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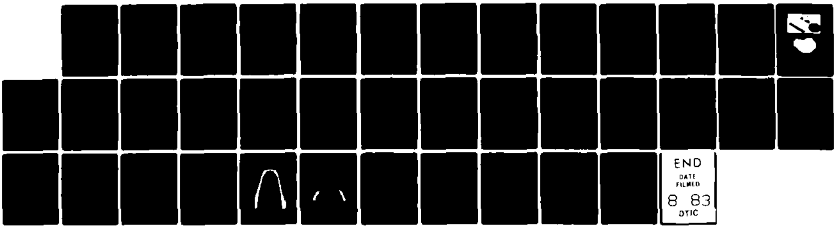

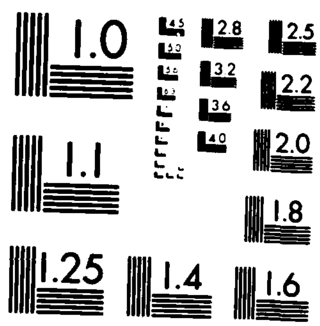

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Technical Report 645

J.C. Lee

A Compact Q-/K-Band Dual Frequency Feed Horn

3 May 1983

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A COMPACT Q-/K-BAND DUAL FREQUENCY FEED HORN

J.C. LEE
Group 61

TECHNICAL REPORT 645

3 MAY 1983

LEXINGTON MASSACHUSETTS

ABSTRACT

A mm-wave dual-frequency circularly polarized feed for an offset reflector antenna is being developed for a portable satellite ground terminal. The two frequency bands are Q- and K-bands for transmit and receive, respectively. Requirements for the antenna feed design are: low cost, compact size, rugged construction, high efficiency, and low sidelobes in both of the frequency bands.

The chosen feed design consists of a single corrugated horn designed for the two separate frequency bands with two circular waveguide concentric openings at the horn throat. The inner circular waveguide is used for transmit, and the outer coaxial circular waveguide is used for receive. In these waveguides, separate circular polarizers, orthomode transducers, and impedance matching elements for each frequency band are designed and integrated in a compact and solid fashion.

Electrically, good impedance match and small axial ratio are obtained for both frequency bands. Radiation patterns with approximately equal illumination taper at the reflector edge and coincident phase centers are obtatined in both frequency bands. Detailed design considerations and measured performance data are presented.

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Figure No.

I. INTRODUCTION AND GENERAL REQUIREMENTS

A mm-wave, dual-frequency, circularly-polarized feed for an offset reflector antenna is needed for a portable satellite ground terminal. Detailed design considerations to optimize the feed rf performance and mechanical construction, and final measured data are presented in this report.

General requirements for the feed system design are:

1. Low cost: simple geometry with few parts and few critical dimensions.
2. High performance: good impedance match, low loss, high gain, low far-out sidelobes, equal E- and H-plane beamwidths in both frequency bands, suitable beamwidth to illuminate an offset paraboloidal reflector.
3. Compact size: multi-function component design, integrated package,
4. Rugged construction: self-jigged, possible loose ends pinned down,
5. Proven technology: reliable material and technology.

Specific electrical requirements for the feed system design are:

1. Frequency bands are 43.5 to 45.5 GHz for transmitting uplink (Q-band) and 20.2 to 21.2 GHz for receiving downlink (K-band).
2. Left-hand circularly polarized for both bands with small axial ratio.*

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*The feed is left-hand so that after reflection from the reflector, the resulting polarization is right hand. The design is such, however, that simple modifications in assembly can reverse the sense of polarization at either frequency.

3. Good impedance match for both frequency bands.

4. Adequate isolation between the two separate frequency bands without added filters.

5. Approximately equal primary radiation patterns for both bands. At the edge of the total angle of 85° subtended by the main reflector, the desired amplitude taper is about 14 dB from the peak, to obtain low secondary pattern sidelobes.

6. Approximately coincident phase centers for both bands.

With these requirements in mind, various possible feed design approaches were considered initially. The two finalists that emerged were:

1. A single dual frequency prime focus feed horn.

2. Feed with dichroic subreflector: a prime focus horn for one frequency band and a Cassegrain horn for the other frequency band with a dichroic subreflector in between.

After more scrutiny, the dual frequency feed horn approach was chosen for the following reasons:

1. The present center frequency ratio (high frequency/low frequency) is about 2. If a dichroic subreflector approach is used, a rather complex dichroic surface design is needed to minimize both the return loss in one frequency band and the transmission loss in the other band. To accomplish this, either a single layer dichroic surface structure with both parallel and series resonances, or double layer of single resonance dichroic surfaces with precise separation is needed.

2. Analysis of doubly curved dichroic surface and the technology for making it need to be developed.

3. Losses associated with the dichroic surface may be appreciable.

4. Tolerance required on the resonant elements, the subreflector surface finish, and location alignment could be costly.

5. The state-of-the-art construction of dichroic surfaces is rather delicate. It was not clear that such a subreflector could pass stringent environment tests. Performance consistency and reliability are causes of concern.

6. Compared to the dual-frequency feed approach, the dichroic subreflector approach will be larger in size and heavier in weight, and require careful alignment of three separate parts, i.e., the two feeds and the subreflector.

II. FEED DESIGN

Many descriptions of multi-frequency feeds have appeared in the open literature. Some utilizing coaxial helices,[1] or coaxial probe excited concentric coaxial cavities[2,3] are suitable for lower frequency microwave applications. Some multi-frequency feeds were accomplished with lengthy directional couplers to couple different frequency bands in different waveguides to a common waveguide before ending in a radiating aperture.[4] More recently, long dielectric rods[5,6,7] in the center of the horn are used to control the high frequency bands while letting the horn itself control the patterns for the lower frequency bands.

The present design is influenced by some of the features of all the above-mentioned feeds. In particular, the idea of a coaxial waveguide approach has benefited from feeds used at Goonhilly earth station[8] and Tradex radar[9] terminal. Figure 1 gives a detailed sketch of the dual frequency feed, Fig. 2a shows the feed disassembled, and Fig. 2b shows the feed assembled.

