VLA Feedhorn for Voyager Encounter of Neptune

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A high gain, low noise corrugated feedhorn was designed and developed by JPL for use in Very Large Array (VLA) antennas, near Soccoro, New Mexico. The new feedhorn will enable the VLA to support the Voyager encounter of Neptune in August of 1989. This will significantly enhance the receiving capability of the United States for that historic event.

I. Introduction

The original mission of the two Voyager spacecraft was to fly by Jupiter and Saturn. However, after they successfully completed their objectives at those two planets, Voyager 2 was rerouted to pass by Uranus and Neptune. Figure 1 shows the trajectories of the Voyager spacecraft from launch in 1977 through 1989. As can be seen from the figure, the Voyager 2 signal suffers a significant decline at the times of the encounter with Uranus and Neptune due to large increases in distance. During the Uranus encounter in January of 1986, this decline in signal power was compensated for by on-board control software modifications and increasing the receiving antenna aperture by arraying existing DSN ground stations as well as the Parkes, Australia (CSIRO) radio telescope. However, the 3.5-dB decline in the signal from Uranus to Neptune indicates additional improvement is needed in receiving capability. To accomplish this, further arraying of the DSN antennas to other large aperture systems such as the VLA in New Mexico is planned.

The VLA is owned and operated by the National Radio Astronomy Observatory (NRAO). It consists of 28 dual-shaped Cassegrain reflector antennas, each 25 m in diameter. On the basis of simple area alone, the VLA equals over four 64-m-diameter reflectors. Noise and other differences may change the four factor somewhat, but the conclusion that VLA represents a significant asset to the Voyager Neptune encounter tracking is inescapable.

A major modification plan was drawn for the VLA antennas to make them capable of efficiently receiving the Voyager 8.4 GHz (X-band) signal. Part of these modifications were new 8.0 to 8.8 GHz high performance feedhorns for all VLA antennas. The feedhorns were to be designed and developed by JPL and to be installed and owned by NRAO.

The following sections describe the design criteria, physical dimensions, and theoretical and measured electrical characteristics of these feedhorns.

II. Design Factors

Functionally, the feedhorn must efficiently couple the 25-m dual-shaped reflector system previously designed by NRAO to a specified location designated as the low noise amplifier reference (input) flange. The amplifier flange is a circular waveguide carrying either right- or left-circularly polarized waves, located about 1.9 m (75 in.) below the Cassegrainian focus. The refrigerated amplifier is to be a dual unit with a cryostat-integral polarizer-orthomode. By efficiently couple, we mean maximizing the antenna gain to the system noise temperature quotient. In 1989, Voyager will appear low (30-deg elevation maximum) in the New Mexico sky, and the noise level of the amplifiers was not well known in 1984 when the feedhorn design was done. Accordingly, a noise budget was constructed as follows. Although early model Gallium Arsenide Field Effect Transistor (GASFET) amplifiers were available with 30-K amplifier noise levels (leading to approximately 50-K overall system noise levels) an approach based on expected future high electron mobility transistor (HEMT) development was elected. Present HEMT projections indicate amplifier noise will likely be 20 K, leading to approximately 40-K overall system levels at an elevation angle of 30 deg. The feedhorn design was therefore optimized for a system of approximately 40 K. The noise budget is shown in Table 1.

The design proceeded by computational trial-and-error using the horn aperture variable. The previously determined dual-shaped surface overall geometry and profiles of the VLA 25-m element were not available as design variables. Ordinarily, JPL low noise reflector antenna design is carried out by synthesizing the overall geometry and profiles for a previously proven horn design. Invariably, the JPL synthesis technique results in too much spillover of the subreflector scattered radiation pattern (viewed in reciprocal transmission), therefore collecting ground noise in reception via spillover. JPL then synthesizes an additional annular ring around the main reflector periphery as a noise shield, balancing minimum size against the noise screening benefit. In the VLA case, this was not possible, and the feedhorn aperture was the only design variable of any importance. Of perhaps third order impact was the horn flare angle. Since the design factor of a 1.9-m separation of the Cassegrainian focus from amplifier flange needed to be met, and since nearly all this length was needed for the horn, it was decided to use essentially the total available length as the tapered portion of the horn in order to minimize the dissipation noise of the small-diameter (25.9 mm or 1.02 in.) connecting circular waveguide. Thus, the horn design consisted of iteratively varying aperture size, flare angle, and phase center location to fit the available axial space, to place the horn phase center at the subreflector forward focus, and provide maximum G/T for the approximately 40-K system noise level.

The software used to accomplish this design consists of the JPL developed HYBRID HORN, RUSCH SCATTERING, and EFFICIENCY programs (Refs. 1, 2, 3). A simplified symmetric analysis provided by the Rusch scattering software is considered sufficiently accurate in this instance, even though the VLA feeds are disposed asymmetrically (similar to the NASA-JPL 64-m tricone arrangement).

