND APPLICATION

Braun's method[4] provides a convenient means of extending the range of the gain curves and eliminating the inaccuracy arising from interpolations between curves. He introduces the arbitrary factors k_E and k_H to create a fictitious horn having these dimensions:

$$a = k_H A, \quad \ell_H = k_H^2 L_H$$

$$b = k_E B, \quad \ell_E = k_E^2 L_E$$

where A, B, L_E, and L_H are the actual horn dimensions. By choosing the proper value for k_E and k_H, one can make ℓ_E and ℓ_H fall exactly on one of the respective gain curves for each plane. After the gain of the fictitious horn ($g_{fict.}$) is read from the curves, the gain of the actual horn ($g_{act.}$) is obtained from the relation

$$g_{act.} = \frac{g_{fict.}}{k_E k_H}$$

Since both k_E and k_H are arbitrary, one gain curve for each plane is all that is necessary. The Schelkunoff curves for $\ell_E = 50\lambda$ and $\ell_H = 50\lambda$ are convenient for this purpose and have been accurately recomputed and plotted on an expanded scale in Figs. A-2 (a,b) and A-3 (a,b) so that they may be read with such accuracy that it is no longer necessary to make the detailed calculations involved in using the gain formula. The curves were plotted from formulas (3) and (4). The values obtained from these formulas are tabulated in Table A-1. For maximum accuracy these values may be preferable to those obtained from the curves. Linear interpolation between points will yield good accuracy. The table makes it possible to plot any desired portions of the curves on whatever scale is preferred.

An example will demonstrate the simplicity of the method.

Actual horn: $A = 8.13\lambda, \quad L_H = 19.72\lambda$

$B = 6.67\lambda, \quad L_E = 18.52\lambda$

If it is desired to make use of the 50-λ curves referred to above, the k's are chosen as follows:

$$k_E^2 = \frac{50\lambda}{18.52\lambda} = 2.6998, \quad k_E = 1.643,$$

$$k_H^2 = \frac{50\lambda}{19.72\lambda} = 2.5355, \quad k_H = 1.592.$$

Fictitious horn: $b = k_E\ B = 10.96\lambda, \quad \ell_E = 50\lambda,$

$a = k_H\ A = 12.94\lambda, \quad \ell_H = 50\lambda.$

From the 50-λ gain curves

$$\frac{\lambda}{a} g_E = 80.77$$

$$\frac{\lambda}{b} g_H = 98.92 .$$

From formula (5),

$$g_{fict.} = \frac{\left(\frac{\lambda}{a} g_E\right)\left(\frac{\lambda}{b} g_H\right)}{\frac{32}{\pi}} = 784.40$$

$$g_{act.} = \frac{g_{fict.}}{k_E\ k_H} = 299.88, \text{ or } 24.77 \text{ db.}$$

Detailed calculations using the Fresnel integrals in the gain formula resulted in the same gain figure, 24.77 db. Similar comparisons at each of the other bands showed agreement within 0.01 db.

USE OF CORRECTION CURVES

The procedure for determining the true Fraunhofer gain from the primary gain test data, using Braun's near field correction curves, Fig. A-1 (a, b), is shown in the following example taken from actual measurements:

X-band horn dimensions: $a = 7.654$ in., $\ell_H = 13.484$ in.
$b = 5.669$ in., $\ell_E = 12.598$ in.

$\lambda = 3.20$ cm $= 1.2598$ in.

R (distance between horns) = 140.25 in.

$$\frac{4\pi R}{\lambda} = \frac{(12.566)(140.25)}{1.2598} = 1398.9.$$

From test data $\frac{P_T}{P_R} = \frac{11.3}{0.123} = 91.87;$ $\sqrt{\frac{P_T}{P_R}} = 9.585$

where P_T represents power transmitted and P_R power received.

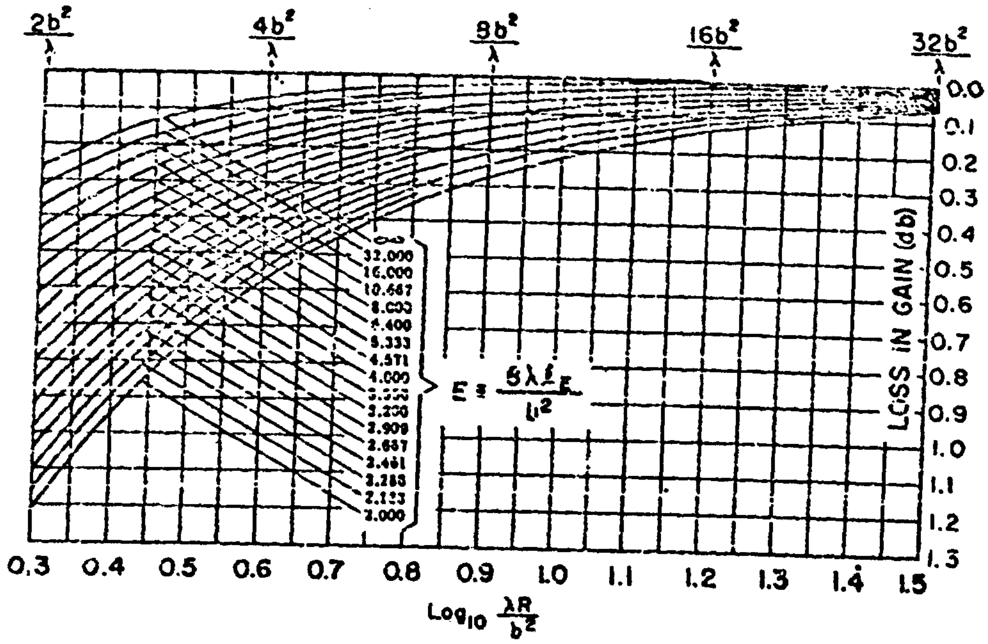
$$\text{Gain}_{\text{uncorrected}} = \frac{\frac{4\pi R}{\lambda}}{\sqrt{\frac{P_T}{P_R}}} = \frac{1398.9}{9.585} = 145.95, \text{ or } 21.64 \text{ db.}$$

Parameters for using the correction curves:

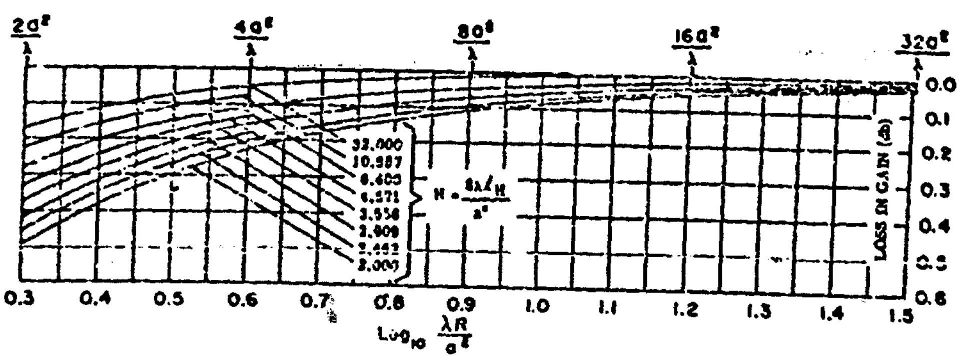
<u>E-plane:</u>

$$\frac{8\ell_E}{b^2} = \frac{(8)(12.598)}{32.13} = 3.1360$$

$$\left.\begin{aligned} E &= \left(\frac{8\ell_E}{b^2}\right)\lambda = (3.1360)(1.2598) = 3.951 \\ \log\frac{\lambda R}{b^2} &= \log\frac{(1.2598)(140.25)}{32.13} = \log 5.498 = 0.740 \end{aligned}\right\}$$



(a) E-plane



(b) H-plane

Fig. A-1 - Braun's E- and H-plane correction curves

H-plane:

$$\frac{8\ell_H}{a^2} = \frac{(8)(13.484)}{58.584} = 1.8413$$

$$\left.\begin{aligned} H &= \left(\frac{8\ell_H}{a^2}\right)\lambda = (1.8413)(1.2598) = 2.320 \\ \log\frac{\lambda R}{a^2} &= \log\frac{(1.2598)(140.25)}{58.584} = \log 3.016 = 0.479 \end{aligned}\right\}$$

Reading from the correction curves:

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

The calculated gain, using Schelkunoff's formula, in this case was the same: 22.14 db.

DETERMINATION OF AN OPTIMUM HORN WITH SPECIFIED GAIN AND EQUAL BEAMWIDTHS

A simple means has been devised for finding the dimensions of a horn which satisfies the following requirements:

(1) Specified gain

(2) Optimum horn*

(3) Equal beamwidths at the half-power points.

Although this can be done empirically, a set of factors was determined from Schelkunoff's gain formula, which yield the required horn parameters as a function of the absolute gain, g, alone.† These are as follows:

*An optimum horn is one for which the aperture dimensions have been chosen to give maximum gain when the slant heights are held fixed. This is the case when $a^2 \cong 3.18\lambda\,\ell_H$ and $b^2 \cong 2.08\lambda\,\ell_E$

†This has been worked out by E. H. Braun in an unpublished report.

$$\frac{a}{\lambda} = 0.4675 \quad \sqrt{g}$$

$$\frac{b}{\lambda} = 0.3463 \quad \sqrt{g}$$

$$\frac{\ell_E}{\lambda} = 0.05764 \quad g$$

$$\frac{\ell_H}{\lambda} = 0.06885 \quad g$$

where a, b, ℓ_E, and ℓ_H are the usual parameters as defined (p.7).

A horn having these dimensions will have exactly the desired theoretical gain, and will be exactly an optimum horn. However, it should be pointed out that where a simple joint between the flared horn and the waveguide is desired, the value of ℓ_H must be modified to make the horn fit the guide. This will change the gain by a small amount, usually a few tenths of a db, since the horn will no longer be exactly optimum. If a discrepancy of this magnitude is not important, ℓ_H can be calculated to fit the waveguide exactly, using formula (2).

When a closer approach to the specified gain is desired, a slight change in the procedure is necessary. This is accomplished by the following steps:

(1) Compute tentative parameters a', b', and ℓ_E' in the same way as a, b, and ℓ_E were computed above.

(2) Obtain the approximate value, ℓ_H', to fit the waveguide, using formula (1), p. 7.

(3) Calculate the tentative gain, g', by the method outlined on p. 9 using the primed parameters.

(4) Recompute a, b, and ℓ_E, substituting g^2/g' for g

(5) Obtain the exact value of ℓ_H from formula (2

(6) Recalculate the gain for the new parameters.

Since the theoretical gain is obtained very accurately in step 6, it is easy to determine the discrepancy between the desired gain and that now resulting from the adjustment to fit the waveguide.