The chosen feed design consists of a single corrugated horn which is optimized for the two separate frequency bands, with two circular waveguides of standard size with concentric openings at the horn throat. The inner circular waveguide is used for the higher frequency band and the outer coaxial circular waveguide is used for the lower frequency band. Rectangular waveguides perpendicular to the feed centerline are used as input/output ports to the feed assembly. The higher frequency port is brought out at right

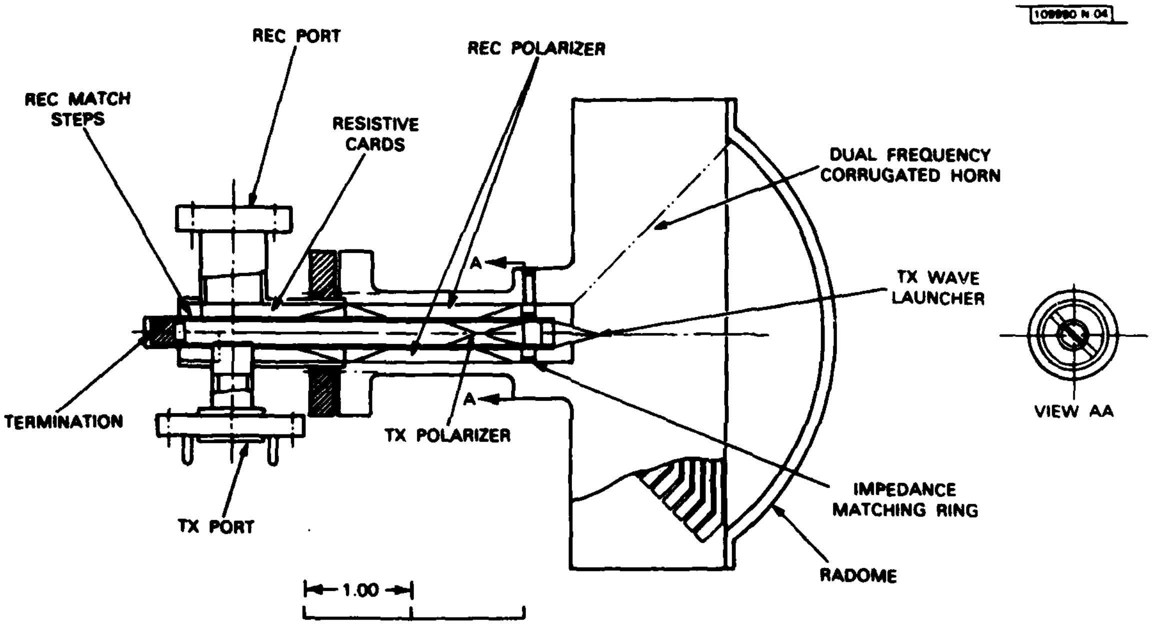

Fig. 1. Dual frequency feed assemble.

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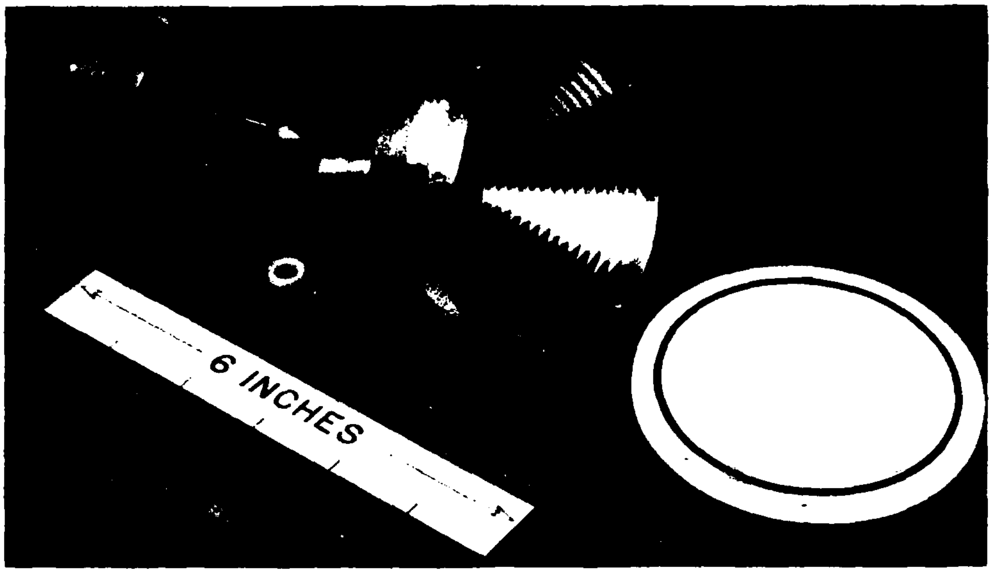
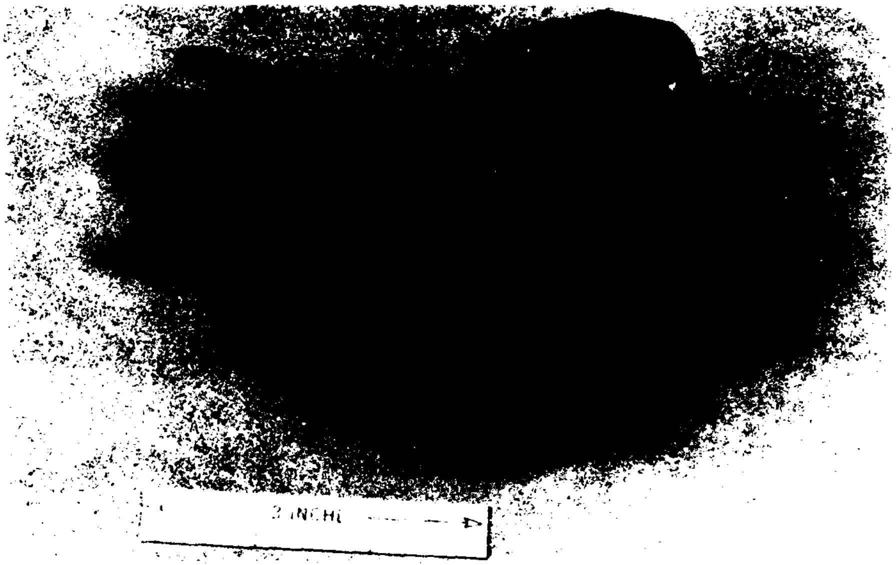


(a)



(b)

Fig. 2(a). Dual frequency feed disassembled. (b) Dual Frequency feed assembled.

angles to obtain a more compact feed package, instead of the more conventional straight out of the rear approach for such a feed.