The horn satisfying the above (for a 40-K total system) is 334.3 mm (13.16 in.) in diameter with a flare angle of 4.28 deg. The midband (8.4 GHz) zenith spillover is computed as 2.3 K, indicative of the higher (than usual for JPL) system noise. That is, from experience, usual JPL systems are sized to produce only 0.7-K zenith spillover noise. Such sizing optimizes G/T for a lower noise system of about 16 to 18 K.

Figure 2 shows the selected horn radiation pattern, and Figure 3 shows the VLA-shaped subreflector scatter pattern, both at 8.4 GHz. Table 2 shows performance factors for the horn alone. Table 3 shows performance factors related to the scatter pattern. Both Tables 2 and 3 cover approximately 10% bandwidth, of interest to NRAO for purposes in addition to Voyager tracking.

For a single narrow band system of about 5%, a smooth walled dual-mode-type feedhorn would have been adequate. The NRAO desired a usable bandwidth of 8.0 to 8.8 GHz. Considerable analytical study of the band-edge performance roll-off of a dual-mode horn was accomplished in order to potentially reduce fabrication costs. It was found the bandwidth requirement of approximately 10% could not be adequately met with a smooth walled dual-mode horn because of poor efficiency and high noise. For this reason, a conventional corrugated horn was necessary, despite increased manufacturing costs. Table 4 shows the theoretical band-edge performance degradation using a smooth walled dual-mode horn carefully tailored to require no throat end phasing section. When bandwidth is of no concern, common practice with dual-mode horns is to size the aperture, select a flare angle, and then bring the two waveguide modes (TE_{11} and TM_{11}) into proper aperture phase relationship by use of a throat-end phasing section. The high dispersion (different velocities) of the two modes in a small waveguide enables a convenient differential phase shifter at one frequency. Over a wideband, however, a small diameter differential phase shifter is counterproductive. The analytical study of a smooth walled dual-mode horn conducted as part of this work therefore carefully arranged the aperture size and flare angle such that no small phasing section was necessary—the horn alone provided the necessary phase shifting, thereby giving best bandwidth performance. However, as seen in Table 4, about 1.2-dB gain at 8.0 GHz and 1.0-dB gain at 8.8 GHz are lost due to degradation in the smooth walled dual-mode horn radiation pattern caused by mode asynchronism away from design frequency. We conclude that the corrugated horn is necessary for the 8.0- to 8.8-GHz application. Despite elimination of the throat end high dispersion phasing section, the rather large (+27.5 dBi) horn still limits the bandwidth of a smooth walled dual-mode horn to approximately 5% for approximately a 10% (-0.5 dB) performance roll-off.

III. Start-up Configuration

Prior to analytical investigation of smooth walled horn performance and prior to final design of the selected corrugated horn, it was necessary to conduct certain systems-level testing at VLA using the Voyager 8.4 GHz (X-band) signal. Testing involved questions centering on signal summing from at least two VLA elements. In order to accomplish this, two microwave horns were needed on a short timescale. JPL had previously developed a large aperture X-band horn with 406.8-mm (16.02-in.) aperture and 6.25-deg flare angle. Although too large in diameter and not long enough for the VLA application, modifications were made by application of JPL software. First, a discrete section of the horn was removed, yielding an aperture near 315 mm (12.38 in.), which was not optimum but acceptable. Second, the remaining horn was juggled fore and aft, balancing the accruing defocusing loss from the misplaced horn phase center to subreflector forward (Cassegrain) focus against the noise increase due to the circular waveguide needed between the horn throat and amplifier location. The final design for temporary service was calculated to be within 0.3 dB of optimum (about 82.6% efficiency on the same basis as Table 3). Horn number one was available from an earlier program and the DSN Advanced Systems Program supplied resources to construct the second. Thus, an early start-up configuration was provided for systems-level testing in 1985.

IV. Feedhorn Physical Configuration

The VLA feedhorn assembly consists of seven sections as shown in Figure 4. Section 1 is a cosine taper, providing a well-matched transition from the VLA amplifier's standard circular waveguide (1.02 in. in diameter) to the JPL horn standard circular waveguide (1.369 in. in diameter) as shown in Figure 5. This taper was designed by an existing JPL program. The tight tolerance on the outside diameter of this section was required by the VLA for mounting purposes. Section 2 (the input section) is a corrugated waveguide used for matching the smooth wall waveguide to the corrugated feedhorn. This part is designed using the method discussed in Section 5.5 of Ref. 4. Sections 3 through 6 make up the main body of the horn and are corrugated uniformly with a constant flare angle of 4.283 deg. Figure 6 shows Section 3 of the horn assembly with detailed dimensions of the corrugations. Section 7 is the radome window and its accessories, as shown in Figure 7. JPL feedhorn windows are ordinarily made from thin Kapton® (trademark of the Dupont Corporation) sheets. However, due to occurrence of heavy hailstorms at the VLA site, a half-wavelength-thick Teflon window was designed for this feed. The window is epoxied to an aluminum frame and then clamped to the horn aperture flange with a rubber O-ring in between. The clamp is used to facilitate the removal or assembly of the window for servicing the feed. The rubber O-ring seals the horn from dust and moisture. By VLA request, two bleed holes are provided: one in the cosine taper and the other near the horn aperture. The bleed holes are used to purge moisture out of the horn by running either dry air or nitrogen through it.