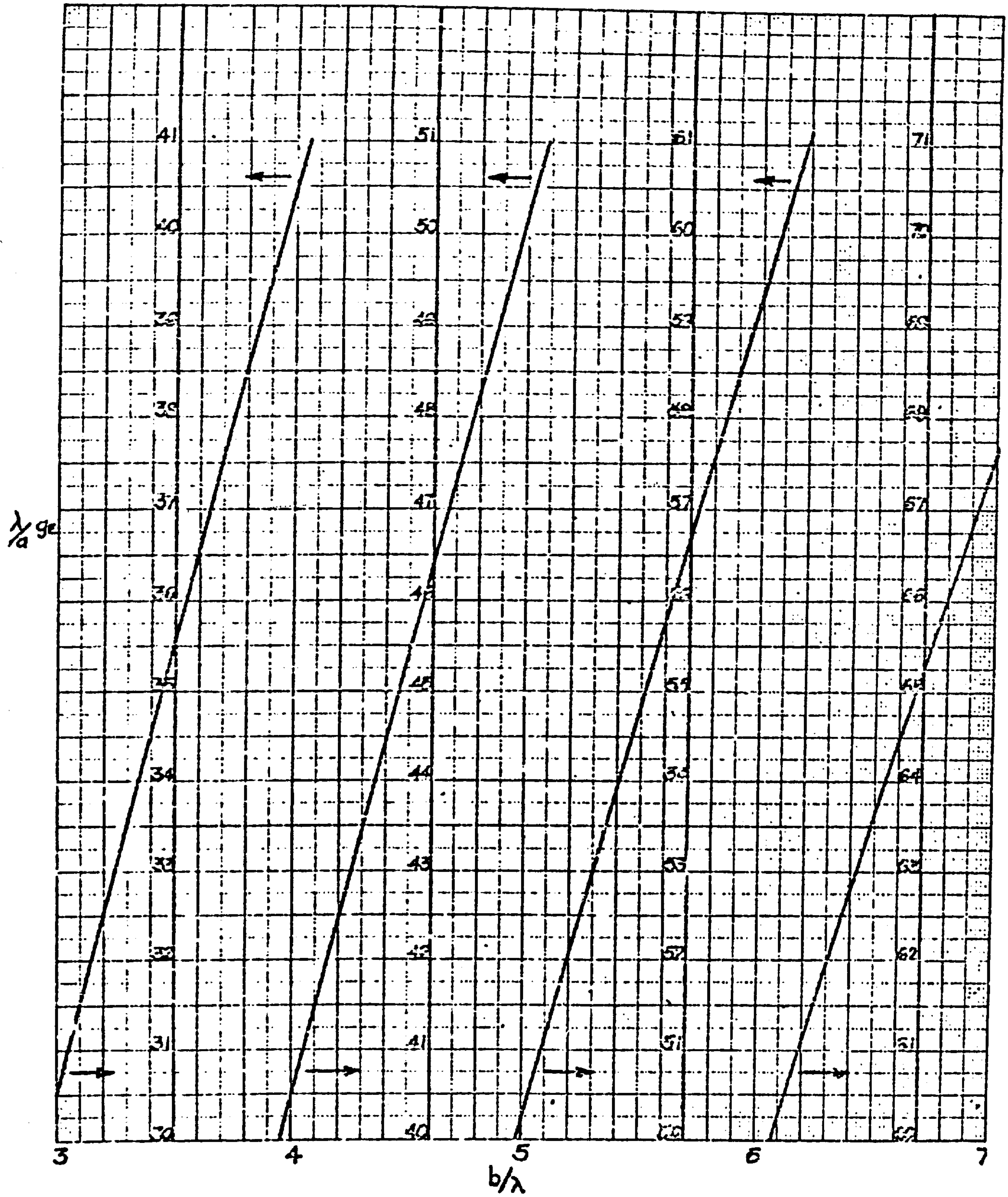


Fig. A-2 (a). Expanded E-plane theoretical gain curve

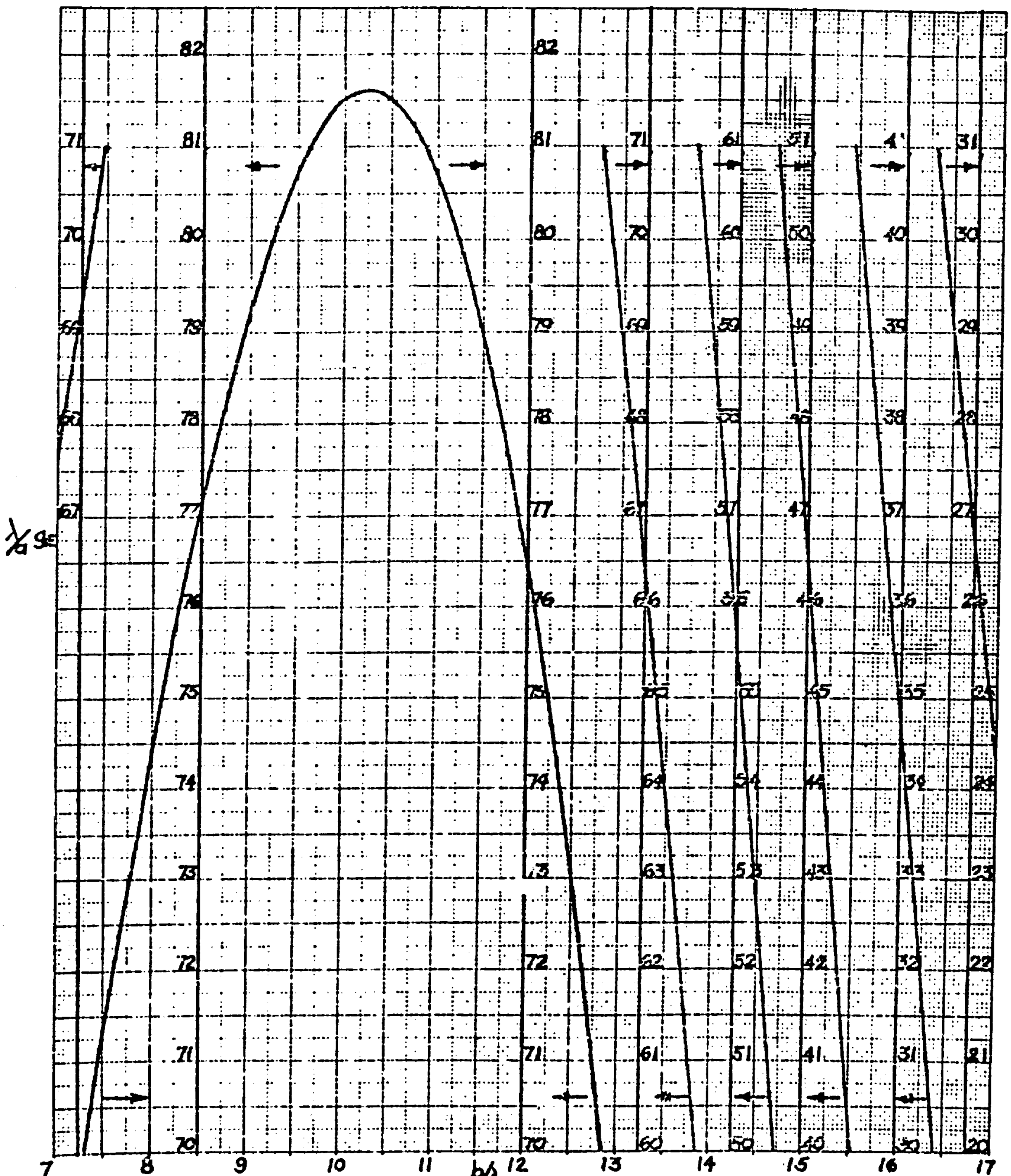


Fig. A-2 (b). Expanded E-plane theoretical gain curve

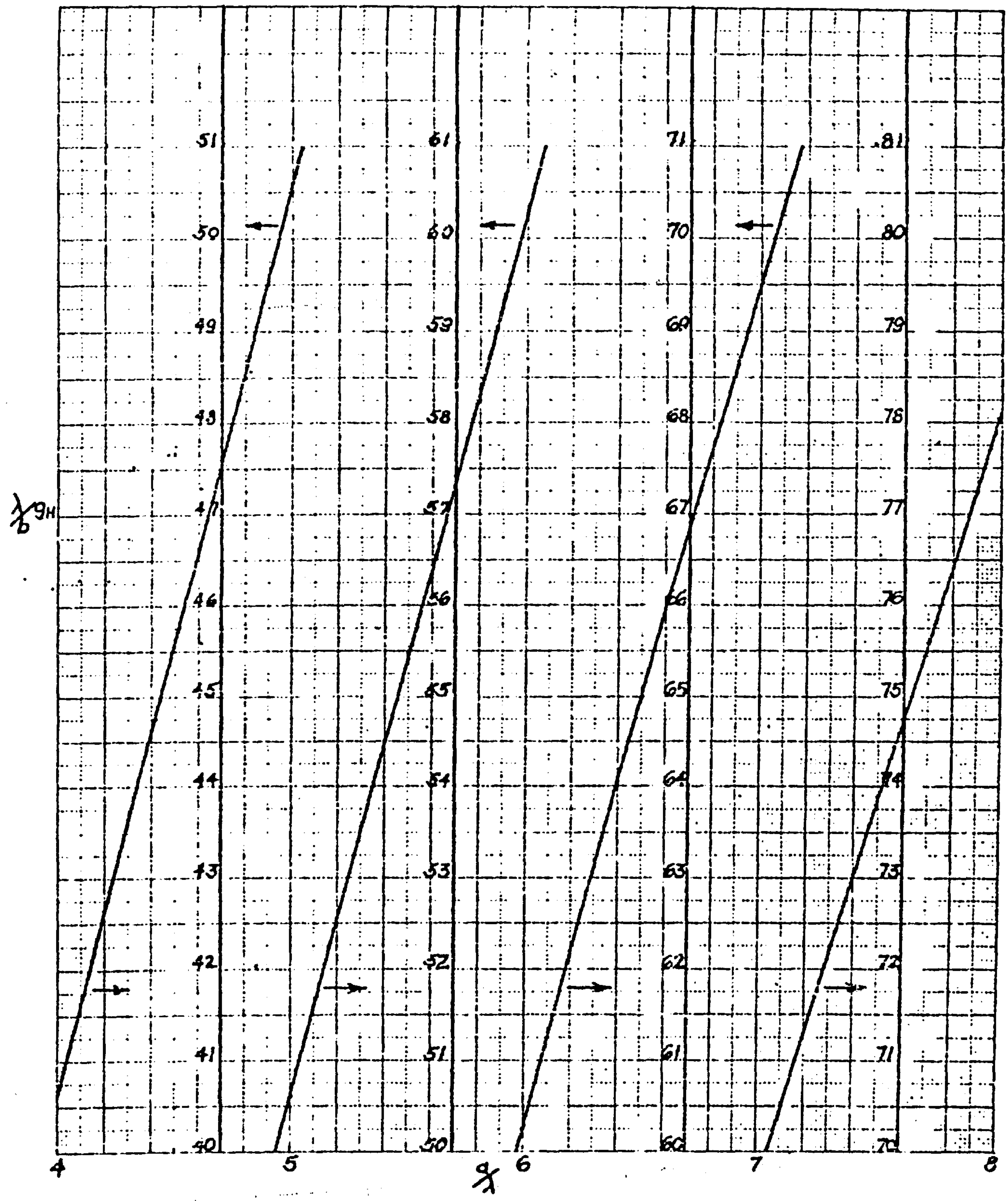


Fig. A-3 (a). Expanded H-plane theoretical gain curve

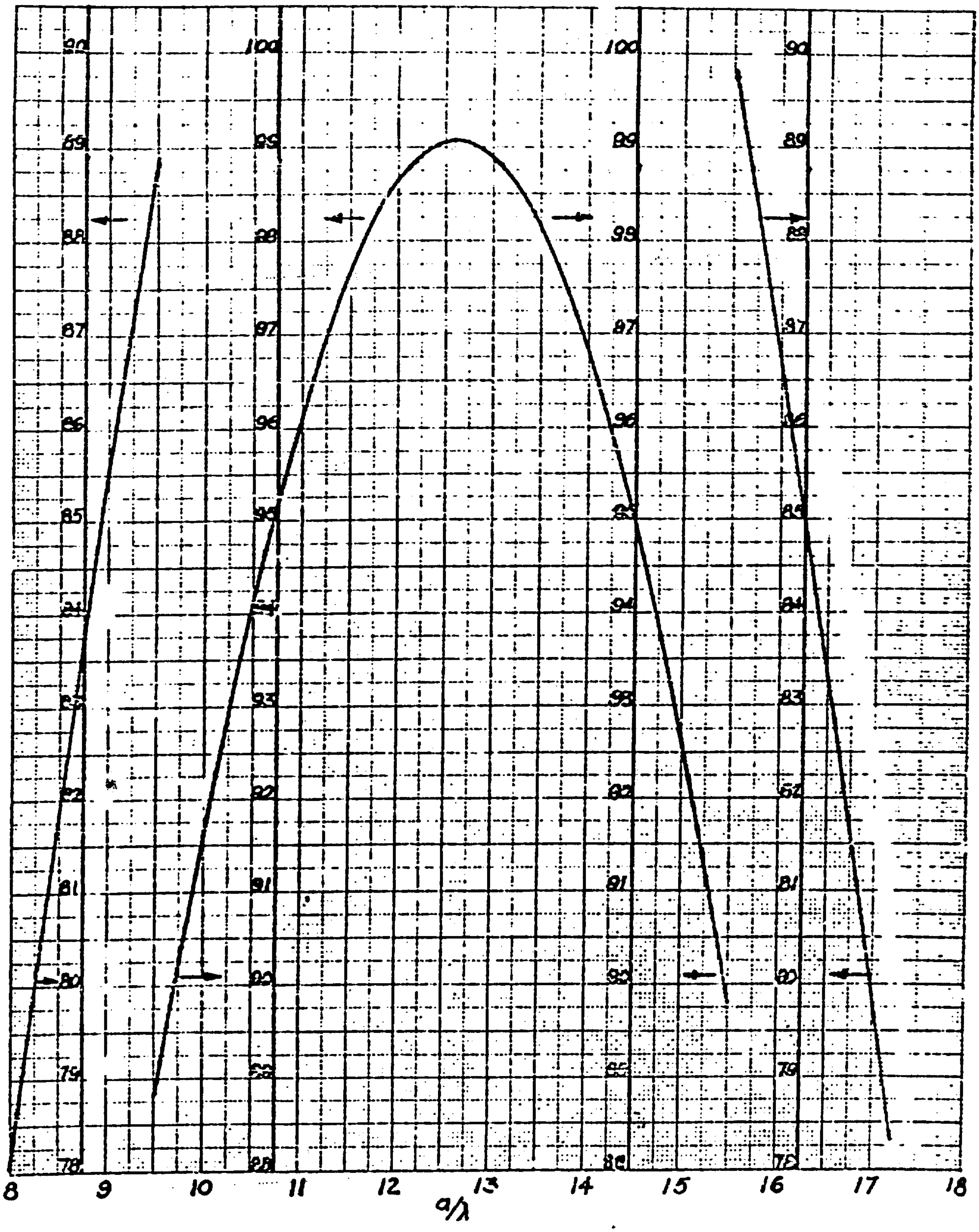


Fig. A-3 (b). Expanded H-plane theoretical gain curve

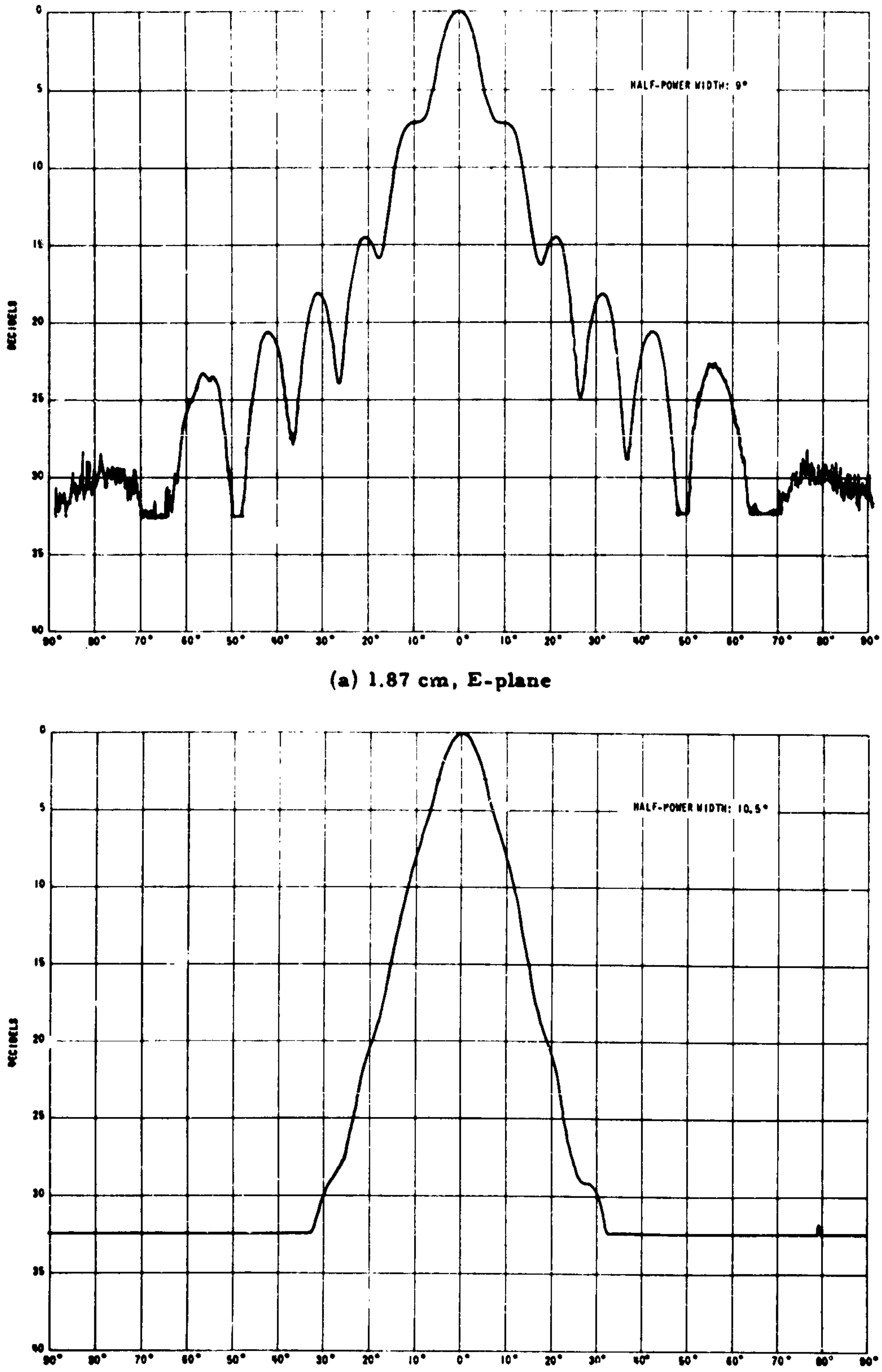
TABLE A-1
Data for Theoretical Gain Curves

(a) E-Plane ($\ell_E = 50\lambda$)

b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$	b	$\frac{\lambda}{a} g_E$
2.0	20.362	4.6	46.397	7.2	69.123	9.8	81.301	12.4	73.784	15.0	46.499	17.6	19.910
2.1	21.381	4.7	47.362	7.3	69.847	9.9	81.426	12.5	73.041	15.1	45.268	17.7	19.316
2.2	22.395	4.8	48.326	7.4	70.555	10.0	81.518	12.6	72.265	15.2	44.040	17.8	18.767
2.3	23.410	4.9	49.283	7.5	71.248	10.1	81.581	12.7	71.459	15.3	42.813	17.9	18.264
2.4	24.425	5.0	50.233	7.6	71.923	10.2	81.611	12.8	70.621	15.4	41.593	18.0	17.805
2.5	25.440	5.1	51.181	7.7	72.586	10.3	81.609	12.9	69.753	15.5	40.379	18.1	17.395
2.6	26.456	5.2	52.123	7.8	73.219	10.4	81.575	13.0	68.856	15.6	39.174	18.2	17.030
2.7	27.472	5.3	53.057	7.9	73.841	10.5	81.510	13.1	67.931	15.7	37.962	18.3	16.714
2.8	28.481	5.4	53.985	8.0	74.441	10.6	81.408	13.2	66.980	15.8	36.801	18.4	16.445
2.9	29.490	5.5	54.908	8.1	75.025	10.7	81.277	13.3	65.991	15.9	35.636	18.5	16.223
3.0	30.503	5.6	55.821	8.2	75.585	10.8	81.110	13.4	64.997	16.0	34.488	18.6	16.048
3.1	31.511	5.7	56.729	8.3	76.127	10.9	80.909	13.5	63.969	16.1	33.359	18.7	15.921
3.2	32.518	5.8	57.626	8.4	76.645	11.0	80.676	13.6	62.917	16.2	32.250	18.8	15.839
3.3	33.527	5.9	58.517	8.5	77.142	11.1	80.405	13.7	61.844	16.3	31.164	18.9	15.804
3.4	34.530	6.0	59.401	8.6	77.616	11.2	80.104	13.8	60.748	16.4	30.104	19.0	15.814
3.5	35.534	6.1	60.272	8.7	78.065	11.3	79.765	13.9	59.635	16.5	29.069	19.1	15.870
3.6	36.534	6.2	61.134	8.8	78.492	11.4	79.393	14.0	58.501	16.6	28.063	19.2	15.967
3.7	37.531	6.3	61.987	8.9	78.892	11.5	78.987	14.1	57.351	16.7	27.086	19.3	16.108
3.8	38.530	6.4	62.828	9.0	79.269	11.6	78.545	14.2	56.188	16.8	26.142	19.4	16.289
3.9	39.524	6.5	63.659	9.1	79.619	11.7	78.068	14.3	55.008	16.9	25.232	19.5	16.521
4.0	40.515	6.6	64.477	9.2	79.944	11.8	77.559	14.4	53.816	17.0	24.355	19.6	16.769
4.1	41.504	6.7	65.285	9.3	80.240	11.9	77.014	14.5	52.614	17.1	23.515	19.7	17.064
4.2	42.490	6.8	66.080	9.4	80.510	12.0	76.435	14.6	51.402	17.2	22.713	19.8	17.394