Matching devices are built into both of these waveguides to account for the transition from one geometric form to the other and for the 90° bend. In addition, there are dielectric polarizers in each circular waveguide which convert the linearly polarized waves into circularly polarized waves. Both polarizers are at an angle of 45° to the incident linear polarization. The hands or senses of polarization can be chosen independently for the two bands.

All of these elements for each frequency band are designed and integrated in a compact and solid fashion. The overall length of the feed is less than 5 inches. The largest cross-section of the feed is at the horn opening which is about 4 inches in diameter. A cross-sectional view of the dual-frequency feed is shown in Fig. 1.

Detailed descriptions for each of the elements are given in the following.

A. Corrugated Horn

To cause the primary patterns to be axially symmetric, a corrugated horn approach was chosen, as opposed to other possible beam-equalizing techniques, such as dielectric loading[10] and multimoding.[11] Corrugation has a wider bandwidth and is a relatively easier way to control the beam shape and width. To achieve appoximately equal beam shape and phase center coincidence for both frequency bands, two design principles are used:

1. A wide horn flare angle[12] is used for wide band mode operation. In this mode, beamwidth is mainly determined by horn flare angle rather than horn aperture size, and phase center is near the horn throat.

2. The corrugation depth was chosen between $3\lambda/4$ and λ in the high frequency band, between $\lambda/4$ and $\lambda/2$ in the low frequency band, so as to obtain capacitive surface reactances[13] in both frequency bands.

A different approach to broadbanding, corrugation ring loading,[14] would complicate the fabrication process, and was not used for broadbanding the scalar feed characteristics. The latter approach would be a "waste" in the sense that, in our case, the two useful bands are widely separated and would be at the band edges, and the best middle part of the band, where performance is best, would not be used.

In a corrugated horn design, the difference, Δ, in wavelengths, between the spherical wave front and plane aperture, is a useful parameter for determining radiation pattern characterization. For $\Delta > 0.75$, wide band operation is obtained.[13] To ensure wide band operation, Δ is chosen equal to unity at the low frequency end of the low frequency band for the corrugated horn design. The semi-flare angle is chosen to be 46°; and the aperture diameter is 2.88 inches. These dimensions gave the desired beamwidths. The width of the corrugations is chosen to be less than $\lambda/2$ in the high frequency band. Fourteen corrugations are used. The corrugation depth is 0.217 inches; pitch is 0.120 inches and tooth thickness 0.013 inches. The horn and a portion of a K-band circular waveguide is machined from an aluminum block.

B. Radome

Since the wide flare corrugated horn will produce spherical waves at the horn opening, a spherical curved-surface is used in the radome design. The radius of the inner surface is 2.1 inches. The radome thickness was chosen to be one wavelength at the center frequency of the high frequency band. Because this thickness is close to a half-wavelength in the lower frequency band, good dual-band transmission characteristics (i.e., losses less than 0.1 dB) are obtained for radomes made of either Teflon or polyethylene. Polyethylene radomes were chosen for this present application because of their low cost. The polyethylene radome thickness is 0.176 inches. Radomes of polyethylene material with forest green color pigment were also made and tested. No measurable rf effects were observed due to the color pigment. A Teflon radome, which has a somewhat better water shedding property, would require a thickness of 0.183 inches.

C. Transmit Q-Band Components

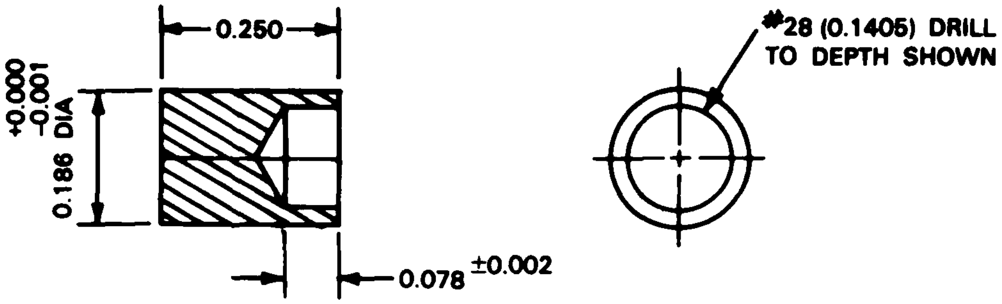
Transmit components are designed with standard size waveguides, circular guide WC-19, rectangular guide WR-22. The orthomode transducer starts with a short section of WR-22 rectangular waveguide joined at right angles to WC-19 circular waveguide with the broadside of WR-22 parallel to the WC-19 axis. A thin conducting septum, 0.10 inches thick, is positioned at the junction in the circular guide 0.102 inches from the WR-22 guide center to match the input impedance and to reflect signals from the rectangular waveguide to the open end of the circular guide. Another septum is used at the junction in the rectangular waveguide to improve the match for the orthogonally polarized mode in the circular waveguide. To avoid tight tolerance problems, no resonant irises are used at the junction; adequate matching was achieved with the septum alone. A short quarter-wave step load (Fig. 2c) designed for the transmit frequency band is placed in the circular guide behind the reflecting septum to terminate the orthogonal polarization port.

A dielectric (Rexolite) plate polarizer is located close to the open end of the circular guide. To achieve broadband performance and solid construction, one end of the polarizer plate is sandwiched in the slot of a tapered Teflon rod. The Teflon rod is pinned into the circular guide with dielectric pins. The other end of the Teflon rod is also tapered and is protruding out of the circular guide to launch a proper wave in the corrugated horn. The dimensions of this rod were arrived at empirically, the criteria used being the beamwidth of the E- and H-plane patterns, the phase center location, and the impedance match. Figure 2d shows the detailed dimensions of the tapered dielectric wave launcher/polarizer unit.

