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NRL REPORT NO. R-3224

FR-3224

ANTENNA FOR RADAR BOMB DIRECTOR MARK 5 (AN/APB-2)

A. S. Dunbar

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Problem No. 34R09-16 January 22, 1948

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ABSTRACT

This report describes the electrical design of the antenna for Bomb Director Mark 5. One of the specifications for the design of the antenna is that it provide a radiation pattern in elevation for uniform ground return from a maximum slant range of 50 miles to the bombing angle for altitudes varying from 1000 feet to 40,000 feet. This requires that the radiation pattern be subject to control both in direction and in the distribution of power.

The antenna consists of a doubly curved reflector and a hog-horn feed. The reflector surface was calculated to produce a $\csc^2\theta \cos\theta$ pattern from the primary radiation pattern of the horn feed, by the method described in NRL Report R-3193. The resulting antenna patterns for three positions of the horn feed permit a variation in altitude from 5000 feet to 40,000 feet. The half-power width of the beam in azimuth is 2.5°.

The hog-horn feed is pressurized by means of a plastic cup over the mouth of the horn. The thickness and position of the cup are adjusted to produce an impedance match such that the standing-wave-voltage ratio is less than 1.11 over a frequency band from 9268 Mc to 9456 Mc.

PROBLEM STATUS

The work described in this report represents the completion of the electrical design of the Antenna for Bomb Director Mark 5, problem No. 34R09-16. Consultative services in regard to the manufacture of the antenna will continue.

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ANTENNA FOR RADAR BOMB DIRECTOR MARK 5 (AN/APB-2)

INTRODUCTION

Statement of the Problem

By BuOrd letter (Re8d-96)NP14, dated 11 June 1946, an antenna and antenna feed for the Bomb Director Mark 5 Mod. 0 were to be designed, in cooperation with the contractor for the complete director.[1] The antenna should provide minimum beam-width consistent with a spherical clearance space, 42 inches in diameter, and the radiation pattern in elevation should provide uniform ground return from a maximum slant range of 50 miles to the aiming point. The antenna design should be based on the following data:

1. Probable mean altitude, 20,000 feet.

2. Altitude over which antenna should provide uniform ground return from maximum slant range of 50 miles to the aiming point, 1,000 to 40,000 feet.

3. Probable mean speed of aircraft, 400 knots.

4. Operating frequency of system, 9375 $\pm$ 55 Mc.
   Operating frequency for beacon, 9310 $\pm$ 2.5 Mc.

5. Horizontal polarization of the radiation from the antenna.

The Proposed Design

The requirement that the antenna should provide a radiation pattern in elevation for uniform ground return over a wide range in altitude is a particularly stringent one, and one that has never before been met except in a limited degree. In view of this fact, it was proposed that the antenna should consist of a doubly curved, shaped reflector with a horn feed. It was known that a doubly curved reflector surface could be calculated to produce, from a given primary feed, a specified radiation pattern. However, the limits between which this pattern could be controlled in shape and direction by simple motion of the feed horn, or of the reflector, was not known. It was felt, nevertheless, that the doubly curved reflector and horn feed formed the antenna design best suited to meet these specifications.

The Radiation Pattern in Elevation

The precise shape of the elevation pattern for an airborne bombing antenna is a matter of conjecture; however, an empirical expression which

1. *Norden Laboratories Corp., New York, N. Y.*

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most nearly fits the physical conditions observed in extensive flight tests is[2]

$$G(\theta) = k \csc^2\theta \cos\theta$$

where $G(\theta)$ is the power radiated by the antenna as a function of the angle of depression θ. Experiment also shows that the elevation pattern should conform as closely as possible to the required curve. A variation from the curve of plus or minus one decibel can be tolerated only if the variation is slow. The change of shape of this required pattern for increasing altitude, with the maximum slant range constant, is illustrated graphically in Figure 1.

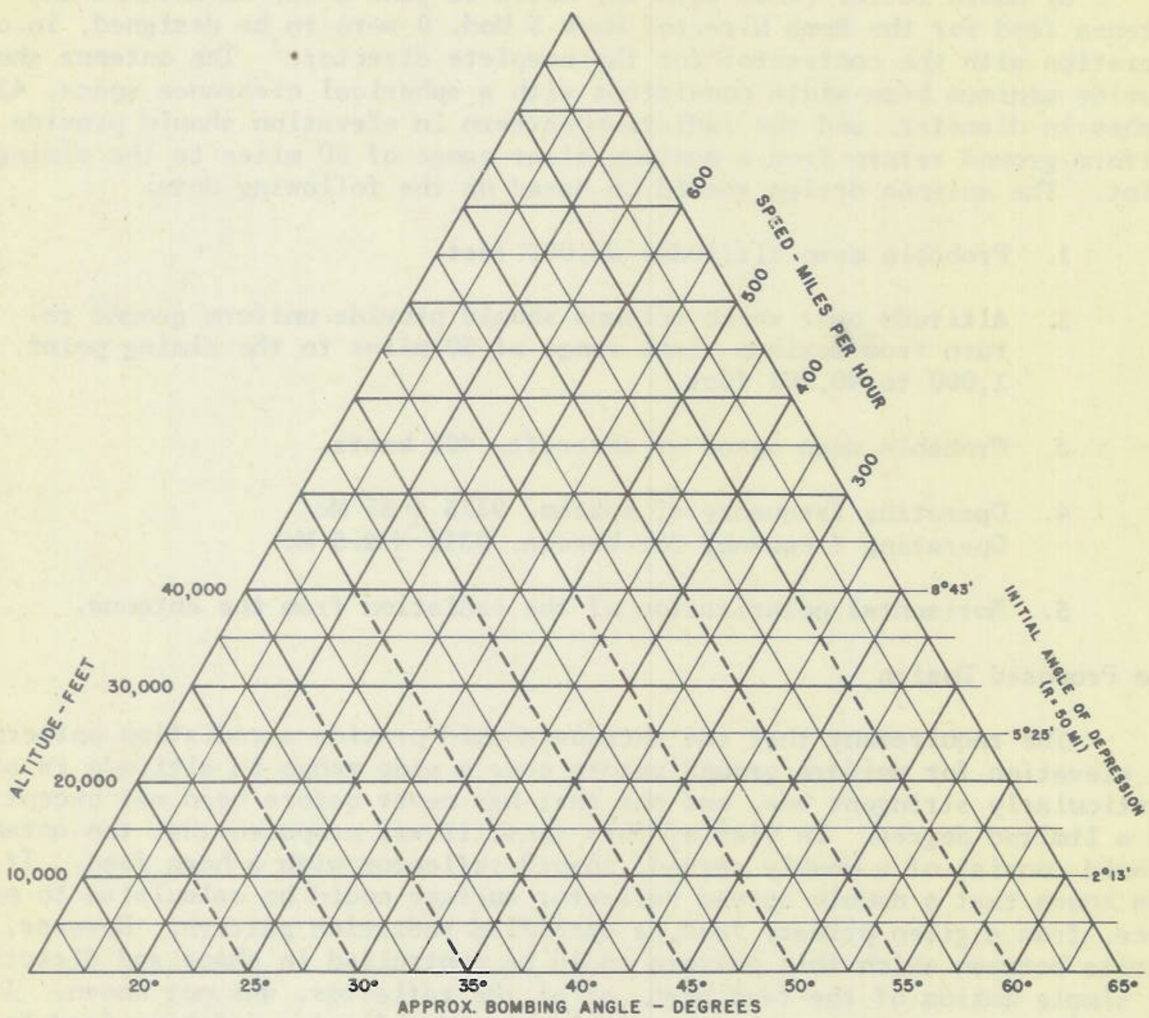


Figure 1. Approximate Bombing Angle vs. Altitude and Speed.