4.3	43.472	6.9	66.862	9.5	80.752	12.1	75.822	14.7	50.183	17.3	21.951	19.9	17.755
4.4	44.450	7.0	67.630	9.6	80.964	12.2	75.176	14.8	48.959	17.4	21.228	20.0	18.147
4.5	45.425	7.1	68.385	9.7	81.146	12.3	74.497	14.9	47.731	17.5	20.548		

(b) H-Plane ($\ell_H = 50\lambda$)

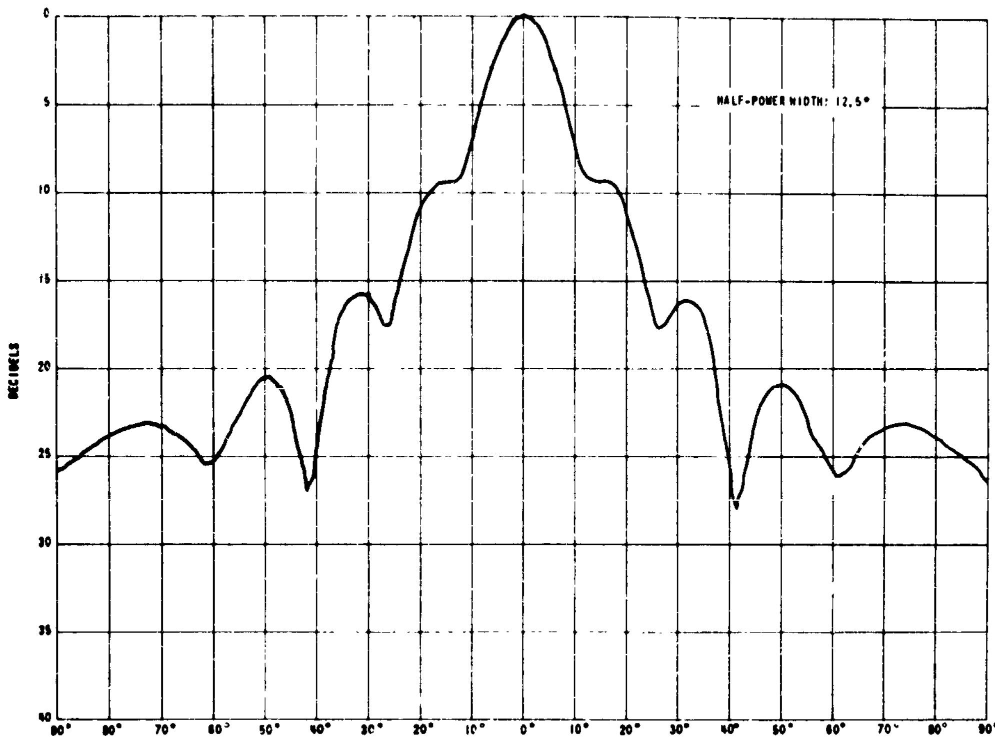
a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$	a	$\frac{\lambda}{b} g_H$
2.0	20.370	4.6	46.635	7.2	71.291	9.8	90.633	12.4	99.019	15.0	92.591	17.6	75.416
2.1	21.387	4.7	47.628	7.3	72.164	9.9	91.195	12.5	99.052	15.1	92.066	17.7	74.701
2.2	22.402	4.8	48.619	7.4	73.031	10.0	91.740	12.6	99.062	15.2	91.525	17.8	73.991
2.3	23.422	4.9	49.609	7.5	73.889	10.1	92.270	12.7	99.051	15.3	90.972	17.9	73.282
2.4	24.439	5.0	50.595	7.6	74.739	10.2	92.781	12.8	99.012	15.4	90.400	18.0	72.581
2.5	25.452	5.1	51.578	7.7	75.580	10.3	93.274	12.9	98.953	15.5	89.822	18.1	71.886
2.6	26.471	5.2	52.559	7.8	76.413	10.4	93.751	13.0	98.871	15.6	89.214	18.2	71.199
2.7	27.488	5.3	53.536	7.9	77.236	10.5	94.208	13.1	98.763	15.7	88.601	18.3	70.516
2.8	28.501	5.4	54.512	8.0	78.049	10.6	94.646	13.2	98.638	15.8	87.976	18.4	69.847
2.9	29.518	5.5	55.475	8.1	78.854	10.7	95.067	13.3	98.486	15.9	87.337	18.5	69.183
3.0	30.532	5.6	56.449	8.2	79.644	10.8	95.470	13.4	98.309	16.0	86.688	18.6	68.534
3.1	31.545	5.7	57.418	8.3	80.427	10.9	95.848	13.5	98.114	16.1	86.026	18.7	67.891
3.2	32.560	5.8	58.377	8.4	81.196	11.0	96.207	13.6	97.894	16.2	85.355	18.8	67.262
3.3	33.573	5.9	59.334	8.5	81.956	11.1	96.547	13.7	97.654	16.3	84.677	18.9	66.643
3.4	34.579	6.0	60.265	8.6	82.703	11.2	96.869	13.8	97.387	16.4	83.990	19.0	66.038
3.5	35.595	6.1	61.232	8.7	83.440	11.3	97.168	13.9	97.101	16.5	83.319	19.1	65.447
3.6	36.605	6.2	62.176	8.8	84.164	11.4	97.445	14.0	96.793	16.6	82.594	19.2	64.871
3.7	37.612	6.3	63.115	8.9	84.875	11.5	97.702	14.1	96.464	16.7	81.858	19.3	64.305
3.8	38.622	6.4	64.046	9.0	85.567	11.6	97.938	14.2	96.113	16.8	81.179	19.4	63.758
3.9	39.629	6.5	64.975	9.1	86.250	11.7	98.149	14.3	95.740	16.9	80.461	19.5	63.222
4.0	40.633	6.6	65.896	9.2	86.923	11.8	98.342	14.4	95.348	17.0	79.742	19.6	62.703
4.1	41.637	6.7	66.810	9.3	87.579	11.9	98.510	14.5	94.936	17.1	79.023	19.7	62.201
4.2	42.645	6.8	67.720	9.4	88.221	12.0	98.658	14.6	94.504	17.2	78.301	19.8	61.714
4.3	43.639	6.9	68.623	9.5	88.844	12.1	98.783	14.7	94.054	17.3	77.578	19.9	61.243
4.4	44.641	7.0	69.518	9.6	89.460	12.2	98.882	14.8	93.565	17.4	76.854	20.0	60.788
4.5	45.639	7.1	70.407	9.7	90.053	12.3	98.965	14.9	93.095	17.5	76.134		