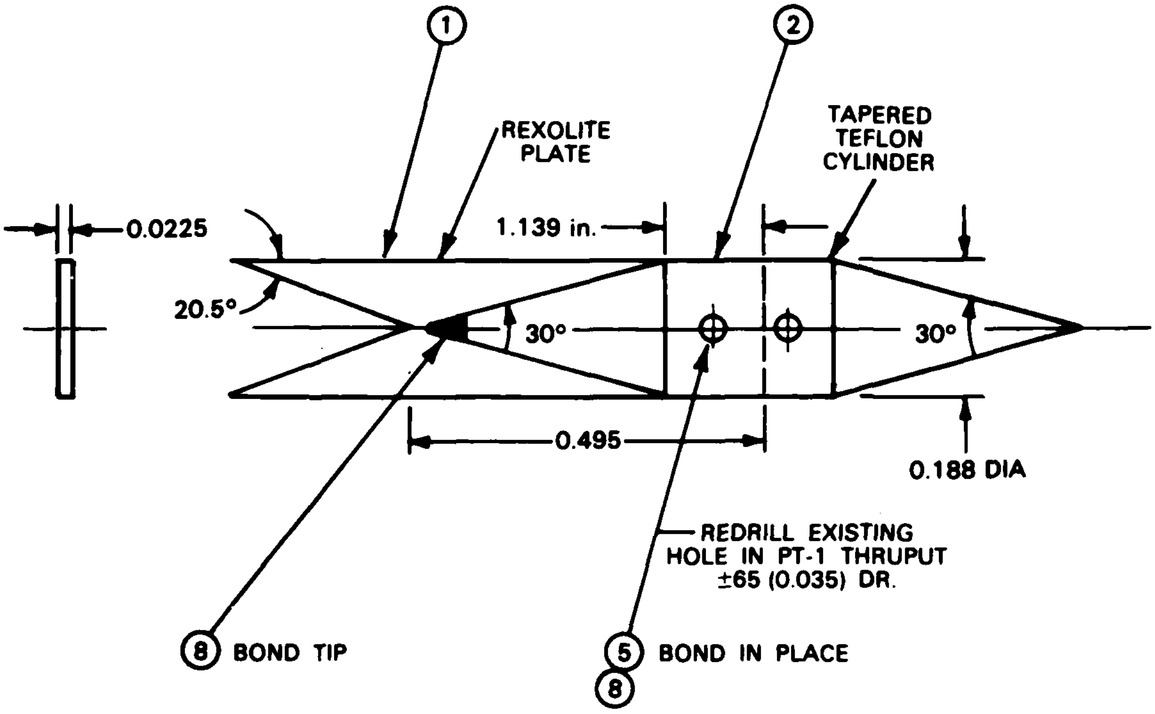
D. Receive K-Band Components

Receive components are designed in standard sized rectangular guide WR-42 and circular guide WC-44. The orthomode transducer (OMT) utilizes a junction of unique design.* It starts with a short section of WR-42 waveguide joined at right angles to WC-44 circular waveguide with the broadside of the WR-42 parallel to the WC-44 axis. The WC-19 circular guide of the transmit OMT is

* Patent applied for.



(c)



(d)

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Fig. 2(c). Q-band short load. (d) Tapered dielectric wave launcher/polarizer unit.

put inside the WC-44 circular guide coaxially. Stepped shorts are used to match the rectangular to coaxial waveguide operating in the TE_{11} mode. The junction has a good match over the whole recommended bandwidth of the WR-42 waveguide. To shorten the overall length, the portion of the transmit WR-19 waveguide inside the receive WC-44 is utilized as part of the receive matching. Two thin resistive cards of 150Ω per waveguide square are put in front of the stepped short to terminate the orthogonally polarized fields.

The quarter-wave plate in the receive frequency band is made of two pieces of thin Rexolite placed next to the resistive cards in a plane 45° from the plane of the resistive cards. Two symmetrical pieces of dielectric are used to maintain field symmetry, to avoid exciting higher order modes (Fig. 2e). Next to the polarizer is an impedance transformer made of a Teflon ring over a thin metal ring (Fig. 2f). This transformer acts to match the junction between the coaxial waveguide and the corrugated horn, and to support and to align the center conductor concentric with the outer waveguide.

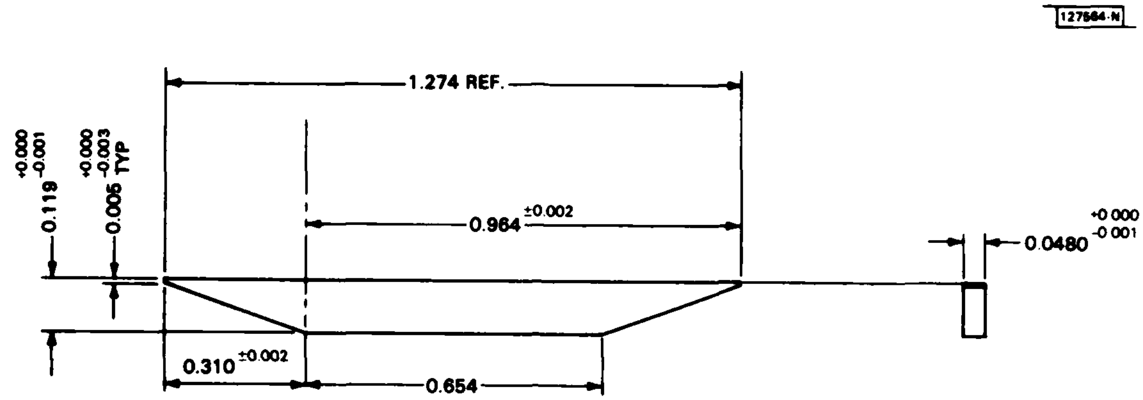

Fig. 2(e). Polarizer plate receive band.