All aluminum parts are fabricated from high quality 6061-T6 alloy. Details of the feedhorn assembly and individual parts are shown in JPL Drawings 9488078, 138372, 138373, and 9488080 (JPL internal documents). Figure 8 shows one complete feedhorn before it was shipped to the VLA site.

V. Measurements

The dissipative loss of the VLA feedhorn was measured by a maser low noise amplifier installed on a rooftop. The sky temperature was measured first using a known feedhorn and then by the VLA feed. From this measurement, the dissipative loss of the VLA horn, without any radome, was found to be 0.023 dB at 8.4 GHz. The additional loss due to the Teflon window was approximately 0.006 dB. The return loss of the horn is measured by an HP 8510 automatic network analyzer. For the feed without the Teflon window, the best return loss is obtained near the upper edge of the 8.0- to 8.8-GHz band (see Figure 9). Therefore, the Teflon window was designed approximately 0.005 in. thicker than the half wavelength at 8.4 GHz (0.488 in.). This adjustment caused the best return loss to be between 8.4 and 8.5 GHz, which is the band of interest for DSN applications. Figure 10 shows the return loss of the horn with an 0.488-in.-thick Teflon window to be better than 34.6 dB (equivalent to VSWR of lower than 1.04:1) between 8.4 to 8.5 GHz.

The far-field pattern of the feed was measured in the JPL 60-ft anechoic chamber. The E- and H-plane patterns, with and without the Teflon radome, are shown in Figs. 11 and 13. The 45-deg-plane co-polar and cross-polar patterns for the same configurations are shown in Figs. 12 and 14. These patterns exhibit low sidelobes and cross-polarization levels and are very close to the theoretically predicted patterns of Fig. 2. Moreover, it can be seen that the Teflon window does not change the far-field pattern of the feed significantly. The slight degradation of 45-deg cross-polarization pattern (worst cross-polar level on axis), for the horn with the Teflon radome, is due to radiation from the non-circularly symmetric clamp (see Figs. 7 and 8).

VI. Summary

A low noise, high performance feedhorn has been designed and developed by JPL for the VLA. The feed shows high performance, very good match, and low loss over the frequency band of interest. The measured data has excellent agreement with the theoretical data.

Acknowledgment

The authors would like to acknowledge Mr. D. Hoppe, who obtained the mode coefficients and their proper relationship for use in the HYBRID HORN program, and Mr. R. Hartop for his original idea of the use of a clamp for the feedhorn radome. Table 5 archives the coefficients used for possible future use on other projects. Additionally, the authors wish to thank Mr. S. Petty and Dr. J. Bautista for providing the X-band maser used for insertion loss measurement.

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Table 1. JPL/VLA 8.4-GHz Feedhorn Design System Noise Budget

Parameter	Noise, K
Amplifier	20
30-deg elevation atmosphere	6
Galactic	3
Quadripod scatter (30°)	5
Horn and other dissipation	3
Spillover (30°)	(1/2 of zenith value; value to be determined in G/T optimization)
Total	Approx. 40

Table 2. Theoretical Horn Selected Performance at 9-deg Half Angle

Frequency, GHz	Taper, dB	Phase center, behind aperture, mm (in.)	Beam efficiency, %	Directivity, dBi
8.0	-15.8	-263 (-10.37)	0.956	+27.13
8.4	-16.65	-315 (-12.42)	0.962	+27.53
8.8	-18.07	-372 (-14.64)	0.966	+27.92

Table 3. Theoretical Scatter Pattern VLA Subreflector With JPL Horn

Frequency, GHz	Overall efficiency, %	Zenith noise, K
8.0	89.2	3.05
8.4	89.6	2.27
8.8	89.4	1.66

Note: Overall efficiency includes illumination amplitude and phase, cross-polarization, spillover, and central blockage. Not included are surface tolerance, quadripod blockage, and dissipation factors.

Table 4. Smooth Wall Dual-Mode Horn VLA Subreflector Scatter Patterns Performance Summary

Efficiency factors	Frequency, GHz				
	8.0	8.2	8.4	8.6	8.8
Forward spillover	0.793	0.862	0.937	0.926	0.863
Rear spillover	0.983	0.983	0.988	0.997	0.989
Noise (rear) at zenith, K	3.3	3.62	2.62	2.05	2.30
Illumination	0.980	0.986	0.980	0.966	0.947
X-polarization	0.983	0.999	0.998	0.980	0.946
Phase	0.913	0.959	0.996	0.984	0.935
Efficiency	0.674	0.786	0.887	0.838	0.700
Total gain degradation, dB	-1.2	-0.5		-0.2	-1.0

Table 5. Amplitude and Phase Coefficients for Dual-Mode Horn Mode Generator*

Frequency, GHz	TE_{11} Mode		TM_{11} Mode	
	Amplitude	Phase	Amplitude	Phase, deg
8.0	1.0	0.0	0.401	67.5
8.2	1.0	0.0	0.653	51.3
8.4	1.0	0.0	0.766	42.2
8.6	1.0	0.0	0.831	35.8
8.8	1.0	0.0	0.871	30.8

*34.77/46.02-mm (1.369/1.812-in.) step discontinuity.