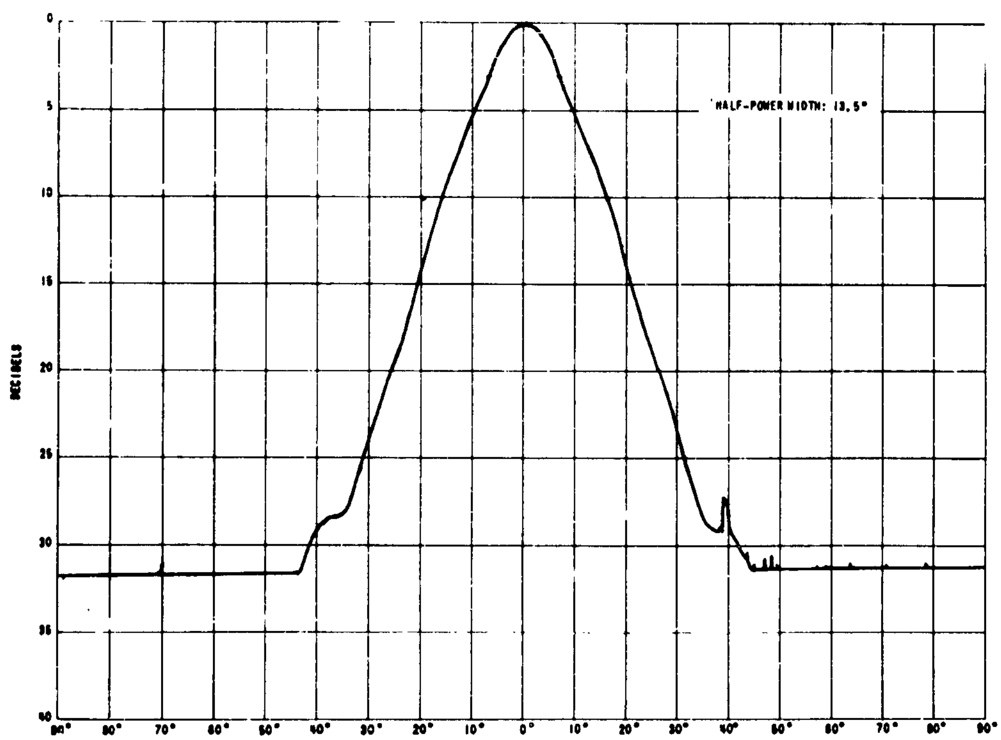
(a) 1.87 cm, E-plane

(b) 1.87 cm, H-plane

Fig. A-4. E- and H-plane field patterns

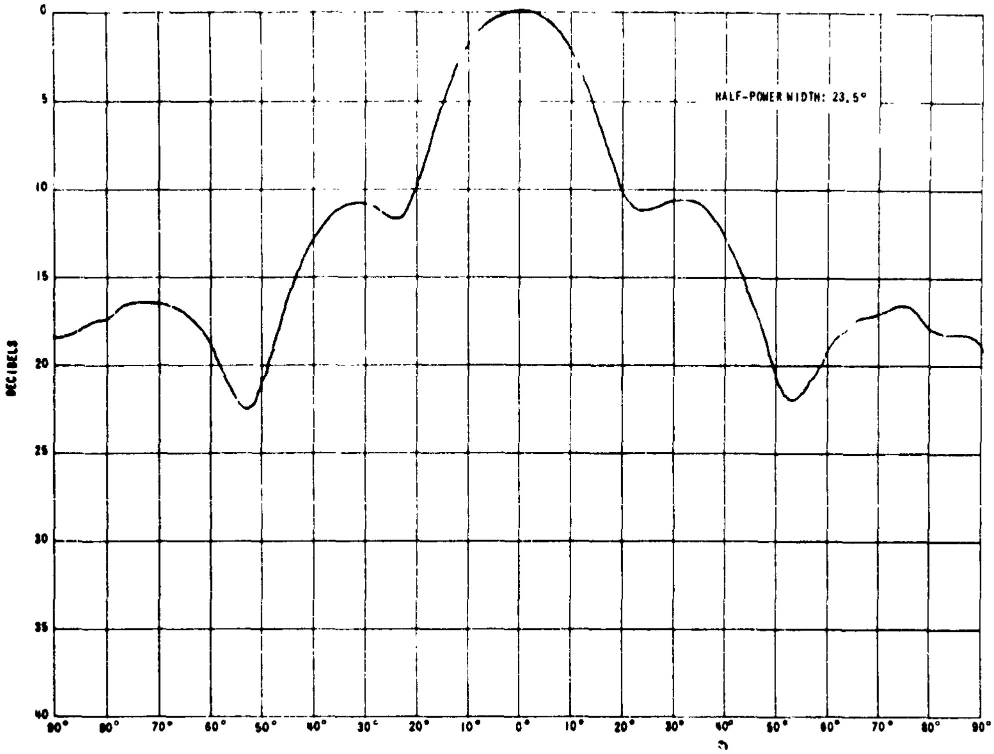


(c) 3.20 .ı, E-plane

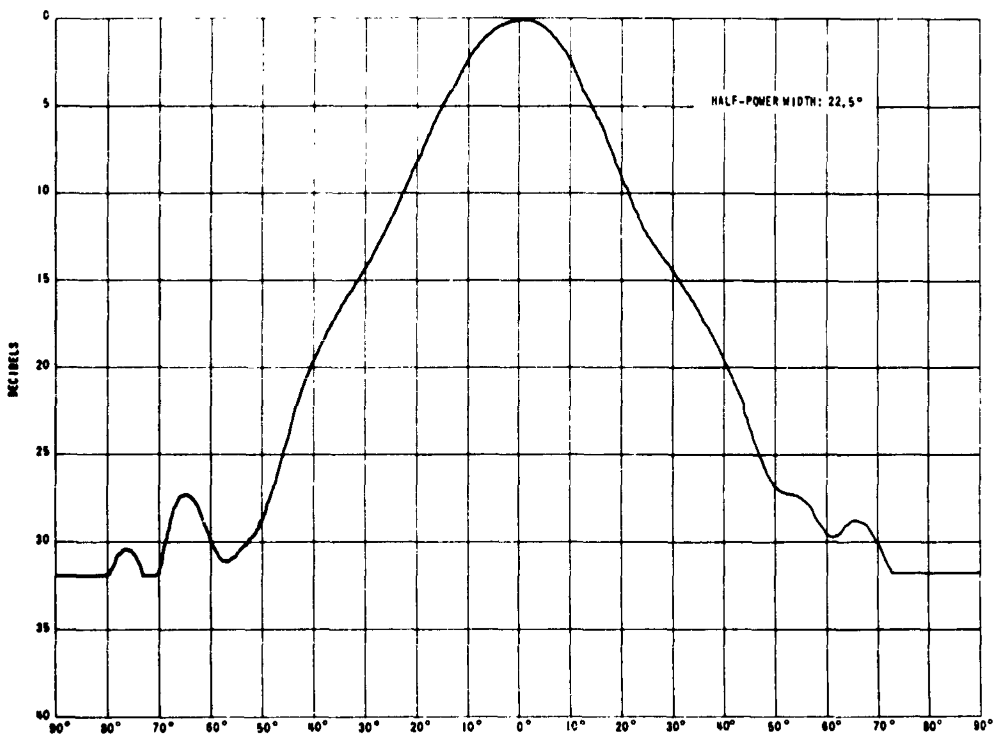


(d) 3.20 cm, H-plane

Fig. A-4. E- and H-plane field patterns



(e) 6.67 cm, E-plane



(f) 6.67 cm, H-plane

Fig. A-4. E- and H-plane field patterns

TABLE A-2

Summary of Gain-Standard Horn Data

Band	Frequency Range	Dimensions (I.D.) (in.)	Design-Point Frequency	Gain at Design Point (db)
8 mm	0.77 - 1.13 cm 26,550 - 38,960 Mc	a = 2.720 b = 2.231 ℓ_H = 6.513 ℓ_E = 6.197	0.85 cm 35,290 Mc	24.7
1.25 cm	1.13 - 1.66 cm 18,070 - 26,550 Mc	a = 4.000 b = 3.281 ℓ_H = 9.706 ℓ_E = 9.113	1.25 cm 24,000 Mc	24.7
1.8 cm	1.66 - 2.42 cm 12,400 - 18,070 Mc	a = 5.984 b = 4.908 ℓ_H = 14.333 ℓ_E = 13.633	1.87 cm 16,040 Mc	24.7
3.2 cm	2.42 - 3.70 cm 8100 - 12,400 Mc	a = 7.654 b = 5.669 ℓ_H = 13.484 ℓ_E = 12.598	3.20 cm 9375 Mc	22.1
4.75 cm	3.60 - 5.20 cm 5770 - 8330 Mc	a = 11.360 b = 8.415 ℓ_H = 20.014 ℓ_E = 18.700	4.75 cm 6315 Mc	22.1
3.95 cm	3.00 - 4.30 cm 6980 - 10,000 Mc	a = 5.041 b = 3.733 ℓ_H = 7.447 ℓ_E = 6.555	3.95 cm 7595 Mc	18.0
6 cm	5.10 - 7.60 cm 3950 - 5880 Mc	a = 8.507 b = 6.300 ℓ_H = 12.462 ℓ_E = 11.062	6.67 cm 4500 Mc	18.0
10 cm	7.60 - 11.5 cm 2600 - 3950 Mc	a = 12.760 b = 9.450 ℓ_H = 18.682 ℓ_E = 16.593	10.00 cm 3000 Mc	18.0
15 cm	11.5 - 17.6 cm 1700 - 2600 Mc	a = 14.508 b = 10.747 ℓ_H = 16.508 ℓ_E = 14.107	15.22 cm 1970 Mc	15.5
23 cm	17.6 - 26.5 cm 1130 - 1700 Mc	a = 21.931 b = 16.245 ℓ_H = 24.955 ℓ_E = 21.325	23.00 cm 1300 Mc	15.5
30 cm	26.0 - 31.5 cm 950 - 1150 Mc	a = 21.931 b - 16.245 ℓ_H = 28.730 ℓ_E = 24.000	30.00 cm 1000 Mc	13.7

Horns in brackets are scaled versions of each other, excep for the ℓ_H dimensions, which are chosen to make a simple butt-joint at the waveguide