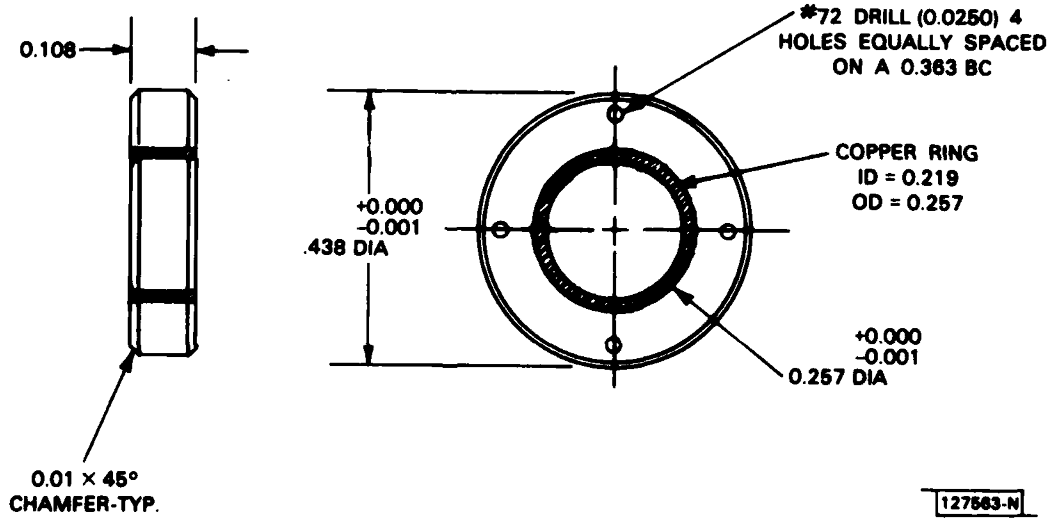

Fig. 2(f). Impedance transformer, receive band.

III. FABRICATION

For the feed fabrication, electroform or die-cast techniques are excluded because of cost and/or tolerance considerations. Instead, low temperature brazing (easy flow 45, melting point 600°C) and soft soldering (melting point 200°C) techniques are used to avoid shape distortion due to excessive heat. First the K- and Q-band circular and rectangular waveguides are each brazed together with necessary septa and flanges. Brazing parts are designed to self-jig. The K-band metal ring part of the impedance transformer is soft soldered on to the Q-band circular guide. Then the K- and Q-band units are are fixed together with the help of alignment fixtures. They are soft soldered together on a hot-plate with a small torch. The short cap is fixed behind the Q-band termination by silver epoxy.

After brazing and soldering, it is often necessary to ream the Q-band circular waveguide to restore it roundness for good axial ratio performance. The corrugated horn with built-in K-band circular guide is then put on the above-mentioned integrated unit, and the distance from the open end of the Q-band circular waveguide to the throat of the horn is measured. This distance is trimmed to 0.140 $\pm$ 0.002 inches machining off excessive length from the circular waveguide side for a good impedance match of the K-band coaxial waveguide to the corrugated horn.

The resistive cards for the terminating K-band cross polarized fields are glued in position with Eastman-910 with the help of alignment fixtures made of Teflon. The K-band polarizer plates are locked in position by grooves on the inner surface of the K-band circular waveguide and by flats on the outer surface of the Q-band circular waveguide. The Q-band polarizer is sandwiched between a slot in the Teflon-tapered wave launcher and fixed there by dielectric pins. The slotted tips of the wave launchers are etched and glued down to the polarizer plate by a drop of Eastman 910. The integrated unit is pinned to the waveguide by dielectric pins. To avoid heat build-up, the slot is cut by a thin coarse-tooth slitting saw on a milling machine at low speed.

No tuning screws or other adjustments are used for impedance matching or axial ratio control in the feed assembly. To keep the interior of the feed free from outside water and moisture, O-rings are wired between the waveguide flanges and between the radome and the corrugated horn opening. Loctite 222 was used to seal possible leakage where setting screws were used to fix the Teflon ring part of the K-band impedance transformer in place.

IV. PERFORMANCE

Several feeds were fabricated as described in the last section. Typical measured results of the corrugated horn feed are shown in Figs. 3-7. For the transmitting frequencies, the return loss at the waveguide input terminal (Fig. 3b) (measured without the polarizer, which would mask the aperture mismatch if present) is greater than 15 dB (VSWR < 1.45) over the entire 43.5 - 45.5 GHz band. The return loss (Fig. 3a) for its orthomode transducer transition between the rectangular and circular waveguide sections is better than 20 dB (VSWR $\leq$ 1.22). The resistive termination in the circular waveguide (Fig. 1) that serves to absorb unwanted reflected energy from the horn and radome (which has the orthogonal sense of circular polarization from the transmitted wave), has a return loss (Fig. 3c) greater than 17 dB over the band (VSWR $\leq$ 1.33). The axial ratio of the dielectric polarizer in the circular waveguide (TX polarizer of Fig. 1), which is a principal factor in determining the polarization of the transmitted wave, is less than 1 dB over the band (Fig. 3d). This corresponds to a polarization loss of less than 0.1 dB for the uplink.

For the downlink, the return loss at the receiver's waveguide output terminal (polarizer removed) is greater than 13 dB (VSWR < 1.60) over the 20.2 to 21.2 GHz band (Fig. 4c). This result is obtained, with the aid of an impedance-matching ring (Fig. 2), from an initially uncompensated return loss which was as poor as 3 dB (VSWR < 6.0; Fig. 4b). The return loss of the orthomode transition from the receiver's input to the coaxial waveguide