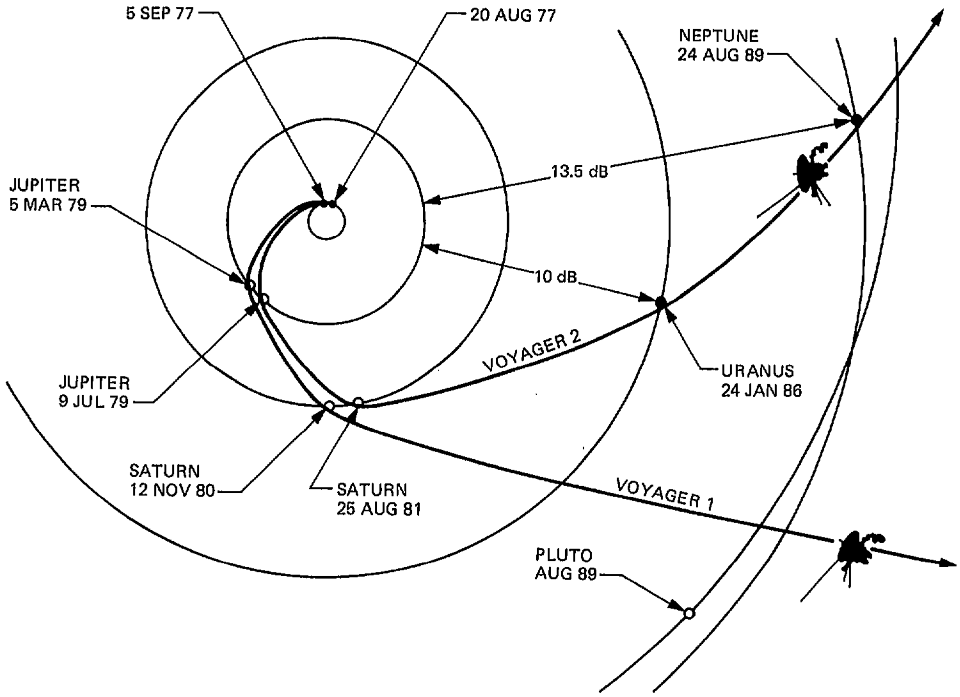

Fig. 1. Voyager heliocentric trajectory

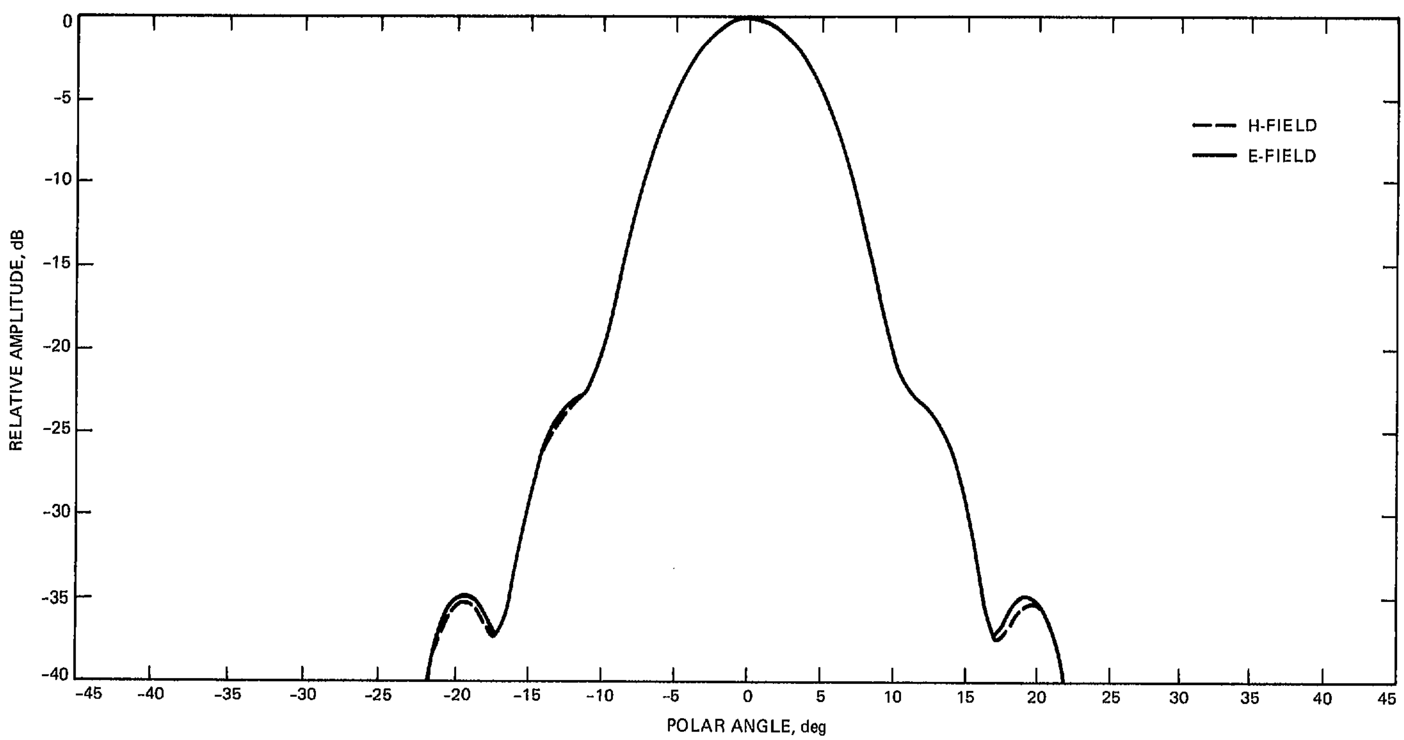

Fig. 2. VLA feedhorn theoretical pattern at 8.4 GHz

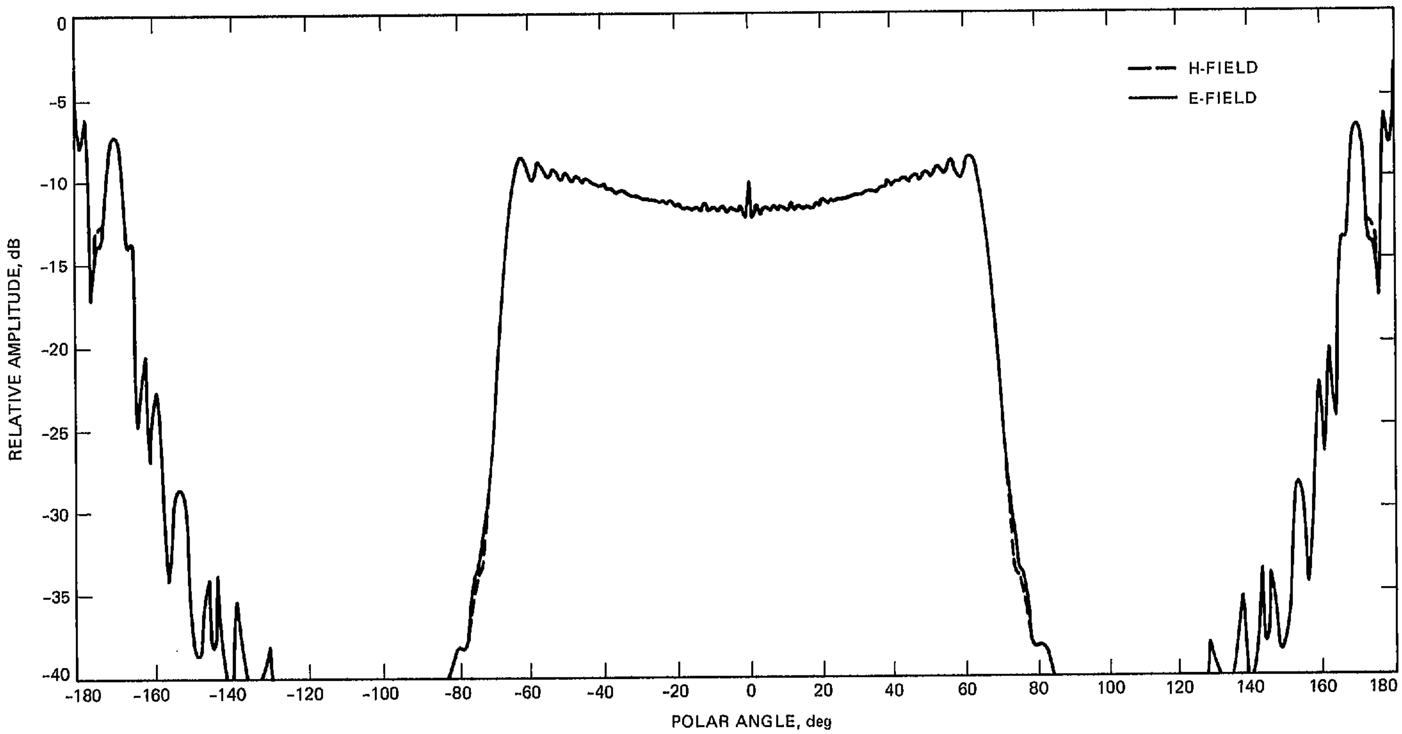