This chart shows that for an altitude of 25,000 feet and a speed of 400 miles per hour, the initial angle of depression for a range of 50 miles

2. Dunbar, A. S. "Calculation of double curved reflectors for shaped beams", NRL report R-3193 (in publication). Silver, S. and James, H. M. Microwave Antenna Theory and Design, McGraw Hill Book Co., Chapter 13, (in process).

is $5^{o}25'$, and the bombing angle is approximately $47^{o}30'$. Thus, the total coverage angle is about 42^{o}. For an altitude of 40,000 feet at the same speed, the initial angle of depression is nearly 9^{o} and the bombing angle is 55^{o}. In addition to the increase in the coverage angle with increasing altitude, the distribution of power in the elevacion pattern must vary, as illustrated in Figure 2. This is a family of curves, $\csc^2\theta \cos\theta$, for different values of the initial angle of depression. The shape of the required pattern is seen to vary considerably as the initial angle of depression, θ_{min}, changes.

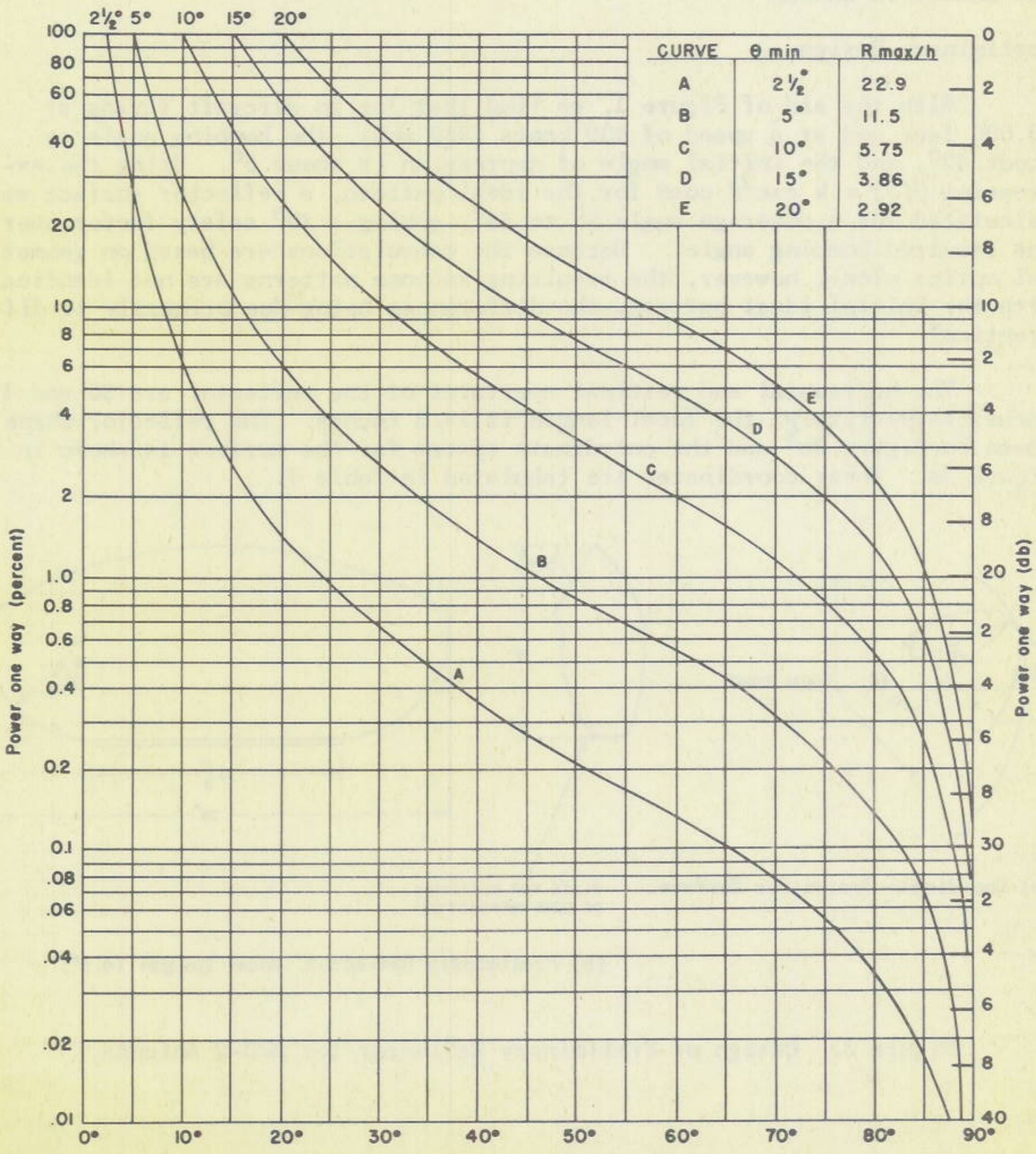


Figure 2. A Family of Curves, $\csc^2\theta \cos\theta$, for Different Values of Minimum Depression Angle.