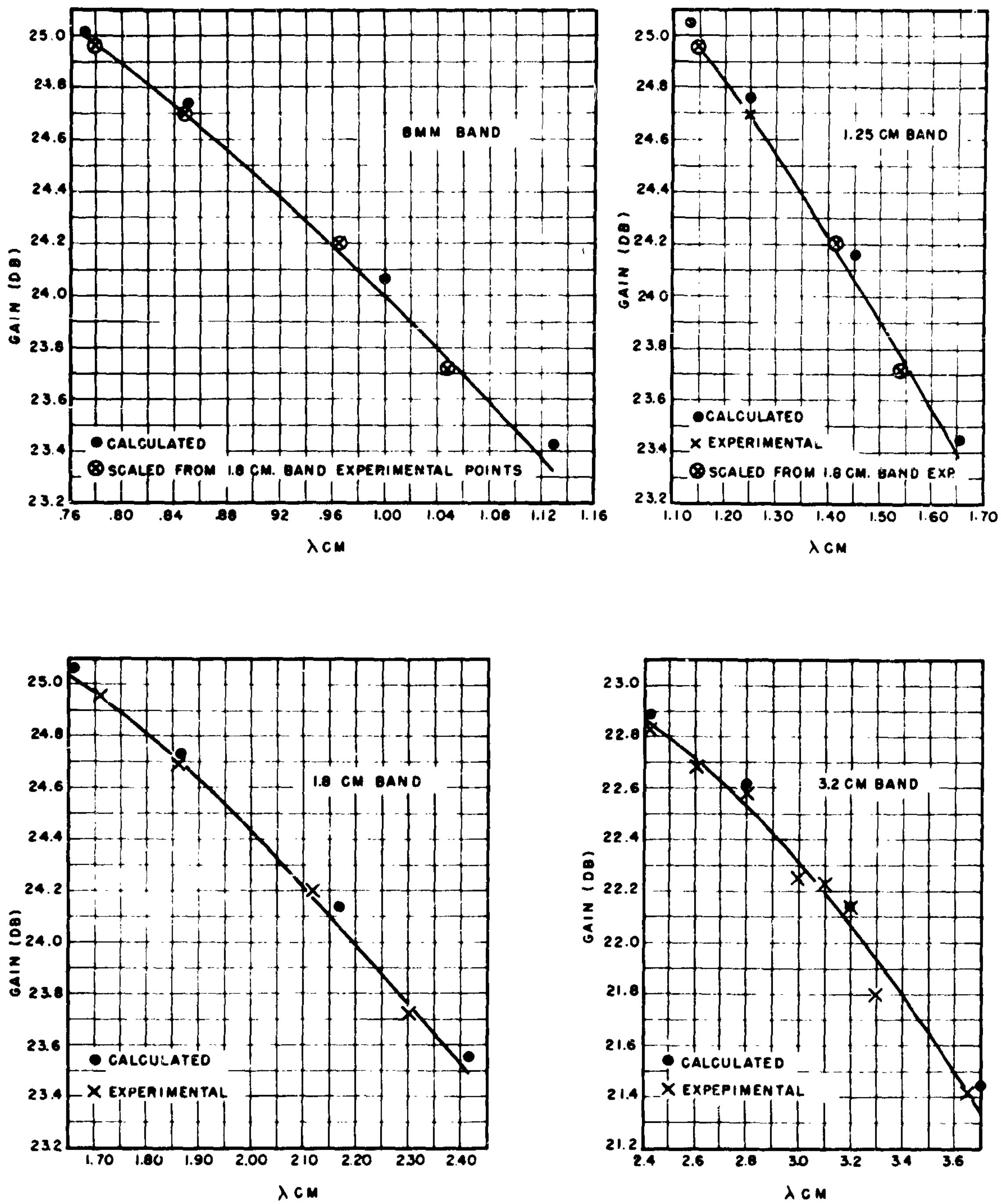


Fig. A-5 (a). Gain curves

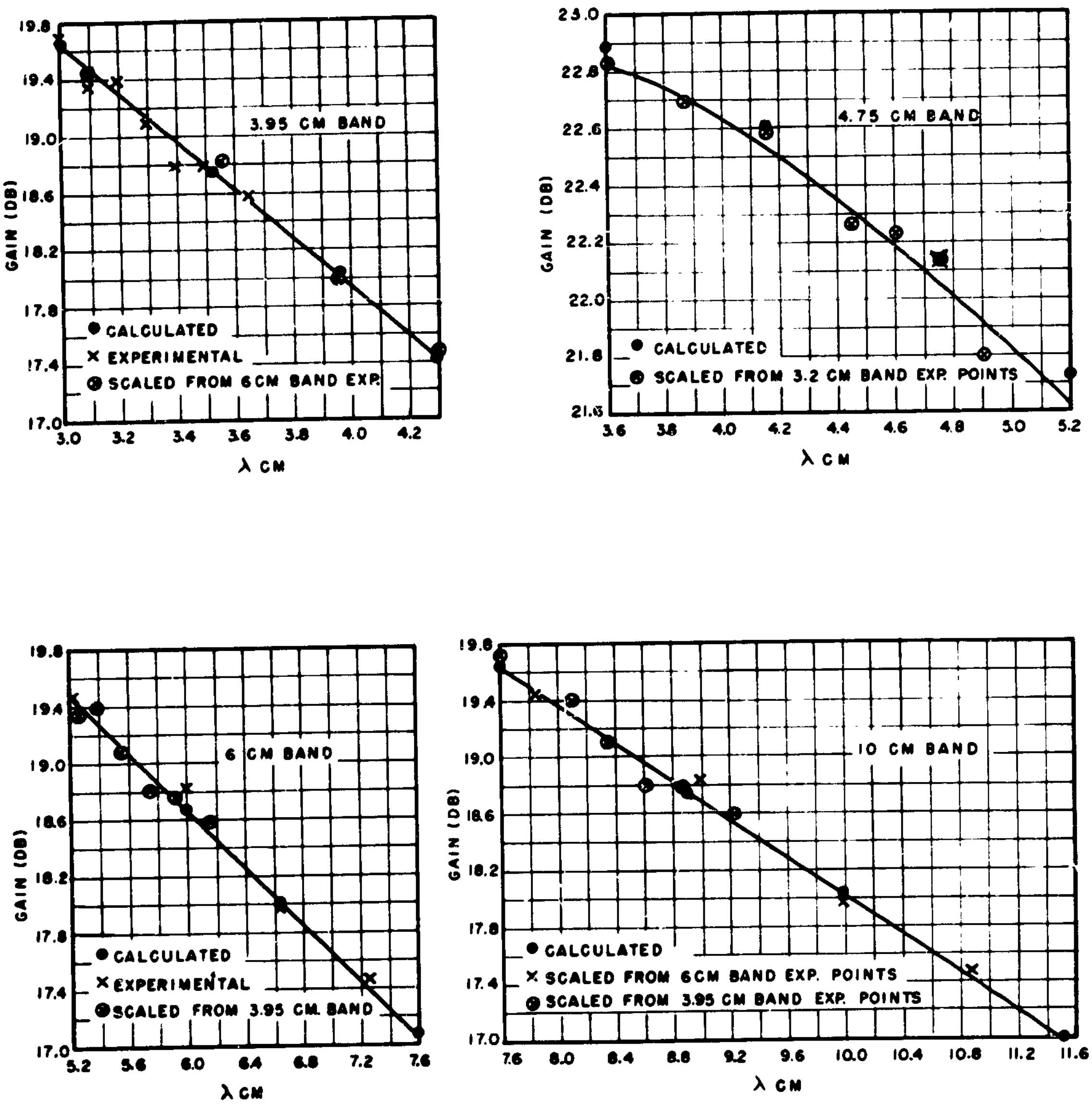
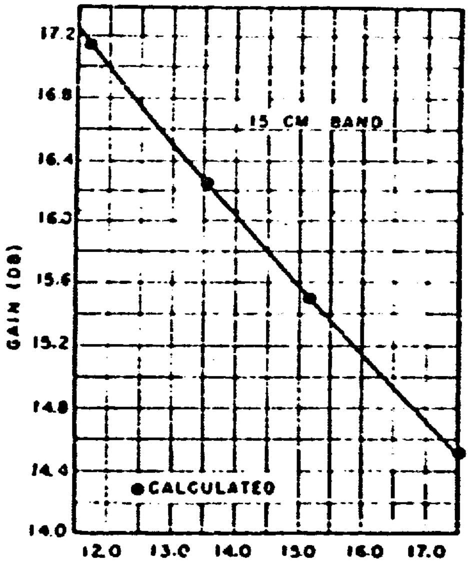
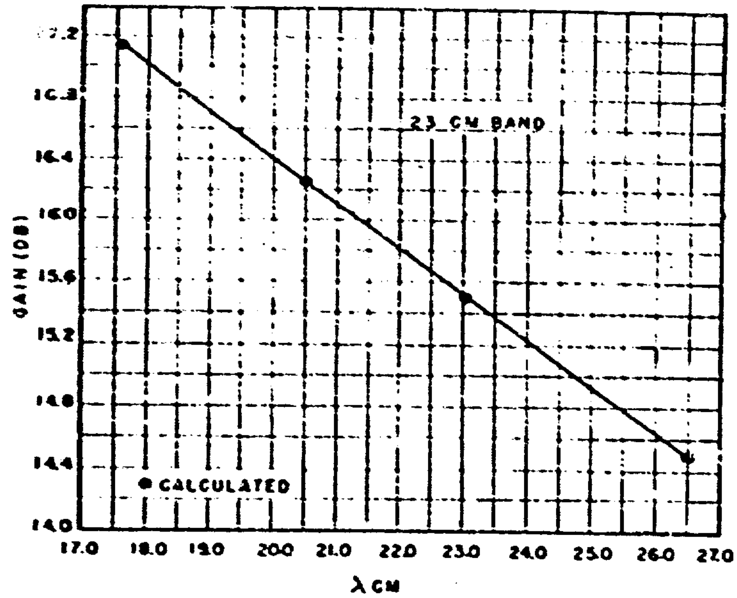
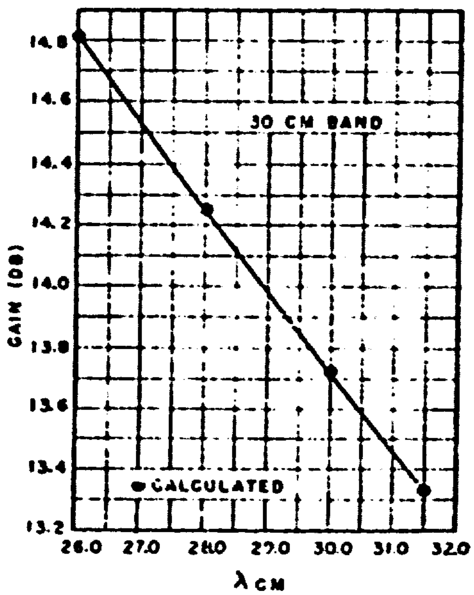


Fig. A-5 (b). Gain curves







CONVERSION CHART

f (Mc)	λ (cm)	f (Mc)	λ (cm)	f (Mc)	λ (cm)	f (Mc)	λ (cm)	f (Mc)	λ (cm)
1000	30.00	2800	10.71	4600	6.52	6400	4.69	8200	3.66
1050	28.57	2850	10.53	4650	6.45	6450	4.65	8250	3.64
1100	27.27	2900	10.34	4700	6.38	6500	4.62	8300	3.61
1150	26.09	2950	10.17	4750	6.32	6550	4.58	8350	3.59
1200	25.00	3000	10.00	4800	6.25	6600	4.55	8400	3.57
1250	24.00	3050	9.84	4850	6.19	6650	4.51	8450	3.55
1300	23.08	3100	9.68	4900	6.12	6700	4.48	8500	3.53
1350	22.22	3150	9.52	4950	6.06	6750	4.44	8550	3.51
1400	21.43	3200	9.38	5000	6.00	6800	4.41	8600	3.49
1450	20.69	3250	9.23	5050	5.94	6850	4.38	8650	3.47
1500	20.00	3300	9.09	5100	5.88	6900	4.35	8700	3.45
1550	19.35	3350	8.96	5150	5.83	6950	4.32	8750	3.43
1600	18.75	3400	8.82	5200	5.77	7000	4.29	8800	3.41
1650	18.18	3450	8.70	5250	5.71	7050	4.26	8850	3.39
1700	17.65	3500	8.57	5300	5.66	7100	4.23	8900	3.37
1750	17.14	3550	8.45	5350	5.61	7150	4.20	8950	3.35
1800	16.67	3600	8.33	5400	5.56	7200	4.17	9000	3.33
1850	16.22	3650	8.22	5450	5.50	7250	4.14	9050	3.31
1900	15.79	3700	8.11	5500	5.45	7300	4.11	9100	3.30
1950	15.38	3750	8.00	5550	5.41	7350	4.08	9150	3.28
2000	15.00	3800	7.89	5600	5.36	7400	4.05	9200	3.26
2050	14.63	3850	7.79	5650	5.31	7450	4.03	9250	3.24
2100	14.29	3900	7.69	5700	5.26	7500	4.00	9300	3.23
2150	13.95	3950	7.59	5750	5.22	7550	3.97	9350	3.21
2200	13.64	4000	7.50	5800	5.17	7600	3.95	9400	3.19
2250	13.33	4050	7.41	5850	5.13	7650	3.92	9450	3.17
2300	13.04	4100	7.32	5900	5.08	7700	3.90	9500	3.16
2350	12.77	4150	7.23	5950	5.04	7750	3.87	9550	3.14
2400	12.50	4200	7.14	6000	5.00	7800	3.85	9600	3.13
2450	12.24	4250	7.06	6050	4.96	7850	3.82	9650	3.11
2500	12.00	4300	6.98	6100	4.92	7900	3.80	9700	3.09
2550	11.76	4350	6.90	6150	4.88	7950	3.77	9750	3.08
2600	11.54	4400	6.82	6200	4.84	8000	3.75	9800	3.06
2650	11.32	4450	6.74	6250	4.80	8050	3.73	9850	3.05
2700	11.11	4500	6.67	6300	4.76	8100	3.70	9900	3.03
2750	10.91	4550	6.59	6350	4.72	8150	3.68	9950	3.02
								10000	3.00

Fig. A-5(c). Gain curves and conversion chart

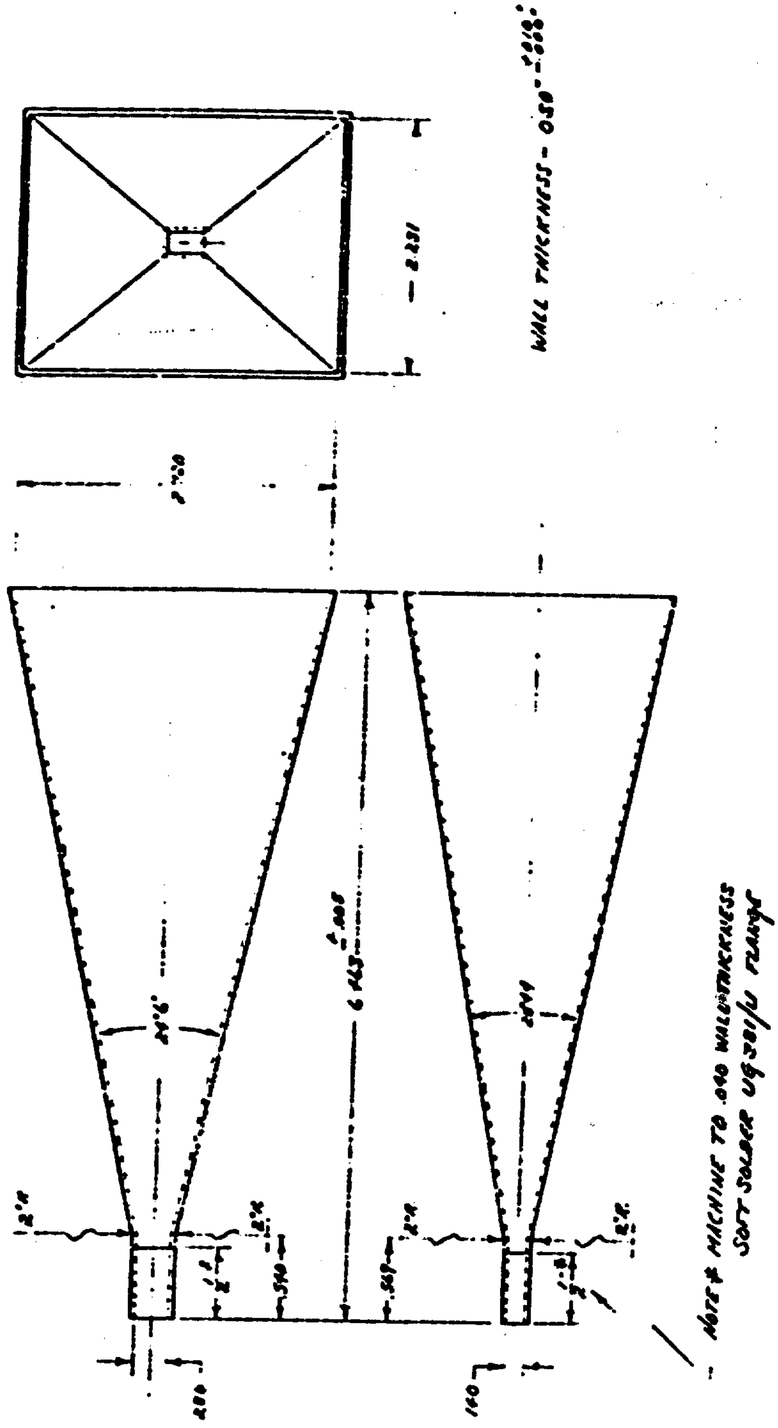


Fig. A-6. Electroformed horn, 8-mm-band gain-standard (0.77-1.13 cm)