Fig. 3. VLA shaped subreflector scatter pattern

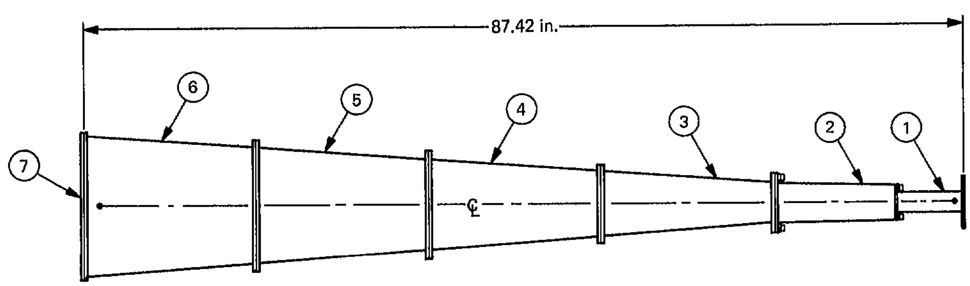

Fig. 4. VLA feedhorn assembly

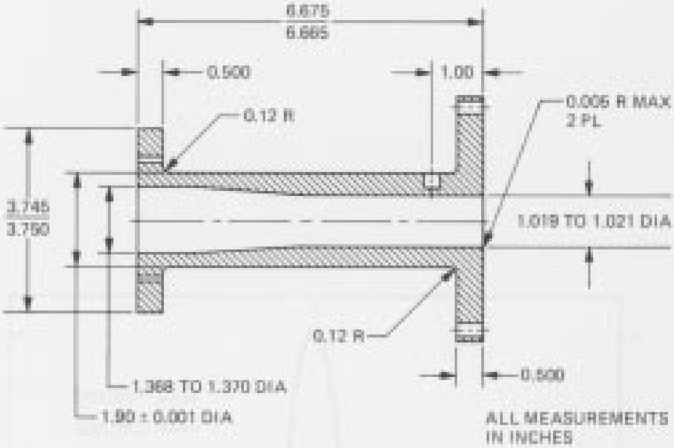

Fig. 5. VLA feedhorn cosine taper

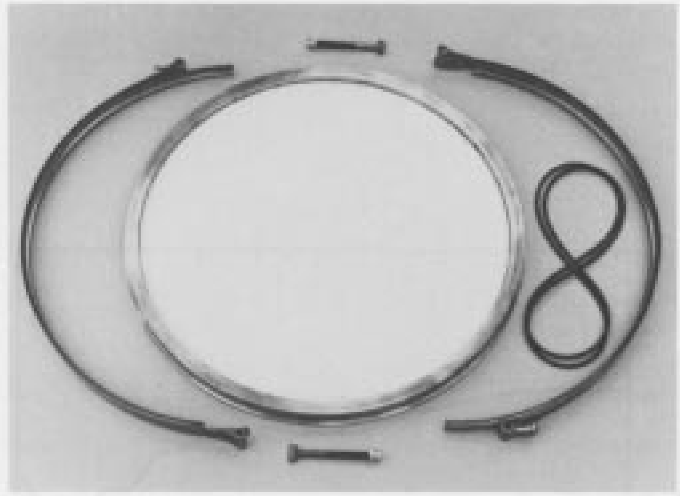