[redacted]

Calculation of the Reflector

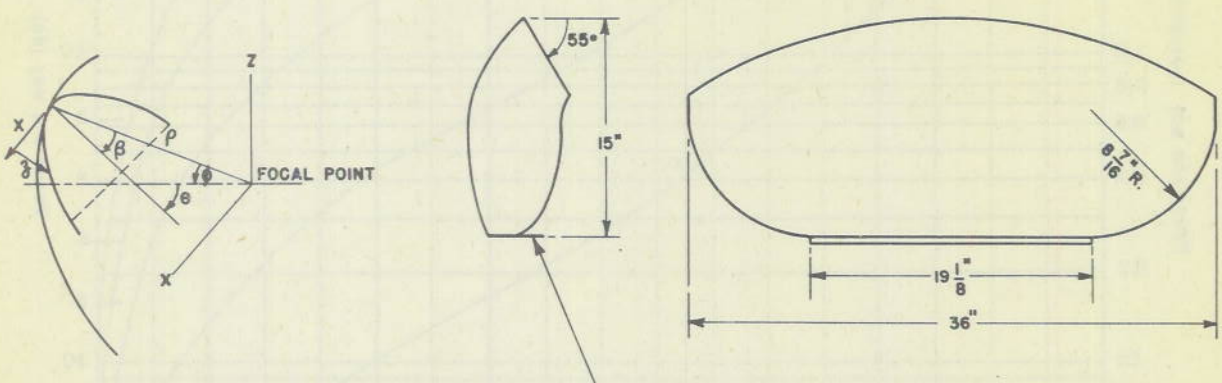
A method for the calculation of doubly curved surfaces to produce from a given point source a prescribed radiation pattern is described in detail in Report R-3193[3]. The reflector for the antenna for Bomb Director Mark 5 was calculated by this method. It is interesting to note that this antenna represents the first application of the method of calculation to a specific problem.

THE REFLECTOR DESIGN

Preliminary Design

With the aid of Figure 1, we find that for an aircraft flying at 20,000 feet and at a speed of 400 knots (460 mph), the bombing angle is about 42°, and the initial angle of depression is about 5°. Using the expression $G(\theta) = k \csc^2\theta \cos\theta$ for the ideal pattern, a reflector surface was calculated for a coverage angle 5° to 55°, giving a 10° safety factor over the required bombing angle. Because the calculations are based on geometrical optics alone, however, the resulting antenna patterns are not identical with the initial ideal pattern, the differences being due primarily to diffraction[4].

The horizontal and vertical apertures of the reflector are 36 and 15 inches respectively; the focal length is 14.5 inches. The reflector shape is shown in Figure 3b[5] and the coordinate system for the surface is shown in Figure 3a. These coordinates are tabulated in Table I.



(a) Coordinate System for Surface.

(b) Preliminary Reflector, Focal Length 14.5".

Figure 3. Design of Preliminary Reflector for APB-2 Antenna.

3. cf of footnote 2.
4. Report R-3193, Appendix I.
5. cf NRL Drawing RA 66F 367.

TABLE I
Table of Coordinates for Preliminary Reflector

ø	ρ	β	θ	X=0	X=3"	X=6"	X=9"	X=12"	X=15"	X=18"
-30°	13.195	25°1'	55°1'	$z = 0$	.179	.716	1.610	2.863	4.473	6.441
-27.5°	13.321	23°54'	51°26'	$z = 0$	.176	.706	1.588	2.824	4.412	6.353
-25°	13.441	22°28'	47°28'	$z = 0$	.174	.696	1.566	2.784	4.350	6.264
-22.5°	13.554	20°33'	43°3'	$z = 0$	.171	.686	1.543	2.743	4.286	6.172
-20°	13.656	18°11'	38°11'	$z = 0$	.169	.676	1.521	2.704	4.224	6.083
-17.5°	13.745	15°34'	33°4'	$z = 0$	.167	.667	1.501	2.668	4.169	6.003
-15°	13.819	13°3'	28°3'	$z = 0$	.165	.660	1.484	2.639	4.124	5.938
-12.5°	13.881	10°55'	23°25'	$z = 0$	.164	.654	1.472	2.617	4.089	5.888
-10°	13.934	9°14'	19°14'	$z = 0$	.163	.650	1.463	2.600	4.063	5.851
-7.5°	13.979	8°4'	15°34'	$z = 0$	.162	.647	1.456	2.588	4.044	5.823
-5°	14.020	7°42'	12°42'	$z = 0$	.161	.645	1.451	2.579	4.030	5.804
-2.5°	14.062	8°5'	10°35'	$z = 0$	.161	.643	1.447	2.573	4.020	5.789
0	14.109	9°1'	9°1'	$z = 0$	.160	.642	1.444	2.567	4.012	5.777
+2.5°	14.162	10°22'	7°52'	$z = 0$	.160	.641	1.442	2.563	4.004	5.767
+5°	14.223	12°0'	7°0'	$z = 0$	.160	.640	1.439	2.559	3.998	5.758
+7.5°	14.293	13°52'	6°22'	$z = 0$	.160	.639	1.438	2.556	3.994	5.751
+10°	14.374	15°55'	5°55'	$z = 0$	.160	.638	1.436	2.553	3.990	5.745
+12.5°	14.467	18°6'	5°36'	$z = 0$	.159	.638	1.435	2.552	3.987	5.741
+15°	14.573	20°24'	5°24'	$z = 0$	.159	.638	1.435	2.550	3.985	5.738
+17.5°	14.695	22°45'	5°15'	$z = 0$	.159	.637	1.434	2.549	3.983	5.735
+20°	14.832	25°10'	5°10'	$z = 0$	.159	.637	1.433	2.548	3.981	5.733
+22.5°	14.985	27°36'	5°6'	$z = 0$	.159	.637	1.433	2.547	3.980	5.732
+25°	15.155	30°3'	5°3'	$z = 0$	.159	.637	1.432	2.546	3.979	5.730
+27.5°	15.344	32°31'	5°1'	$z = 0$	.159	.636	1.432	2.546	3.978	5.729
+30°	15.547	35°0'	5°0'	$z = 0$	.159	.636	1.432	2.546	3.978	5.728
+32.5°	15.737									

Note:
Tolerances for above dimensions to be held within .015 over entire surface.

[redacted]

The measured antenna patterns for the preliminary reflector design are shown in Figure 4. The dotted curves are the corresponding $\csc^2\theta \cos\theta$ curves normalized to half power. These patterns indicate first that the