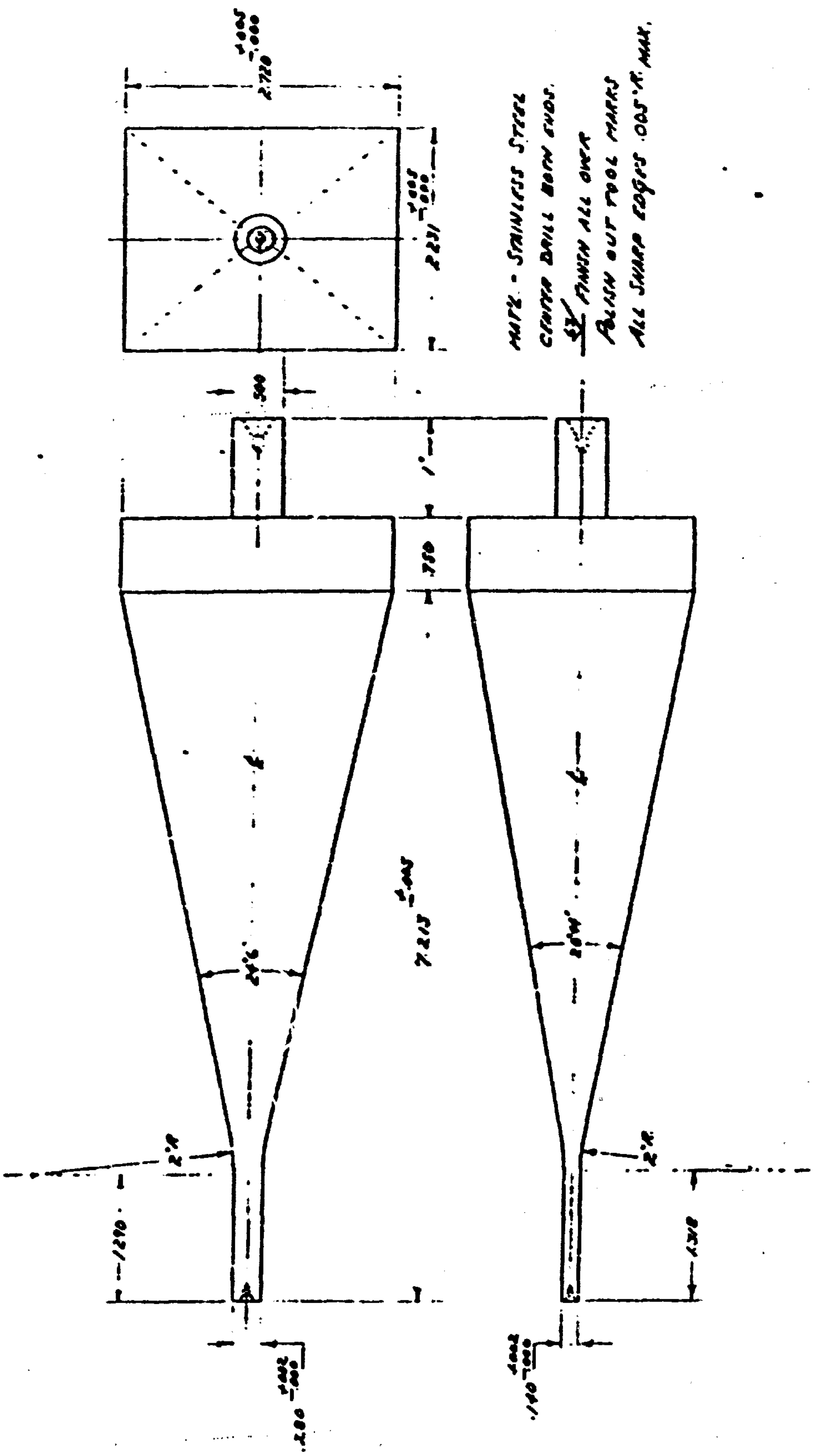


Fig. A-7. Mandril for electroforming 8-mm-band gain-standard horn

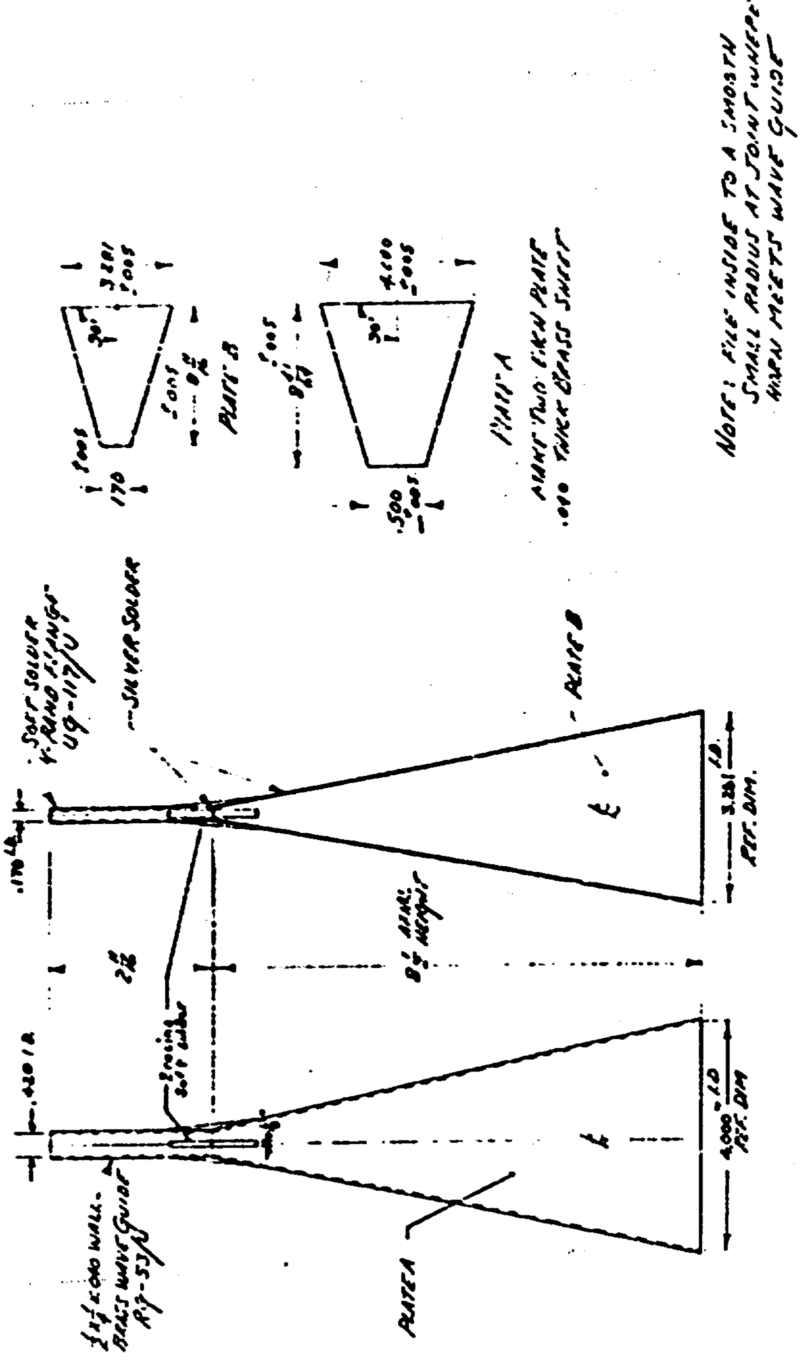


Fig. A-8. 1.25-cm-band gain-standard horn (1.13-1.66 cm)

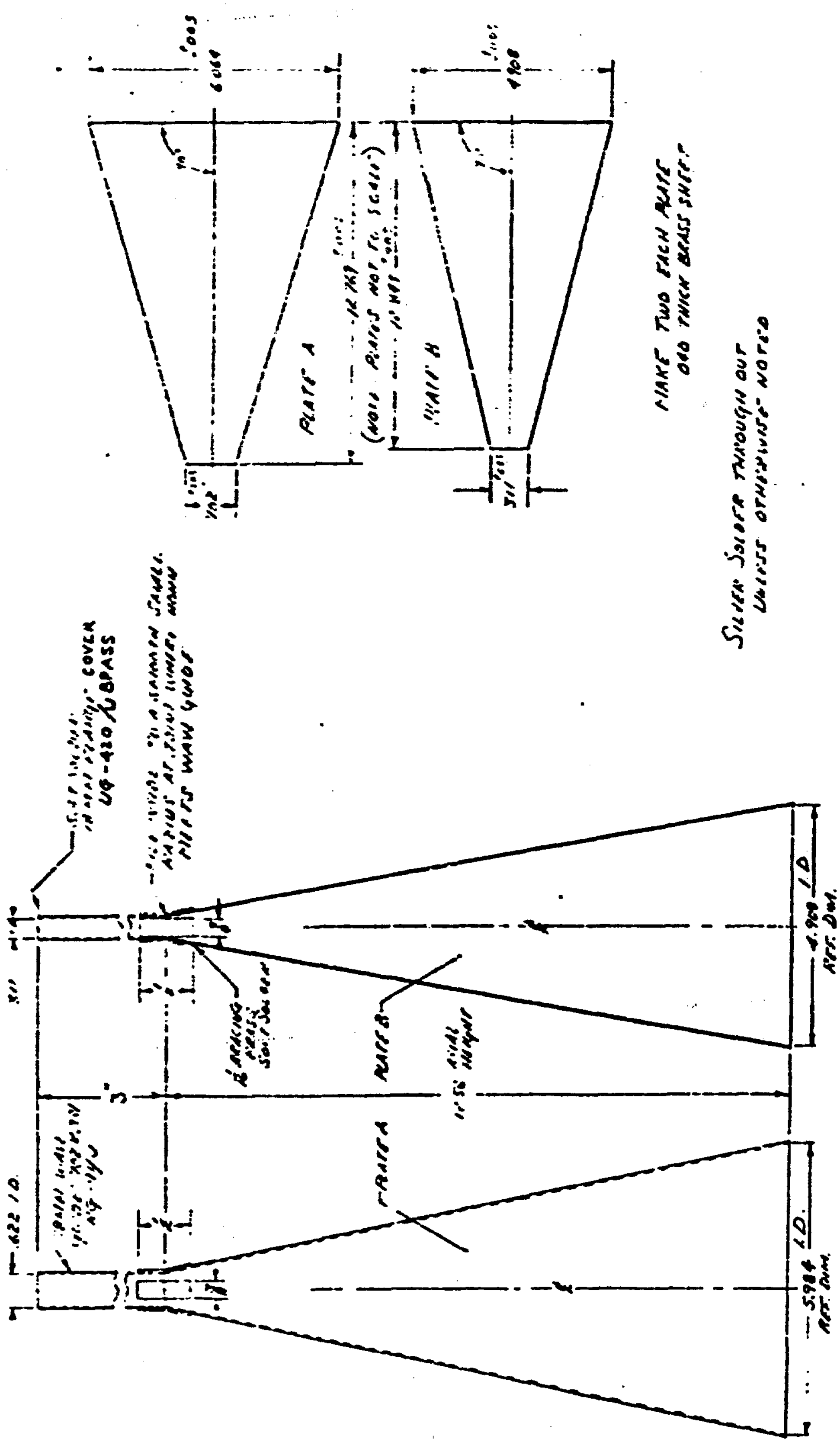


Fig. A-9. 18-mm-band gain-standard horn (1.66-2.42 cm)

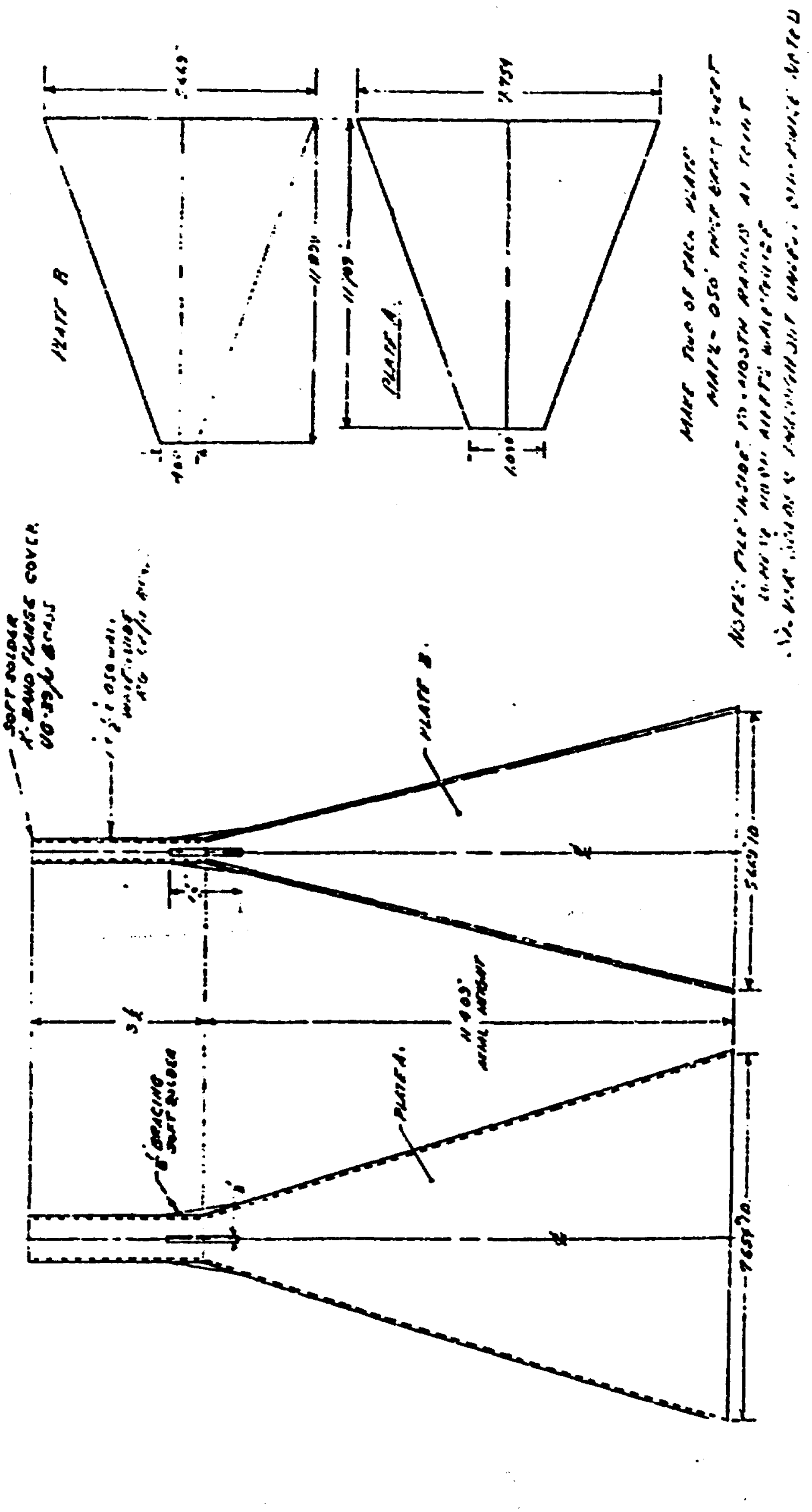


Fig. A-10. 3.2-cm-band gain-standard horn (2.42-3.70 cm)