Fig. 7. Teflon window and accessories

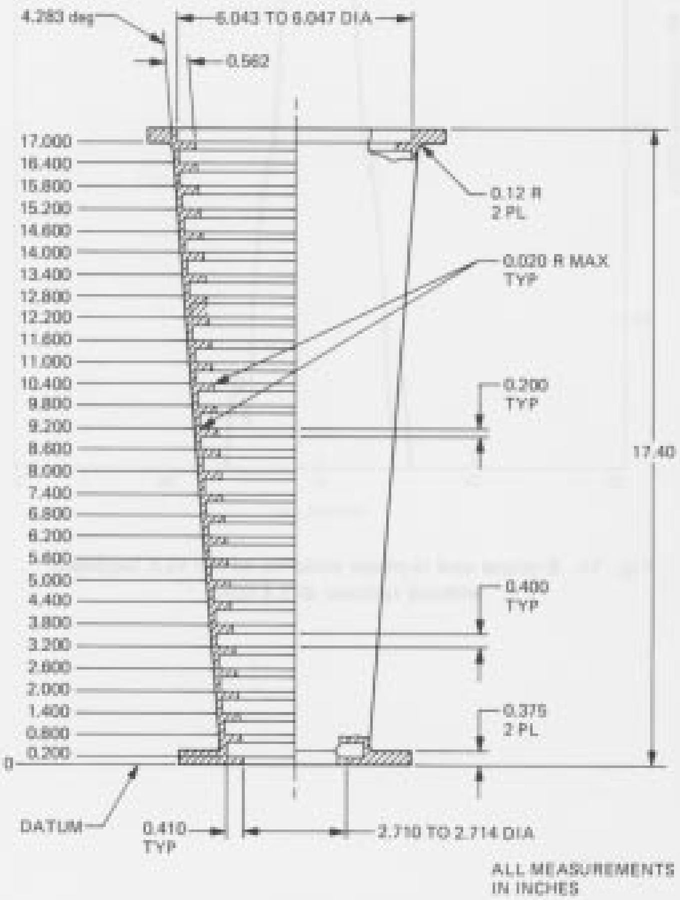

Fig. 6. Section 3 of the feedhorn assembly

Fig. 8. VLA feedhorn assembly

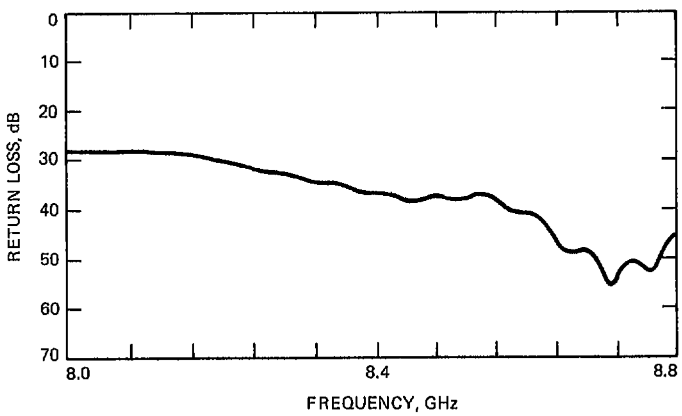

Fig. 9. Return loss of VLA feedhorn without window