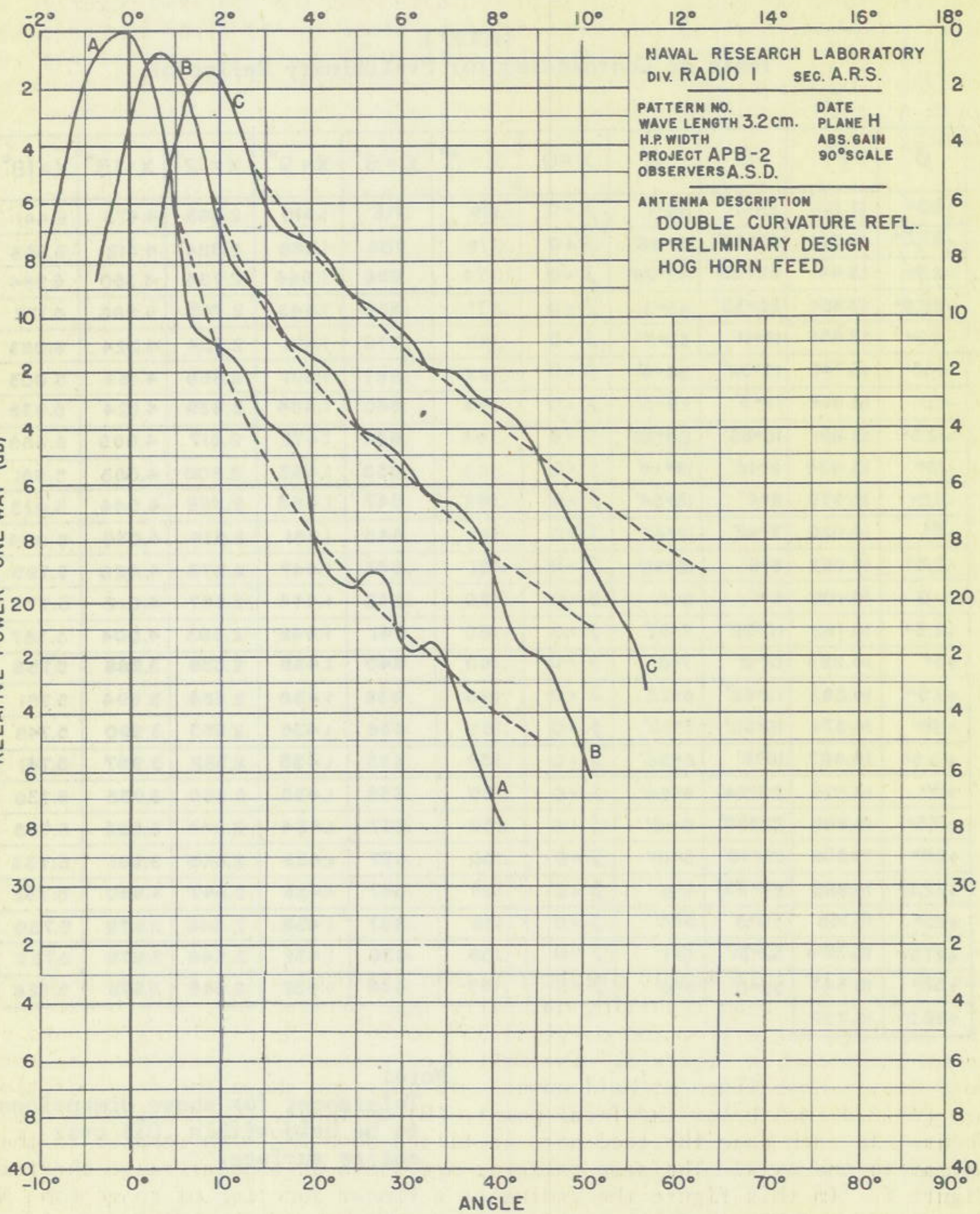


Figure 4. Antenna Patterns for Preliminary Reflector Design Showing Control of Pattern for Altitude.

antenna will permit a reasonably wide latitude in the control of the pattern for altitude. They indicate secondly that the pattern remains within the tolerance of ± 1 db in relation to the corresponding $\csc^2\theta \cos\theta$ curve over the realized coverage angle. They also indicate that the realized coverage angle falls somewhat short of the desired width, since the realized coverage angle is about 38° (i.e. from 4° to 42° for pattern B) which is just the required coverage angle for bombing. It was considered essential that the coverage angle be extended in order that the realized pattern should reach beyond the bombing angle.

The feed positions for the three patterns shown in Figure 3 are (A) 1 inch below the focal point, (B) on focus, (C) 1 inch above the focus. In each case the feed was tilted 5° down with reference to the normal to the axis through the focal point. For these patterns a metal plate extending 2-3/8 inches from the center of the reflector's bottom edge was placed as shown in Figure 3b. The purpose of this plate is to reduce the diffraction lobes superimposed on the pattern by straight-edge diffraction from the bottom of the reflector[6].

Final Design

Because it was deemed essential that the coverage angle of the antenna be extended, a new reflector design was undertaken. In order to compensate for the shortcomings of the geometrical optics and in an attempt to use an expression for the ideal pattern that was physically attainable, the expression for $G(\theta)$ was taken as follows:

$$G(\theta) = 100\, e^{-k(\theta - \alpha)^2} \Bigg]_{\theta = 0^\circ}^{\theta = 6^\circ}$$

$$G(\theta) = k \csc^2\theta \cos\theta \Bigg]_{\theta = 6^\circ}^{\theta = 66^\circ}$$

The purpose of this was to predict, within reasonable limits, the shape of the peak of the beam resulting naturally from diffraction, and to extend the coverage angle from the original 55° to 66°. The resulting antenna patterns are shown in Figure 5. The dotted curves are the corresponding $\csc^2\theta \cos\theta$ curves normalized at half power. In patterns shown the feed positions are (A) 3/4 inch below the focal point, (B) on focus, (C) 3/4 inch above the focus. In each case the feed horn is tilted down 2½° with respect to the normal to the axis. The same patterns are shown on a polar range chart in Figure 6. In this figure the radius is a linear function of range (one way). Pattern (B) of Figure 5 is seen to extend well beyond the bombing angle, in

6. cf footnote 4.