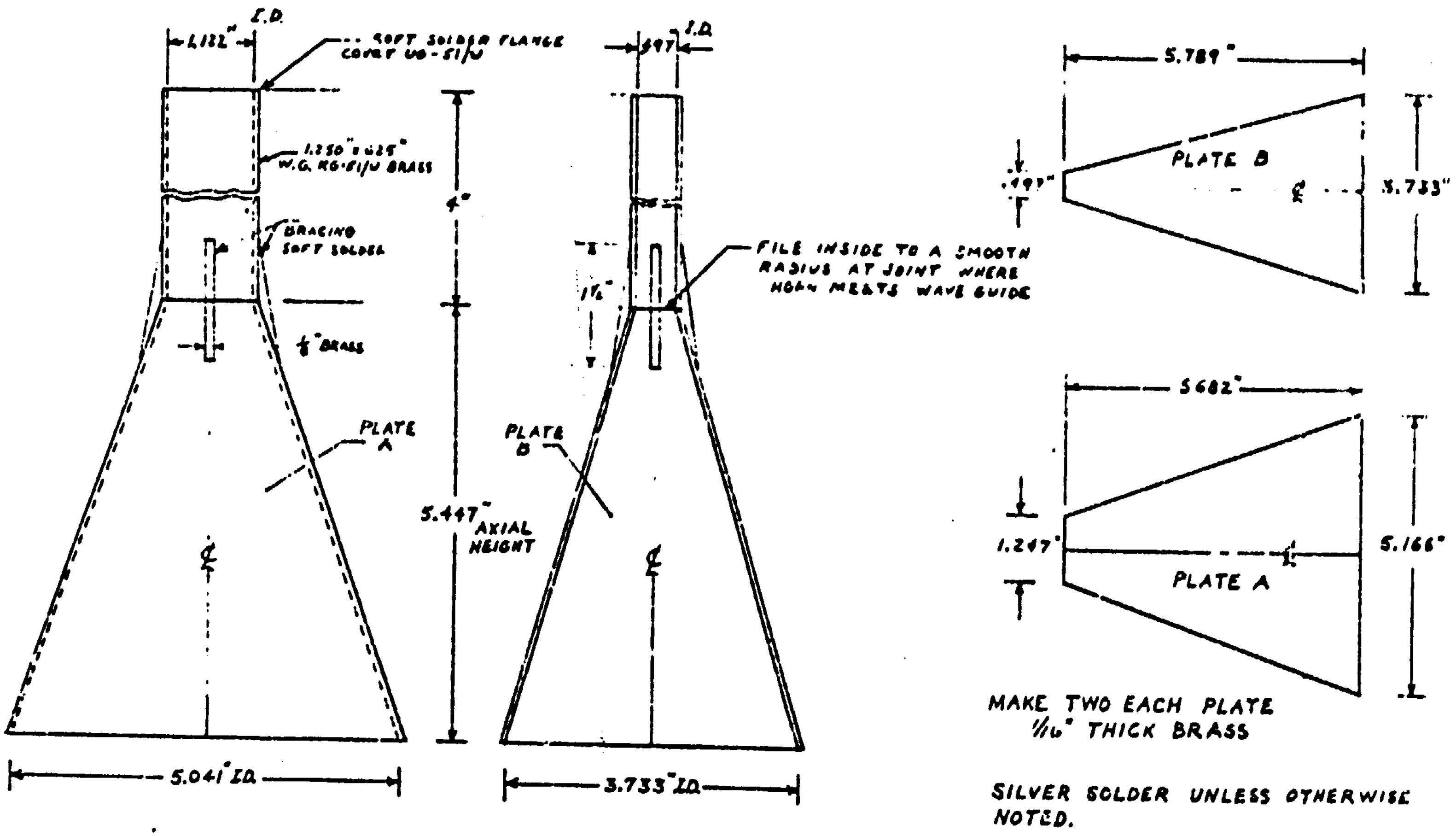


Fig. A-11. 3.95-cm-band gain-standard horn (3.0-4.30 cm)

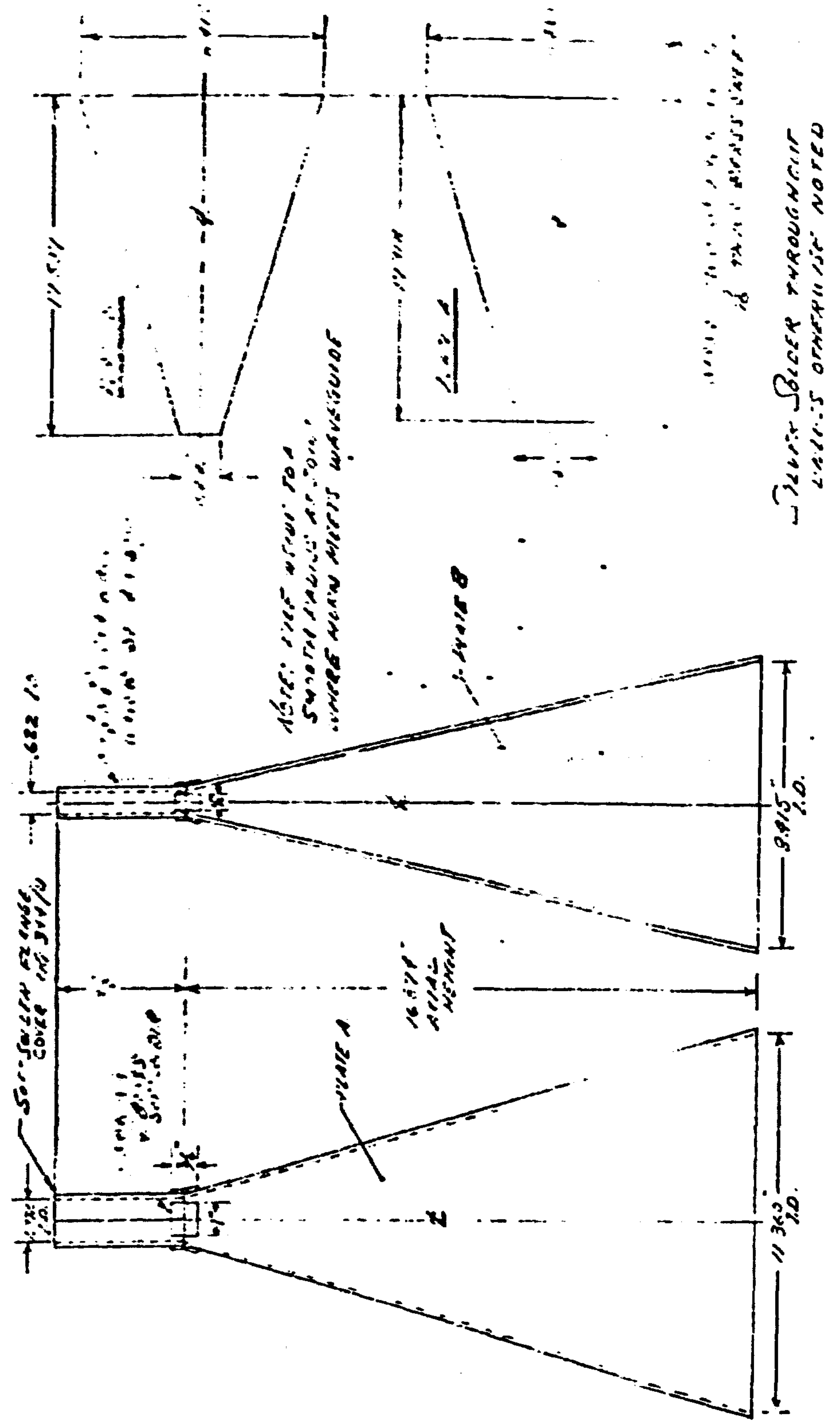


Fig. A-12. 4.75-cm-band gain-standard horn (3.60-5.20 cm)

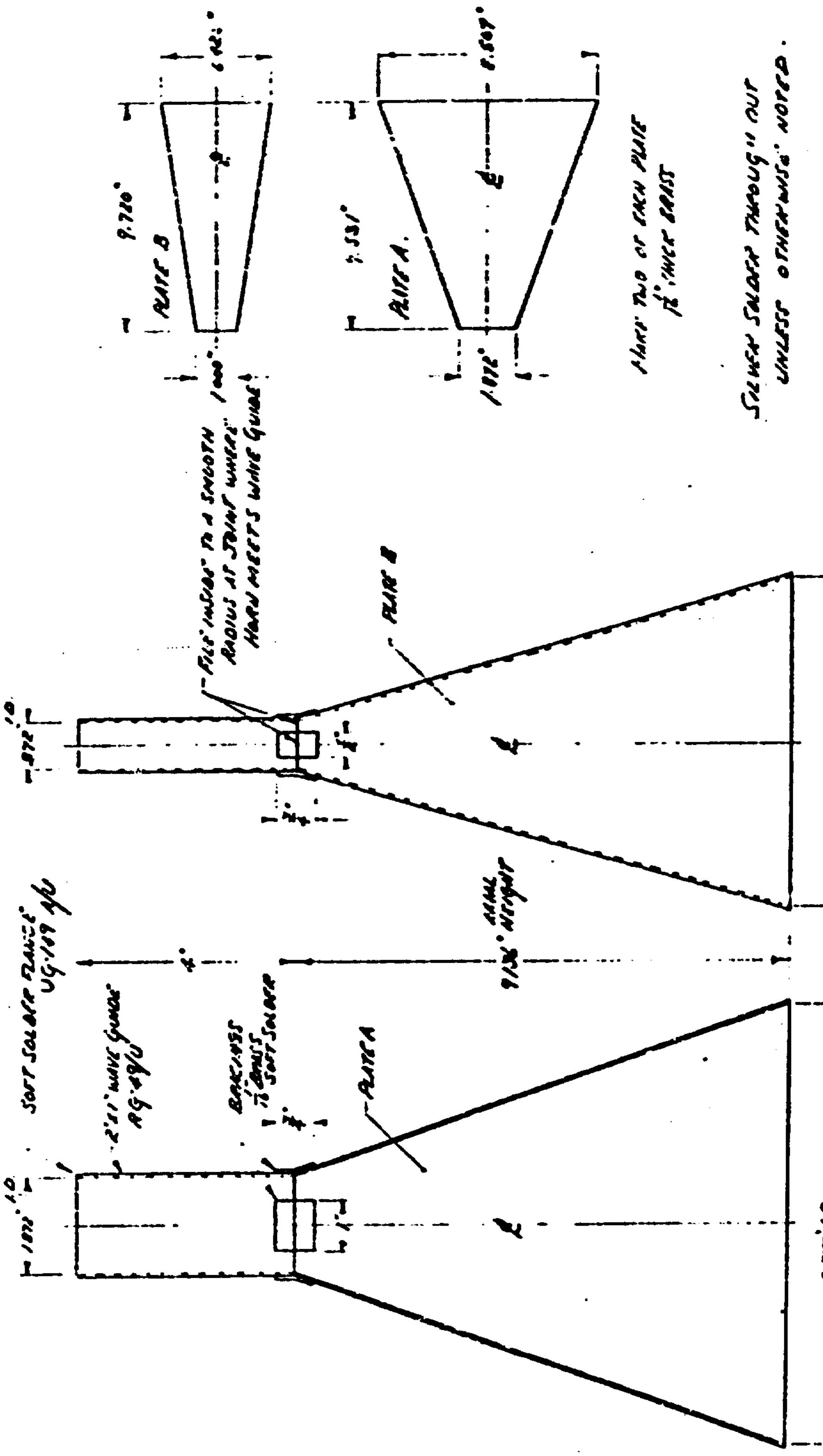


Fig. A-13. 6-cm-band gain-standard horn (5.10-7.60 cm)