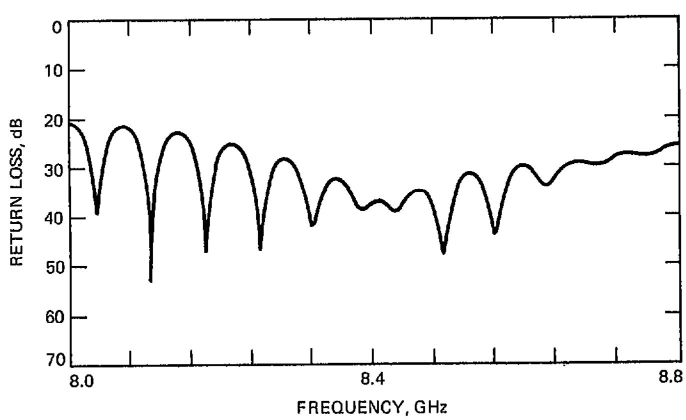

Fig. 10. Return loss of VLA feedhorn with 0.488-in.-thick window

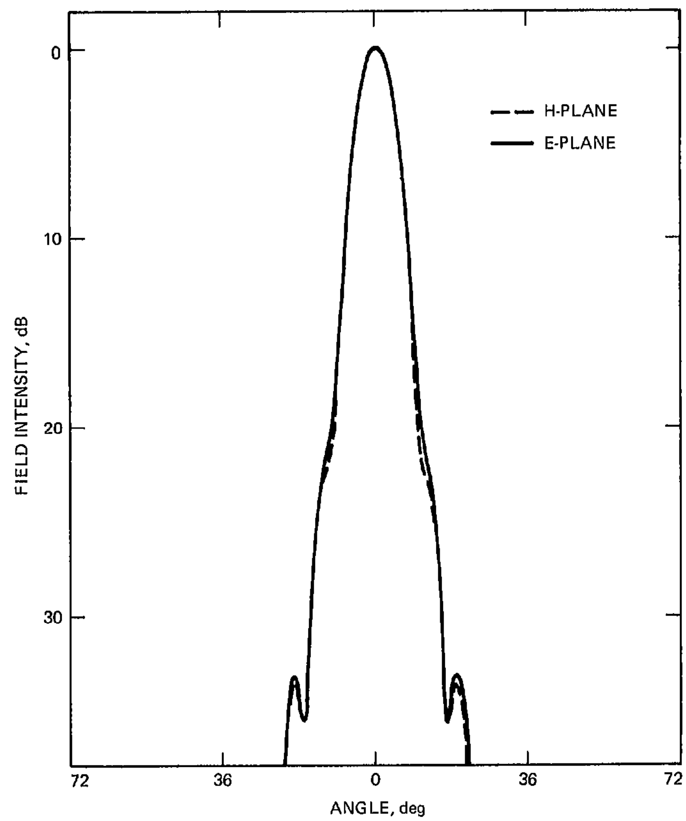

Fig. 11. E-plane and H-plane patterns of the VLA feedhorn without radome at 8.4 GHz