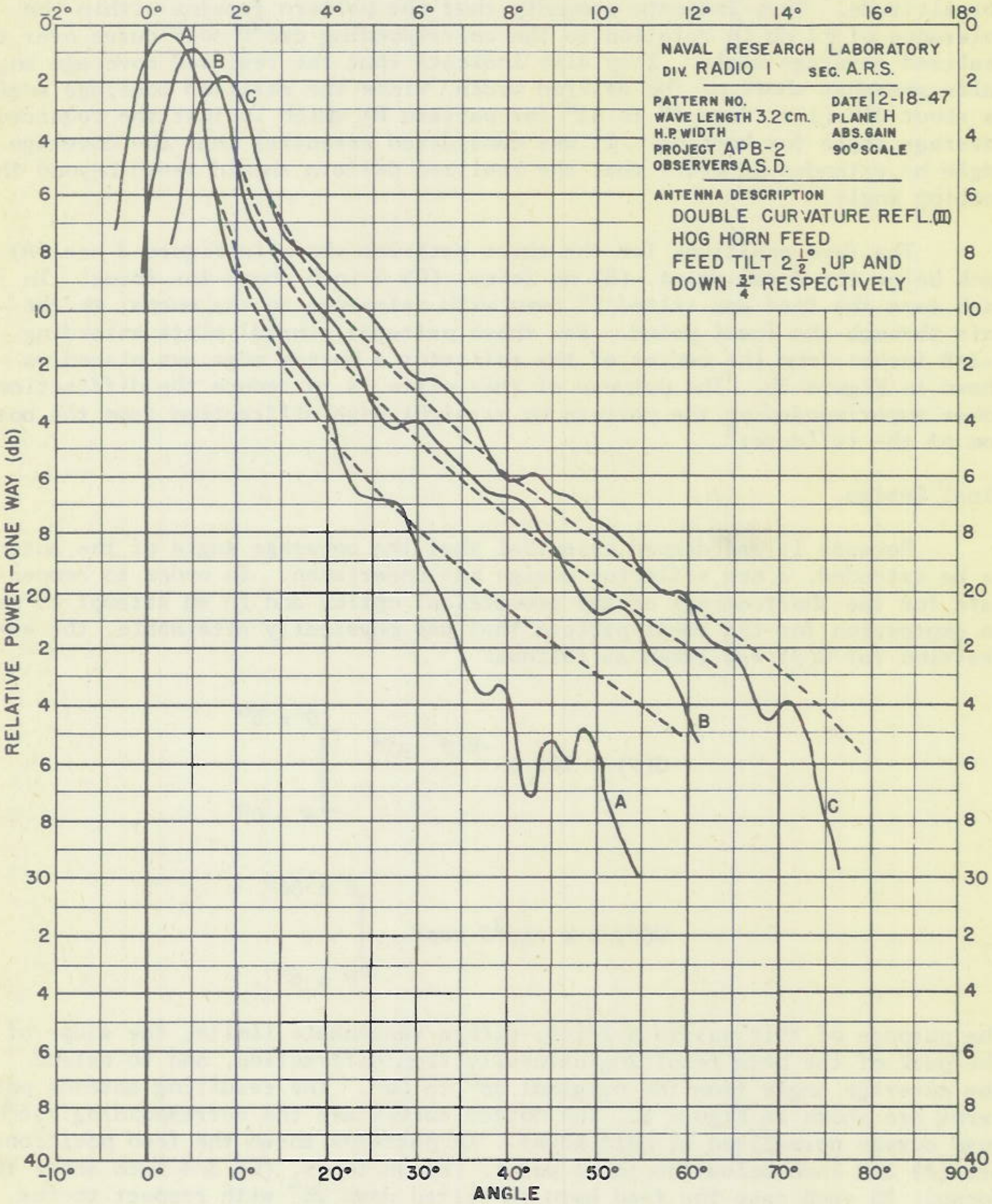


Figure 5. Antenna Patterns for Reflector (II) Showing Control of Patterns for Altitude.

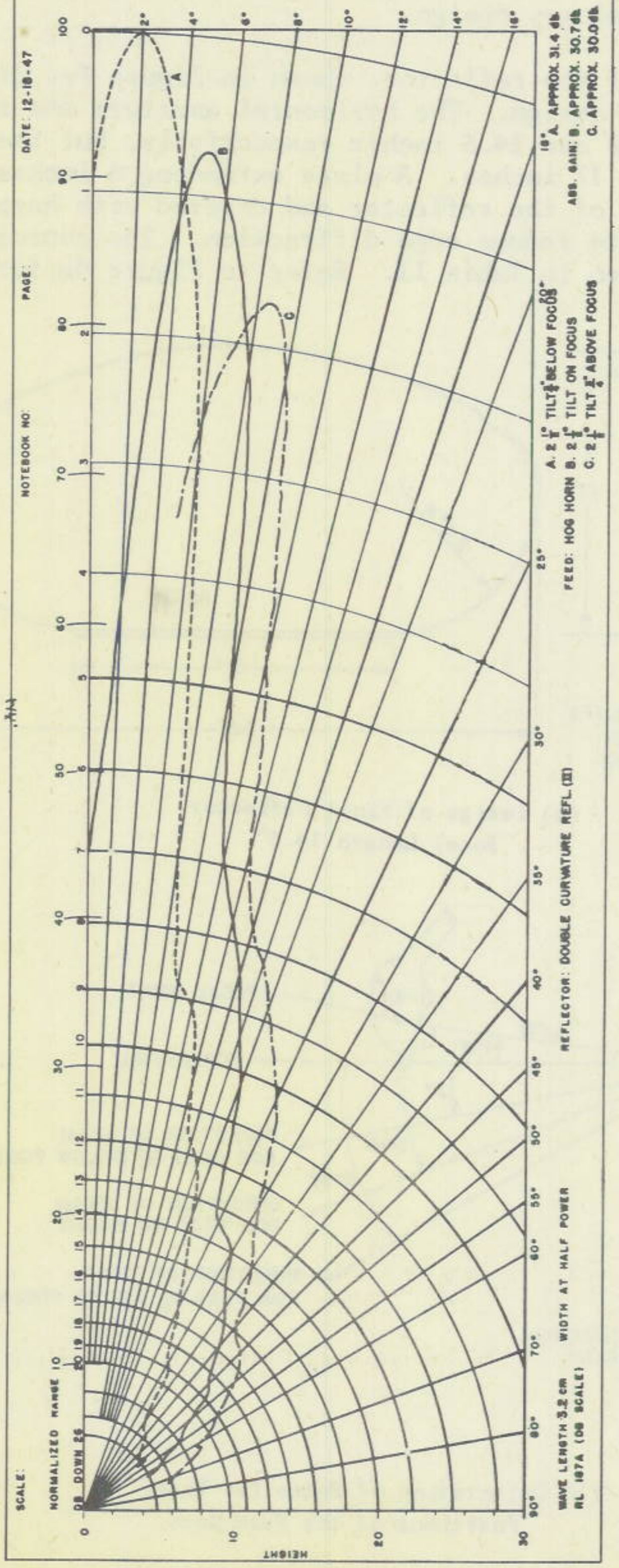
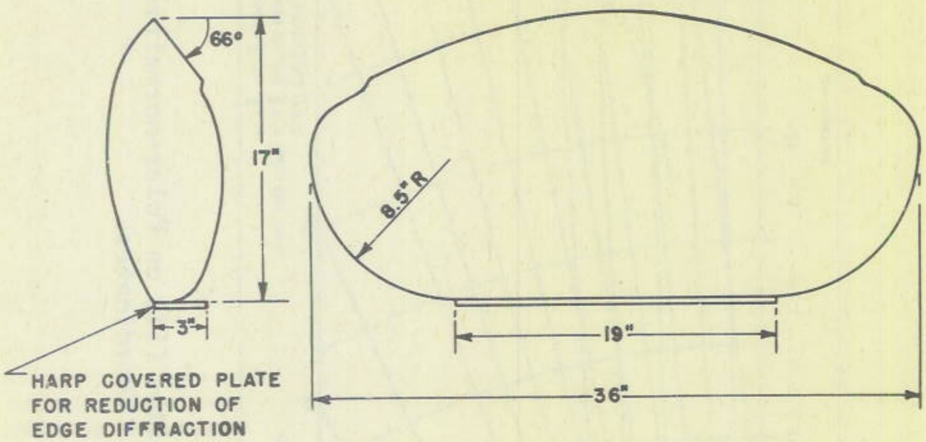