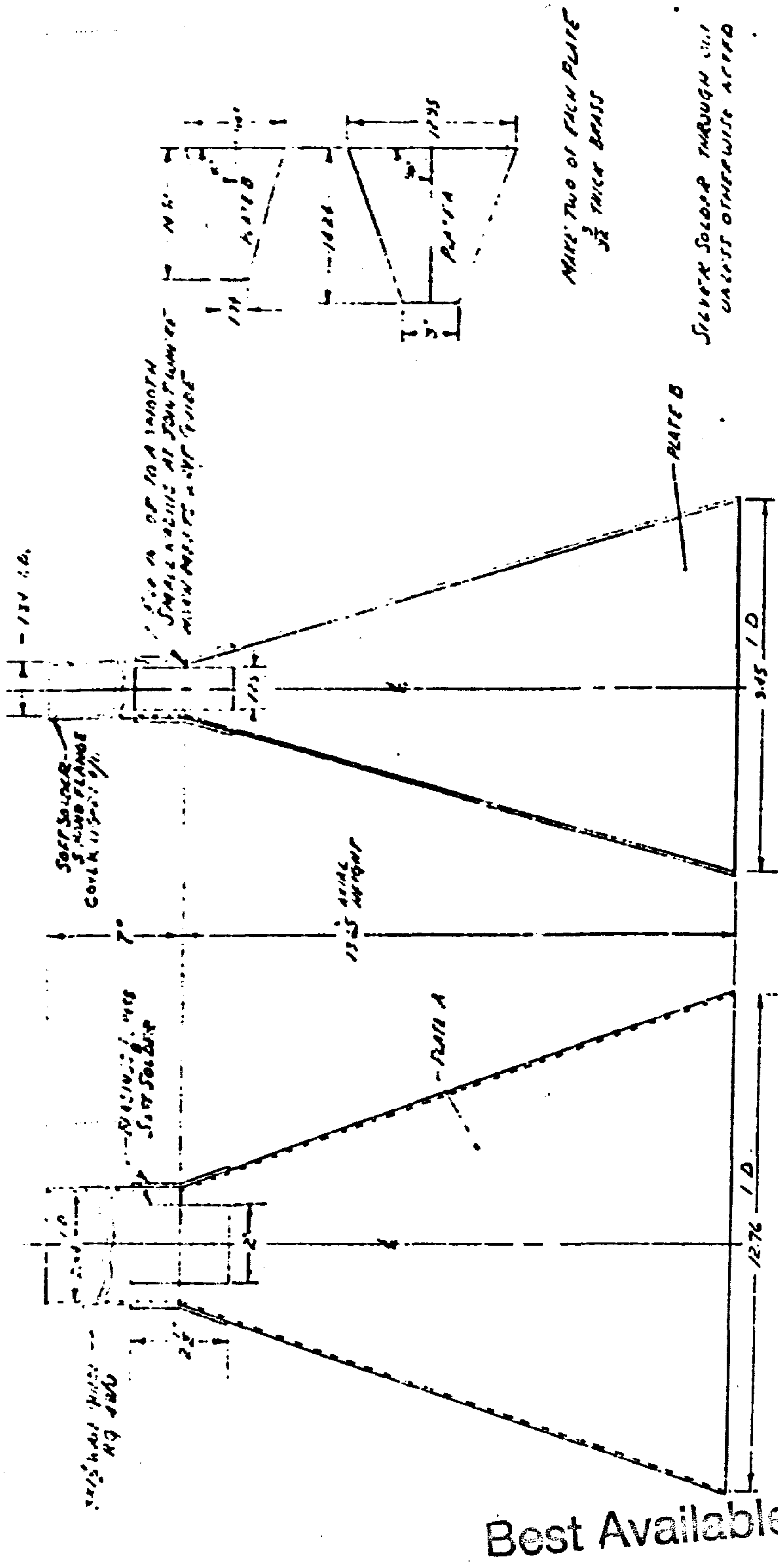
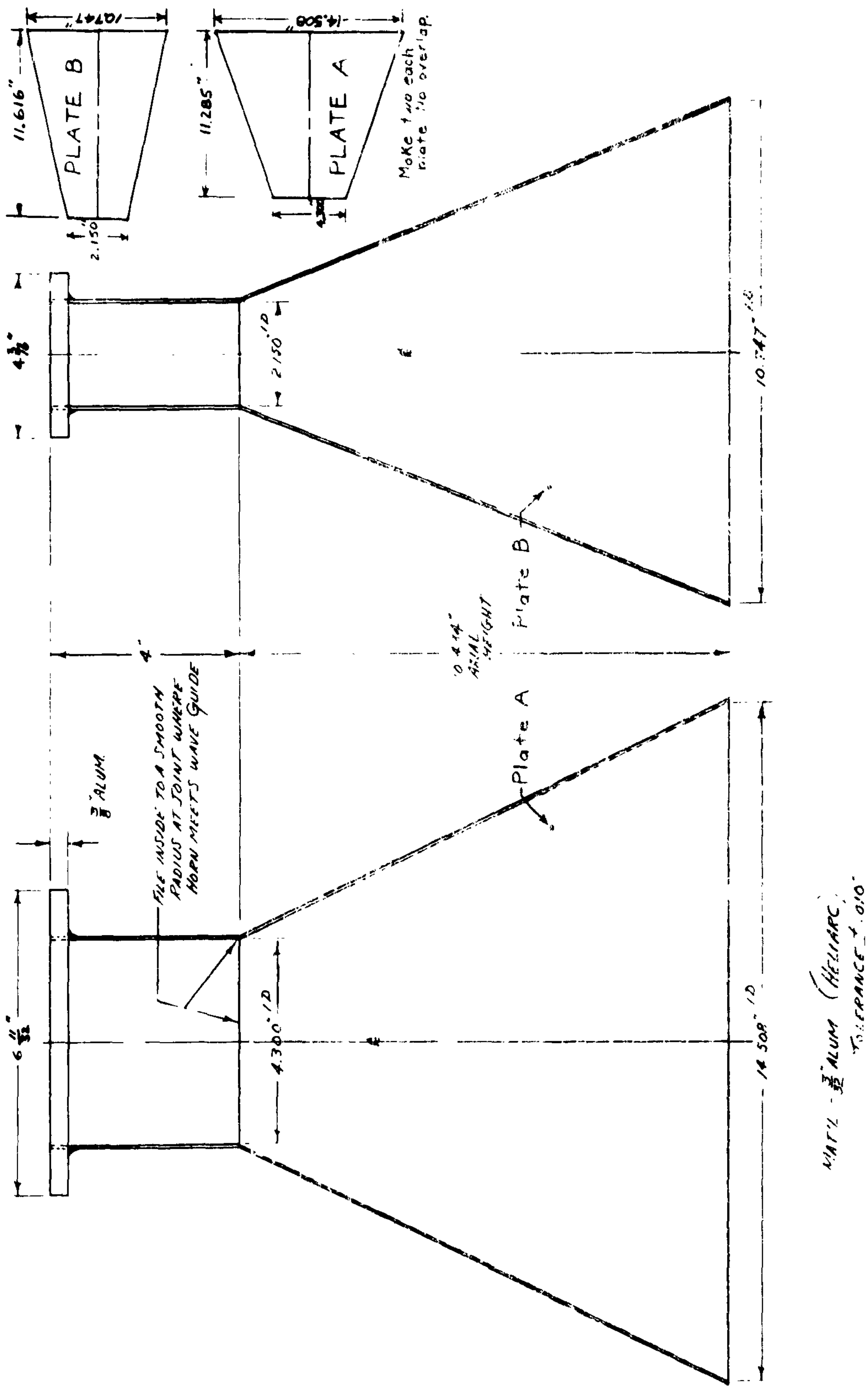


Fig. A-14. 10-cm-band gain-standard horn (7.60-11.5 cm)



.. 15-cm-band gain-standard horn (11.5-17.6 cm)

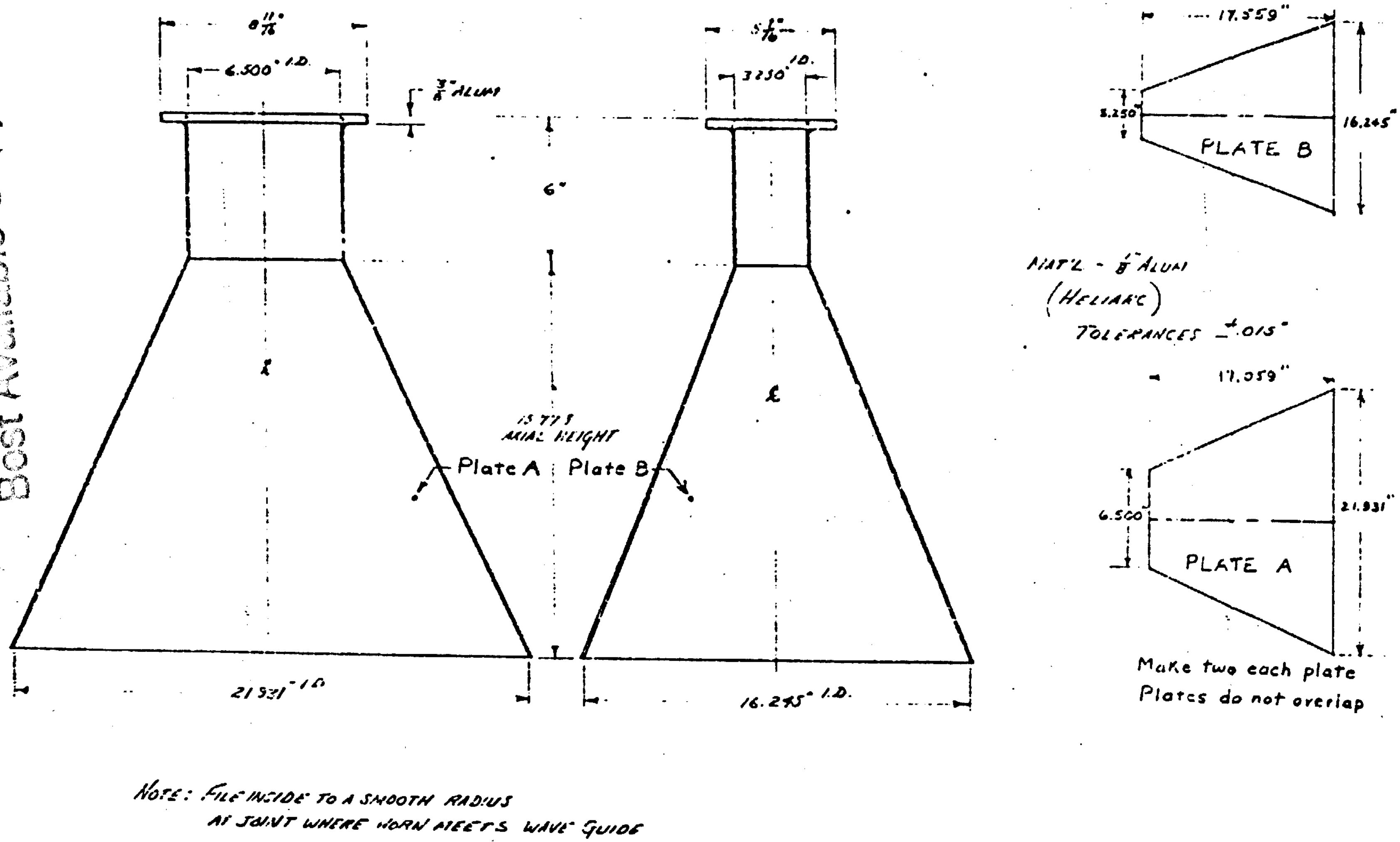


Fig. A-16. 23-cm-band gain-standard horn (17.6-26.5 cm)

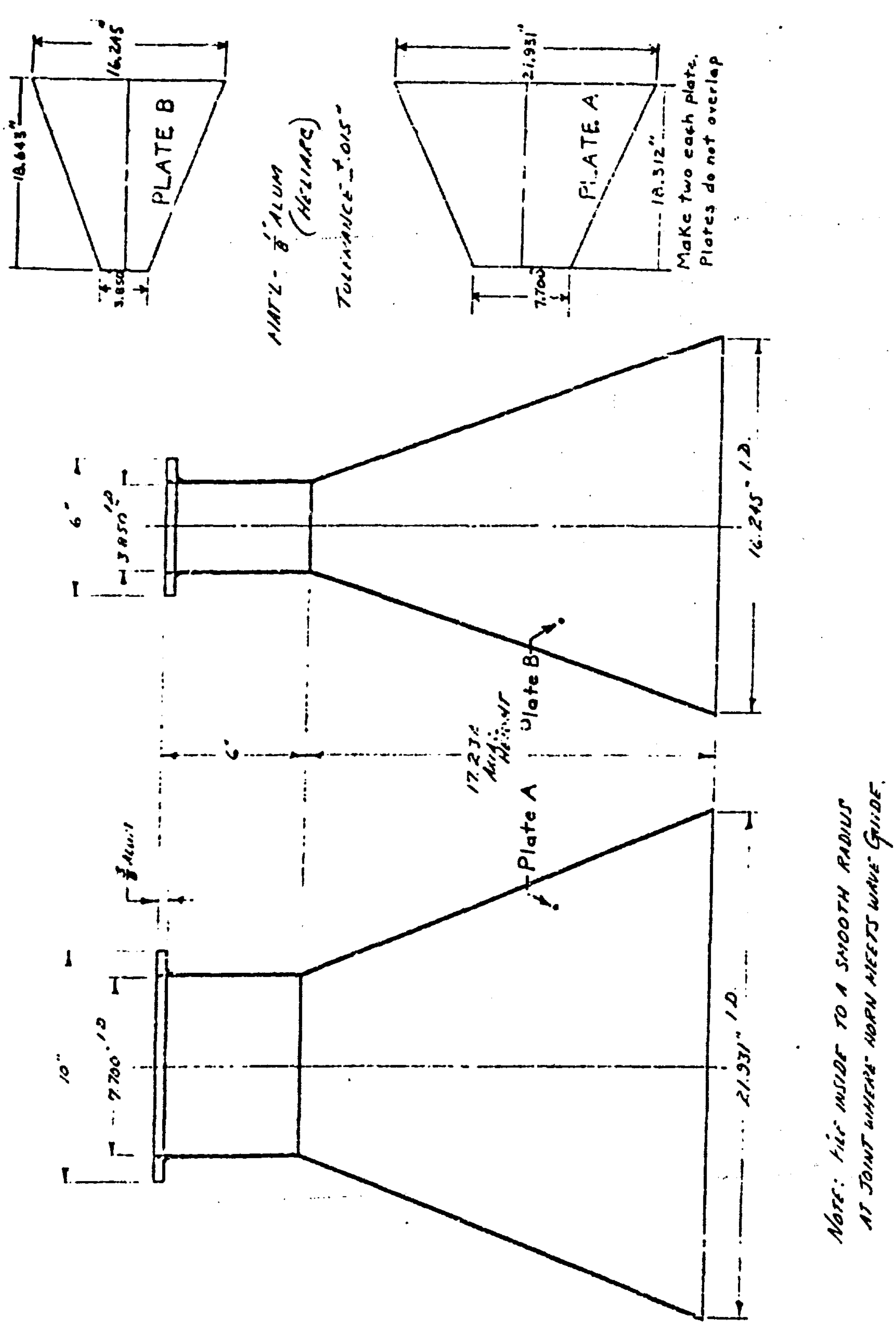


Fig. A-17. 30-cm-band gain-standard horn (26.0-31.5 cm)