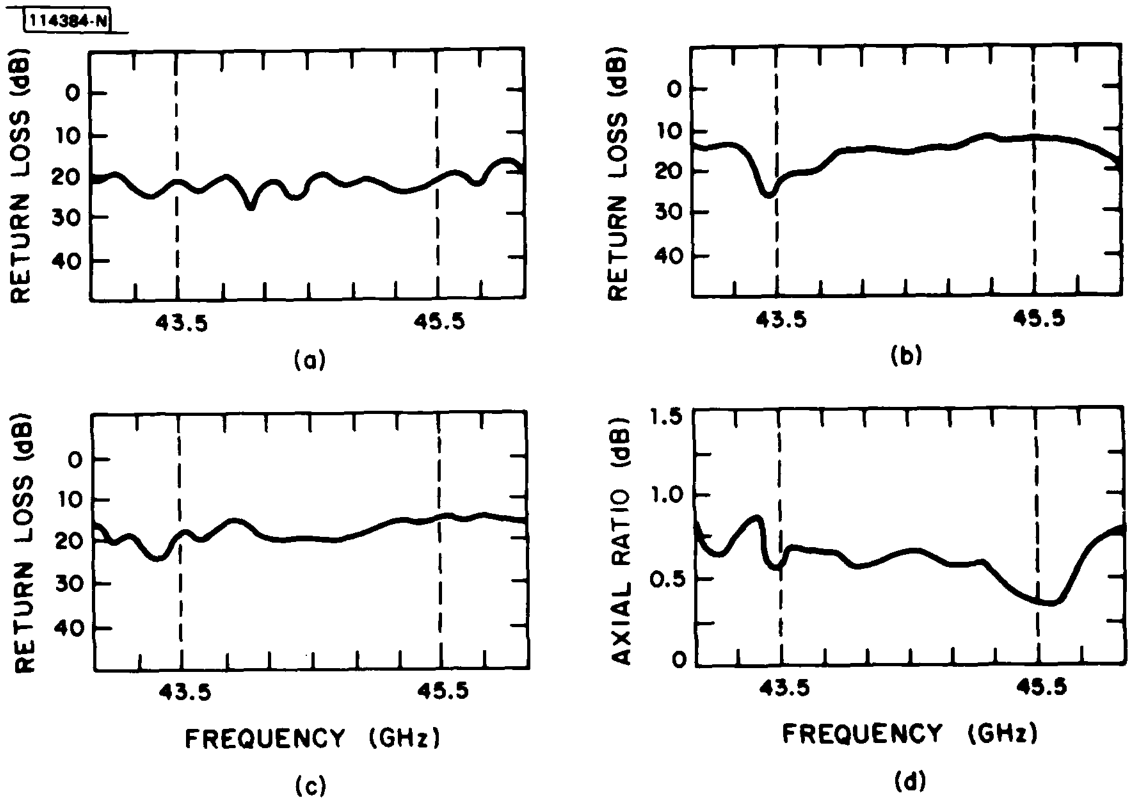

Fig. 3. Dual frequency feed, transmit components: (a) Match of orthomode transducer, with circular waveguide terminated. (b) Match at waveguide input, with wave launcher and horn, (c) Match of short load. (d) On-axis axial ratio of polarizer.

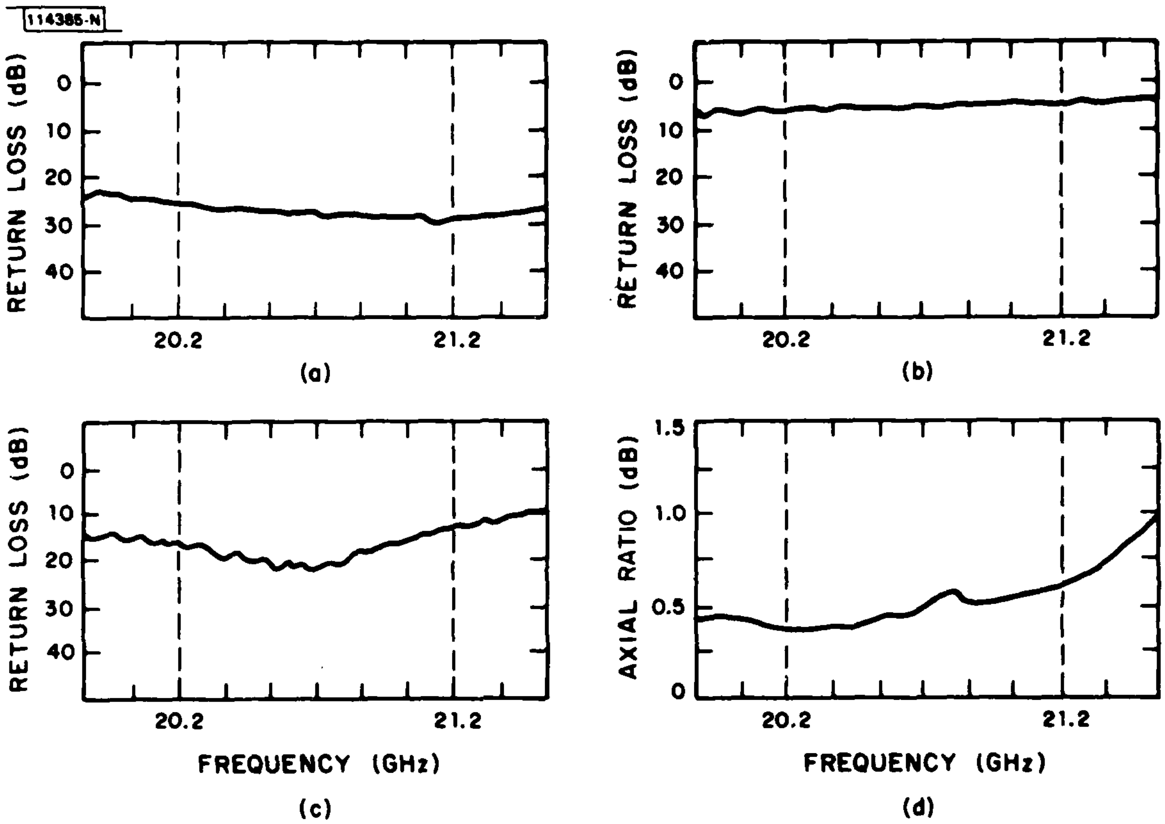

Fig. 4. Dual frequency feed, receive components: (a) Match of orthomode transducer. (b) Match at waveguide input, without matching ring. (c) Match with matching ring. (d) On-axis axial ratio of polarizer.

section of the feed is matched to a return loss of 23 dB (VSWR < 1.20; Fig. 3a). The axial ratio of the feed on reception, as determined by the receiver's dielectric polarizer, is likewise less than 1 dB (Fig. 4d).

The mutual coupling between the transmitter and receiver terminals is relatively low, being less than -30 dB over the uplink band. Figure 5 shows the isolation from 40 to 45 GHz. The portion of the uplink band between 45 and 45.5 GHz is not shown but is likewise below the -30 dB limit. This degree of isolation assures that the insertion loss due to coupling is negligible.

The Q- and K-band receiving radiation patterns for this feed without polarizer are given in Figs. 6 and 7. The average on-axis gain are about 12.4 and 12.0 dBi, respectively. The corresponding phase patterns are given in Figs. 8 and 9. The parameters in the phase patterns are related to the location of the center of rotation, with the 0 reference at the throat of the corrugated horn (where the 46° semi-flare angle starts). A positive sign refers to moving outward to the mouth of the horn; a negative sign refers to moving inward toward the circular waveguides. The Q- and K-band radiation patterns of the feed with polarizers were also measured with a rotating linear transmitter to show some added information on its axial ratio characteristics. Typical results are given in Figs. 10 and 11.