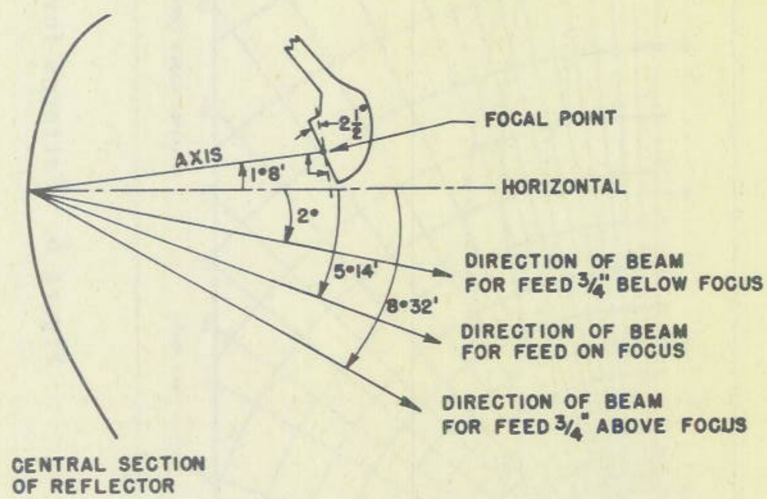
Figure 6. Patterns for Reflector (II) on Polar-normalized Range Coordinates.

fact, nearly to 60°. Patterns (A) and (C) are correspondingly improved over the patterns of the preliminary design.

The final design of the reflector, shown in Figure 7a, differs somewhat from the preliminary design. The horizontal aperture and the focal length were maintained, 36 and 14.5 inches respectively, but the vertical aperture was increased to 17 inches. A plate extending 3 inches from the center of the bottom edge of the reflector and covered with harp (r-f absorbing material) serves to reduce edge diffraction. The coordinates of the reflector surface are given in Table II. Refer to Figure 4a for the coordinate system.



(a) Design of Final Reflector
Focal Length 14.5".



(b) Orientation of Beams for Three
Positions of the Feed Horn.

Figure 7. Final Design of Reflector For APB-2 Antenna.

[redacted]

TABLE II
Table of Coordinates for Final Reflector

ϕ	ρ	θ	X=0	X=2	X=4	X=6	X=8	X=10	X=12	X=14	X=16	X=18	X_o	z_o
-30°	13.522	66°	$z=0$	.082	.327	.737	1.310	2.047	2.948	4.012			14.619	4.375
-28°	13.674	62°33'	$z=0$											
-26°	13.820	57°40'	$z=0$	.078	.313	.704	1.252	1.957	2.818	3.836			14.950	4.375
-24°	13.946	51°52'	$z=0$											
-22°	14.060	45°32'	$z=0$	.074	.297	.668	1.188	1.857	2.674	3.730			15.349	4.375
-20°	14.156	39°6'	$z=0$											
-18°	14.230	33°6'	$z=0$	.071	.286	.644	1.144	1.788	2.575	3.504			15.642	4.375
-16°	14.289	27°30'	$z=0$											
-14°	14.335	22°34'	$z=0$	.070	.281	.631	1.122	1.754	2.526	3.438	4.490		16.129	4.563
-12°	14.368	18°25'	$z=0$											
-10°	14.392	15°3'	$z=0$	.069	.278	.627	1.114	1.741	2.506	3.411	4.456		16.949	5.000
-8°	14.412	12°21'	$z=0$											
-6°	14.432	10°14'	$z=0$	.069	.277	.624	1.110	1.735	2.498	3.400	4.441		17.709	5.440
-4°	14.452	8°33'	$z=0$											
-2°	14.475	7°14'	$z=0$	.069	.277	.623	1.108	1.731	2.493	3.393	4.431	5.608		
0	14.500	6°10'	$z=0$											
+2°	14.528	5°17'	$z=0$	.069	.276	.622	1.106	1.728	2.488	3.386	4.423	5.598		
+4°	14.564	4°44'	$z=0$											
+6°	14.606	4°11'	$z=0$	.069	.276	.621	1.104	1.725	2.483	3.380	4.415	5.588		
+8°	14.654	3°40'	$z=0$											
+10°	14.708	3°12'	$z=0$	.069	.275	.620	1.102	1.722	2.479	3.374	4.407	5.578		
+12°	14.770	2°45'	$z=0$											
+14°	14.838	2°19'	$z=0$	.069	.275	.619	1.100	1.719	2.475	3.368	4.399	5.568		
+16°	14.916	1°56'	$z=0$											
+18°	15.000	1°33'	$z=0$	.068	.274	.618	1.098	1.716	2.471	3.363	4.393	5.560		
+20°	15.097	1°14'	$z=0$											
+22°	15.201	56'	$z=0$	.068	.274	.617	1.096	1.713	2.466	3.357	4.385	5.549		
+24°	15.317	41'	$z=0$											
+26°	15.435	29'	$z=0$	.068	.274	.616	1.095	1.710	2.463	3.353	4.379	5.542		
+28°	15.566	18'	$z=0$											
+30°	15.710	11'	$z=0$	.068	.273	.615	1.093	1.708	2.459	3.347	4.372	5.533		
+32°	15.869	6'	$z=0$											
+34°	16.036	2'	$z=0$	.068	.273	.614	1.091	1.705	2.455	3.341	4.364	5.524		
+36°	16.213	0°0'	$z=0$											
+39°	16.416	0°0'	$z=0$	.068	.273	.614	1.091	1.705	2.455	3.341	4.364	5.524		

Note:
Tolerances for above dimensions to be held within .015 over entire surface.

THE FEED HORN

Hog-Horn Design

The feed horn is a hog-horn of rather unconventional design, since it has smaller wavelength dimensions than are customarily associated with the hog-horn. The design was chosen in view of space considerations, because a flared horn with the same radiation pattern in the magnetic plane is considerably larger in size. A drawing of the hog-horn is shown in Figure 8. The plastic cup shown in the drawing is for pressurization purposes, i.e., to maintain constant atmospheric pressure within the horn and thereby prevent electrical breakdown at high altitude. The cup also serves as a matching device. The magnetic-plane radiation pattern of the horn is shown in Figure 9.

Impedance

It has been indicated that the plastic pressurizing cup serves a twofold purpose since, in addition to maintaining constant pressure within the horn, it is of the proper thickness to cancel the reflections of energy from the horn mouth and thereby serve as an impedance transformer. That is, the amplitude reflection coefficient of a thin dielectric sheet is of the form

$$\Gamma \doteq r\left[1 + t^2 e^{ik2d} + t^2 r^2 e^{ik4d} + \dots\right]$$

where r is the reflection coefficient of the dielectric; t is the transmission coefficient of the dielectric; and d is the electrical thickness. Thus, if the initial mismatch of the horn produces a reflection coefficient Γ_0, the reflection coefficient Γ of the cup can be adjusted by proper choice of thickness and position to cancel exactly the coefficient Γ_0. This method of matching has the feature of producing an impedance match over a broad frequency band.