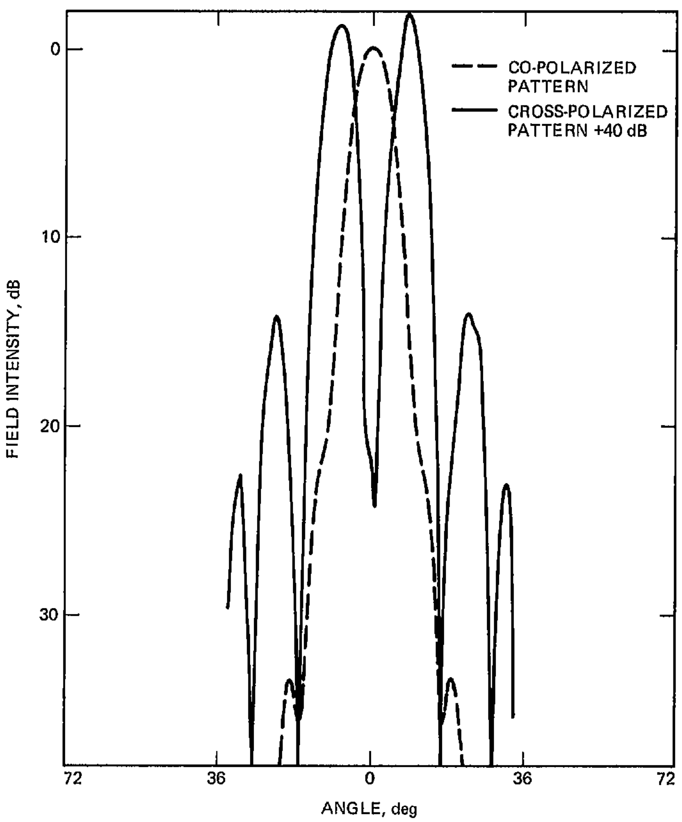

Fig. 12. The 45-deg plane co-polar and cross-polar patterns of the VLA feedhorn without radome at 8.4 GHz

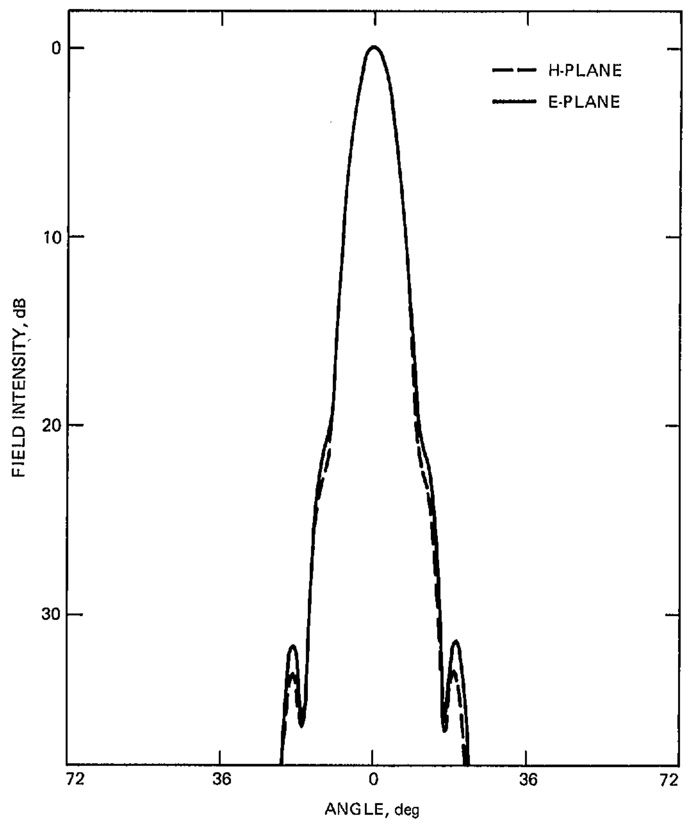

Fig. 13. E-plane and H-plane patterns of the VLA feedhorn with 0.488-in.-thick Teflon radome at 8.4 GHz

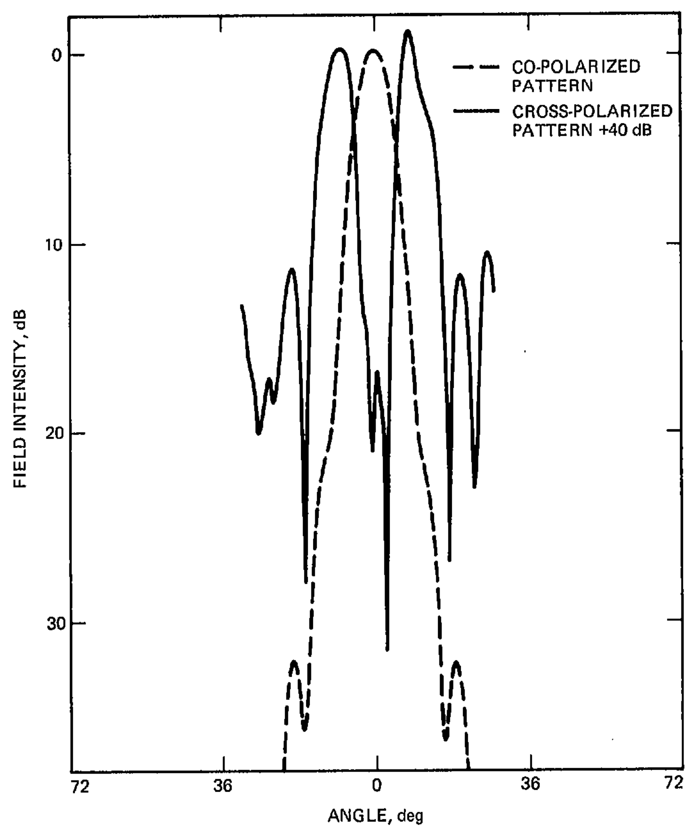

Fig. 14. The 45-deg plane co-polar and cross-polar patterns of the VLA feedhorn with 0.488-in.-thick Teflon radome at 8.4 GHz