From Figs. 6 and 7, we see that there is a very small difference in the amplitude patterns in the E- and H-plane cuts and that the amplitude patterns in the two distinct frequency band are very similar as needed for efficient dual frequency operation with the same reflector. Phase patterns show that

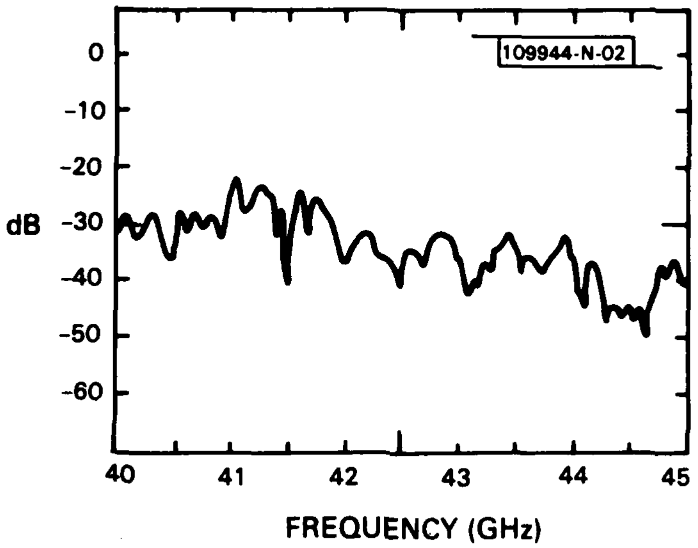

Fig. 5. Isolation between transmit and receive terminals of dual-frequency feed in receive frequency band.

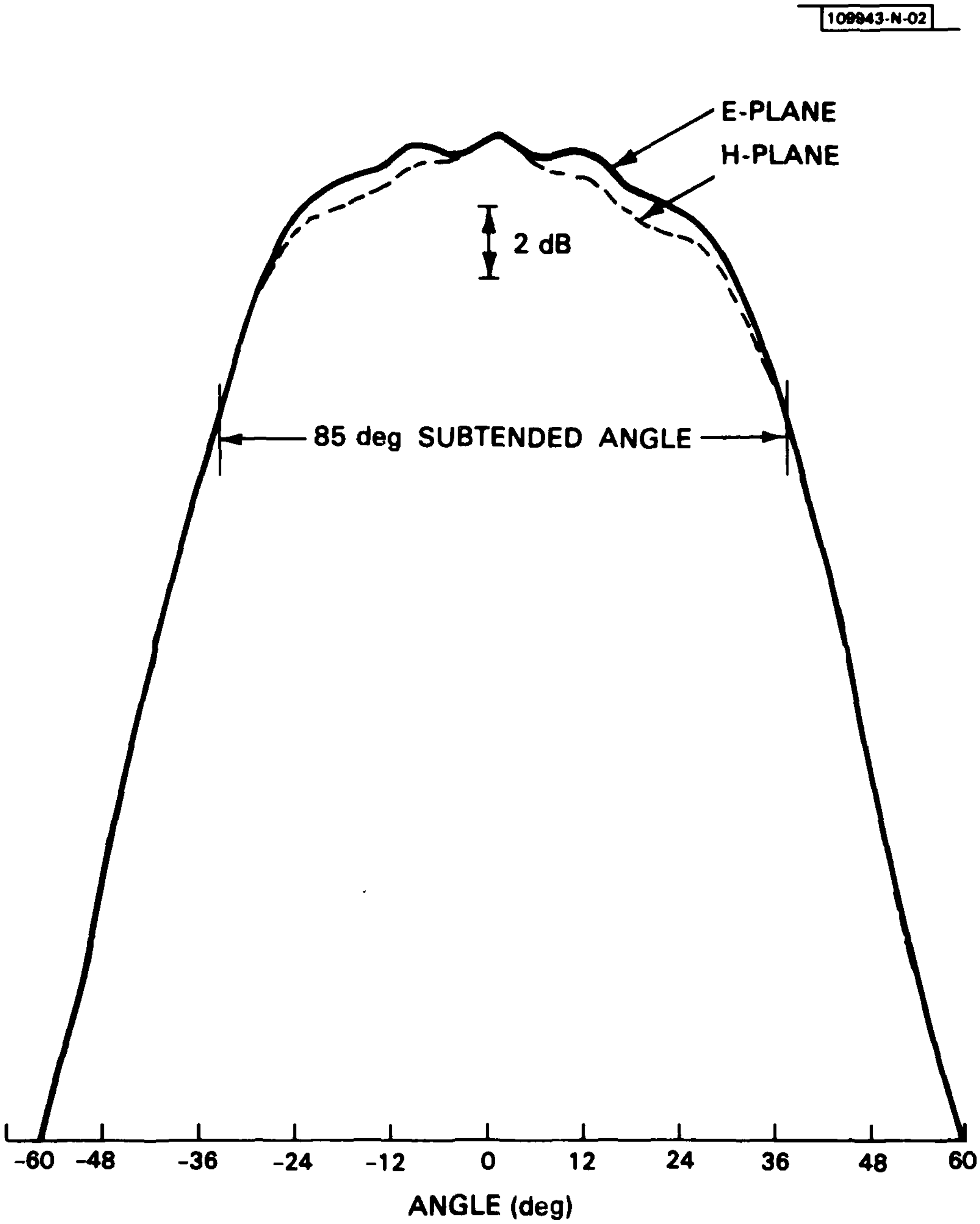

Fig. 6. Feed radiation patterns at 44.5 GHz.