Figure 10 shows the impedance chart for the hog-horn feed. Curve (A) is the impedance plot for the unmatched horn. Curve (B) is the impedance plot of the horn with the pressurizing cup in place. The standing-wave voltage ratio is less than 1.11 from 9268 Mc to 9456 Mc.

Breakdown Test

The horn with the plastic cup in place was tested for pressurization and breakdown.[7] The pressure outside the horn was reduced to the pressure equal to that at an altitude of 40,000 feet, and the input power was slowly increased to a maximum of 230 kw. No sign of breakdown was observed.

ANTENNA PERFORMANCE

Radiation patterns in elevation for the final antenna design are

7. These tests were done in the R. F. Research Section under the supervision of J. E. Sees.

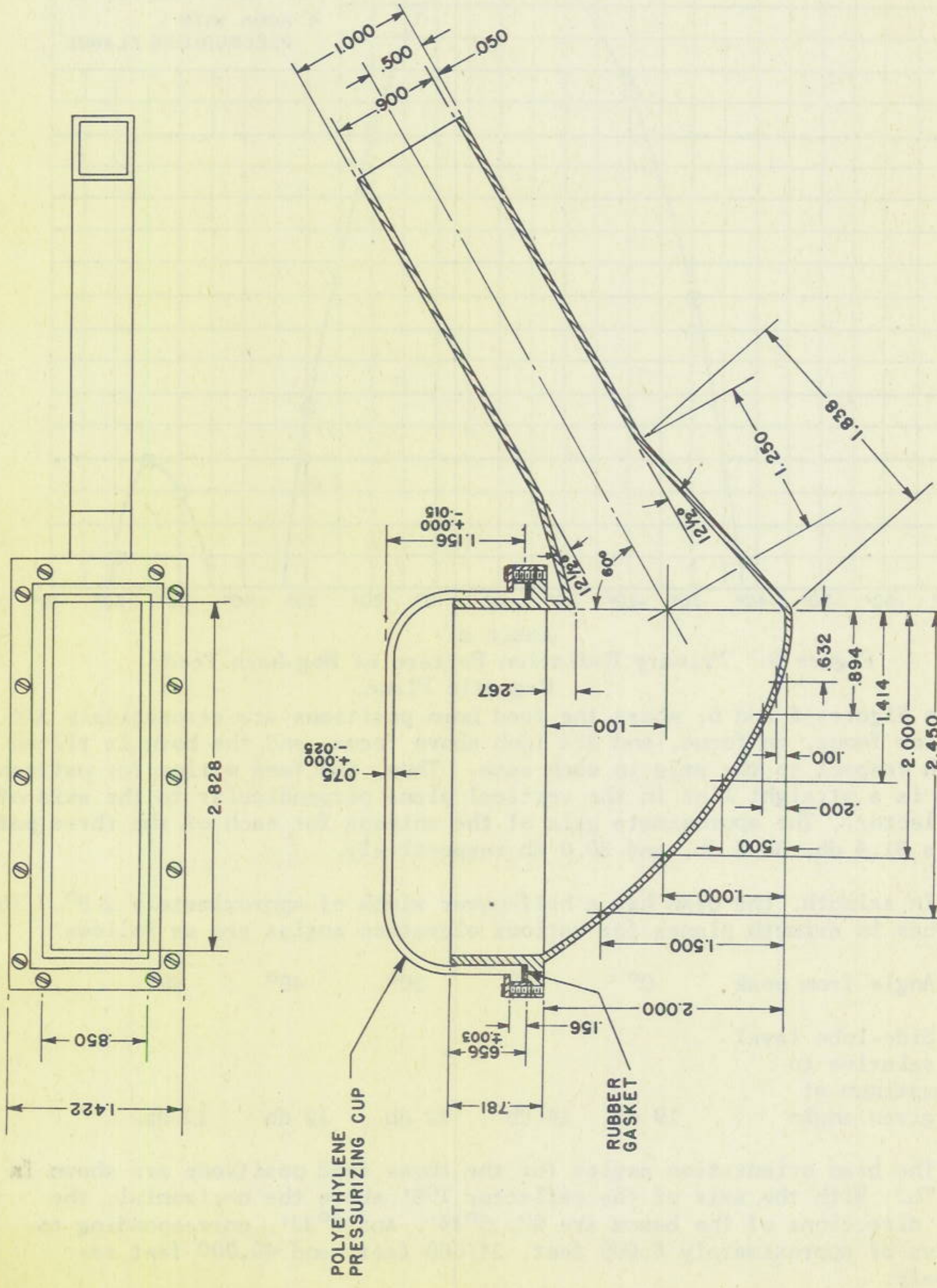


Figure 8. Hog Horn Feed for APB-2 Antenna.

[redacted]

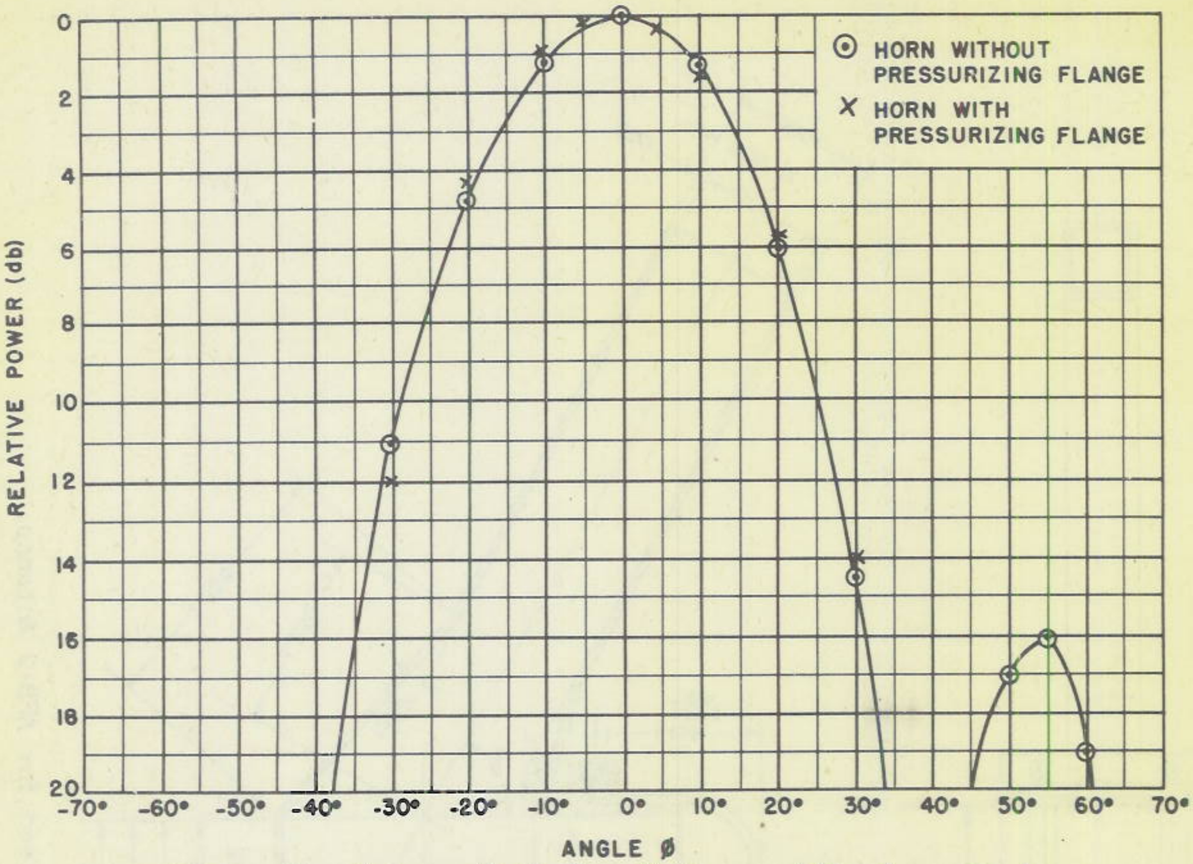


Figure 9. Primary Radiation Pattern of Hog-horn Feed
Magnetic Plane.

shown in Figures 5 and 6, where the feed horn positions are respectively 3/4 inch below focus, on focus, and 3/4 inch above focus, and the horn is tilted $2\frac{1}{2}^{o}$ with respect to the axis in each case. Thus, the feed motion for pattern control is a straight line in the vertical plane perpendicular to the axis of the reflector. The approximate gain of the antenna for each of the three patterns is 31.4 db, 30.7 db, and 30.0 db respectively.

In azimuth, the beam has a half-power width of approximately 2.5^{o}. The side lobes in azimuth planes for various elevation angles are as follows:

Angle from peak	0^{o}	15^{o}	30^{o}	40^{o}	50^{o}
Side-lobe level relative to maximum at given angle	19 db	14 db	12 db	12 db	12 db

The beam orientation angles for the three feed positions are shown in Figure 7b. With the axis of the reflector $1^{o}8'$ above the horizontal, the angular directions of the beams are 2^{o}, $5^{o}14'$, and $8^{o}32'$, corresponding to altitudes of approximately 8,000 feet, 24,000 feet, and 40,000 feet respectively.

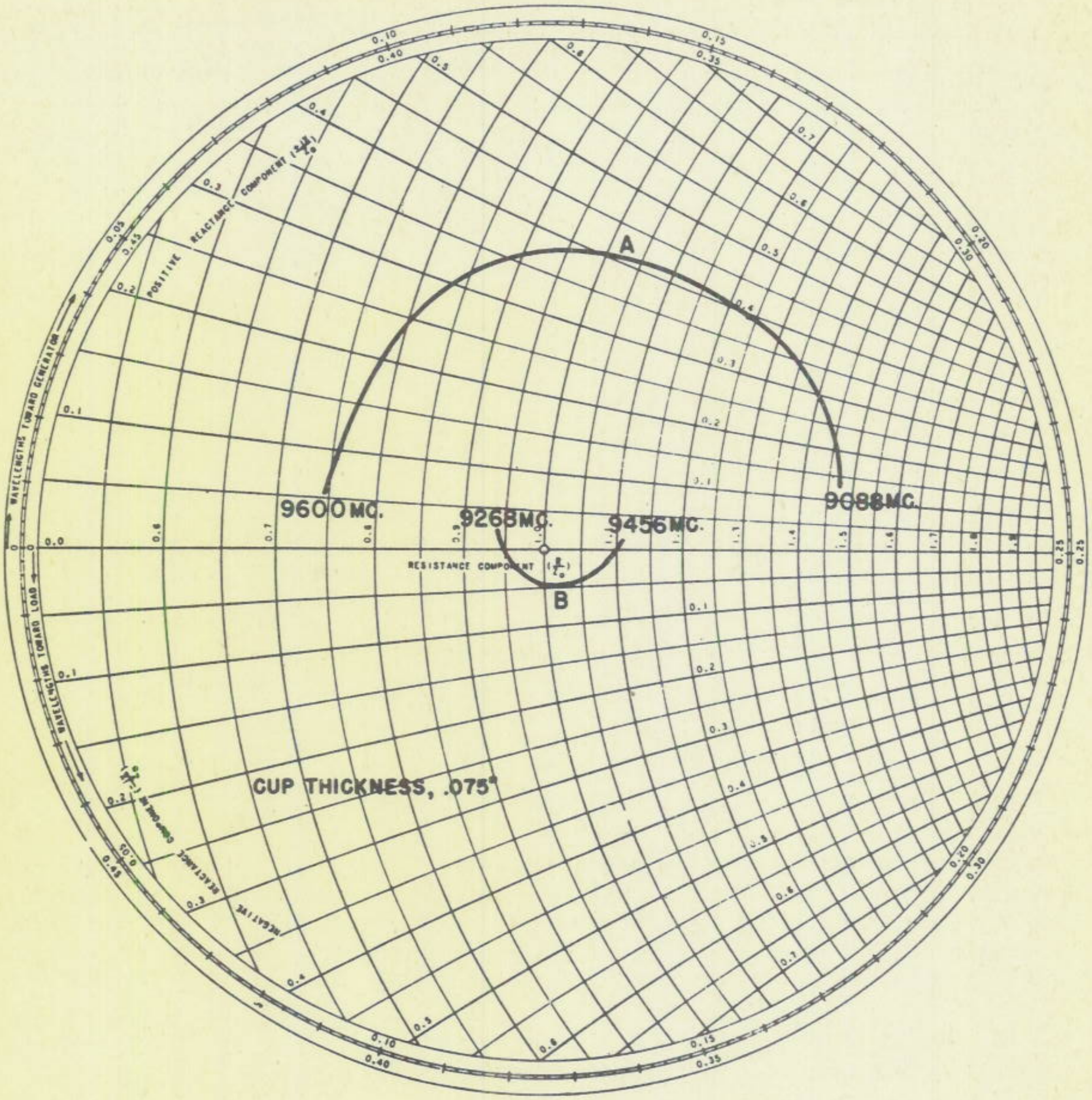


Figure 10. Impedance Chart for Hog-horn Feed.

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Figure 21. Impedance Chart for Dog-bone Feed.

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