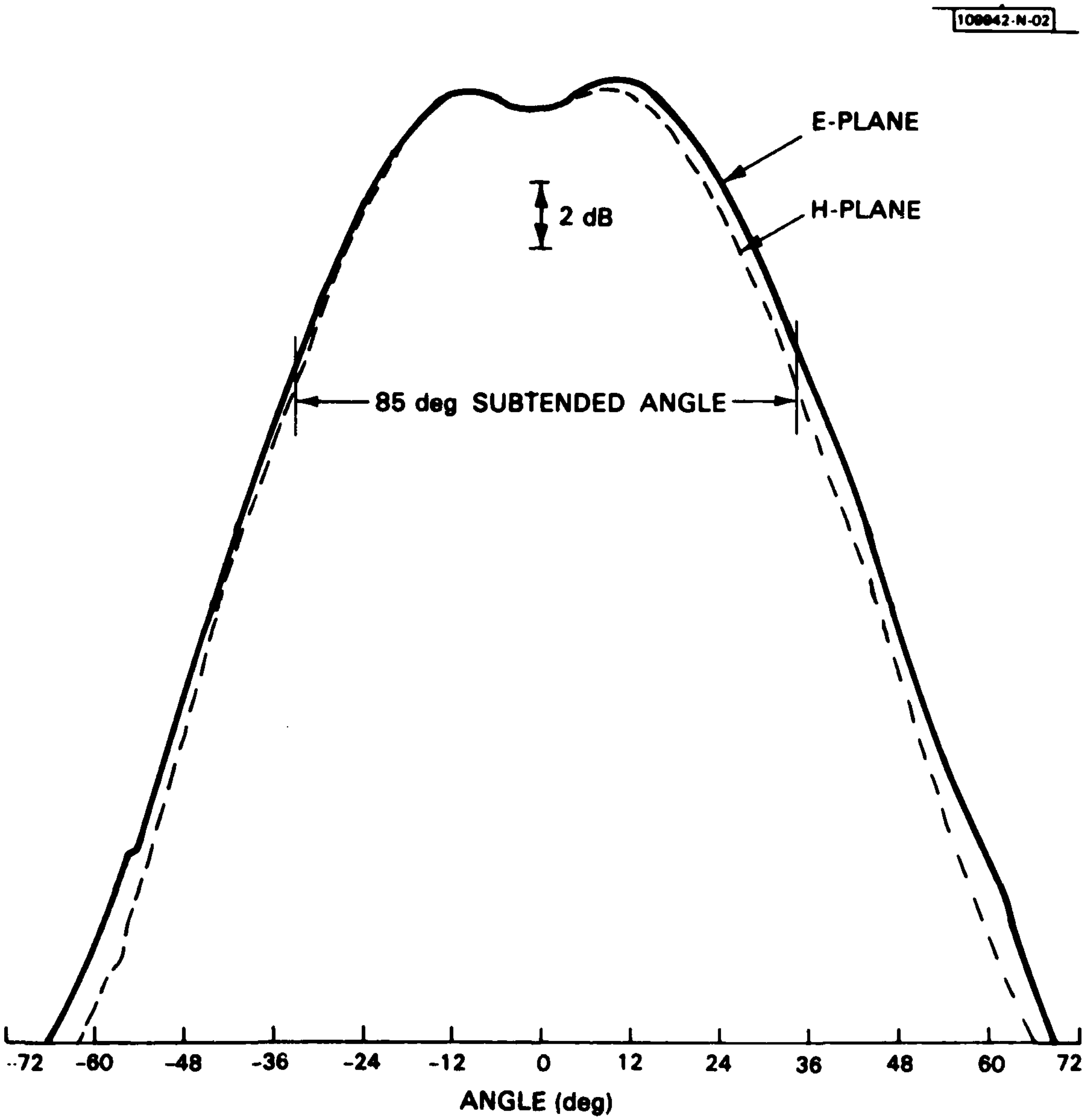

Fig. 7. Feed radiation patterns at 20.7 GHz.

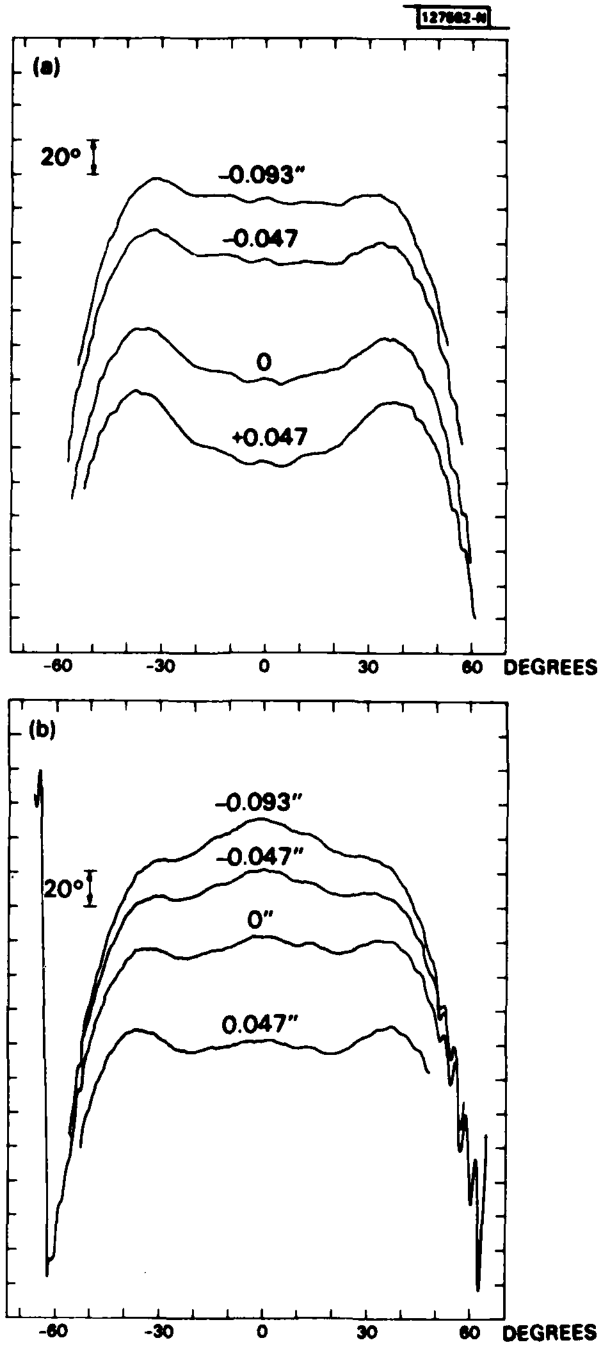

Fig. 8(a). E-plane phase pattern 44.5 GHz. (b) H-plane phase pattern 44.5 GHz.

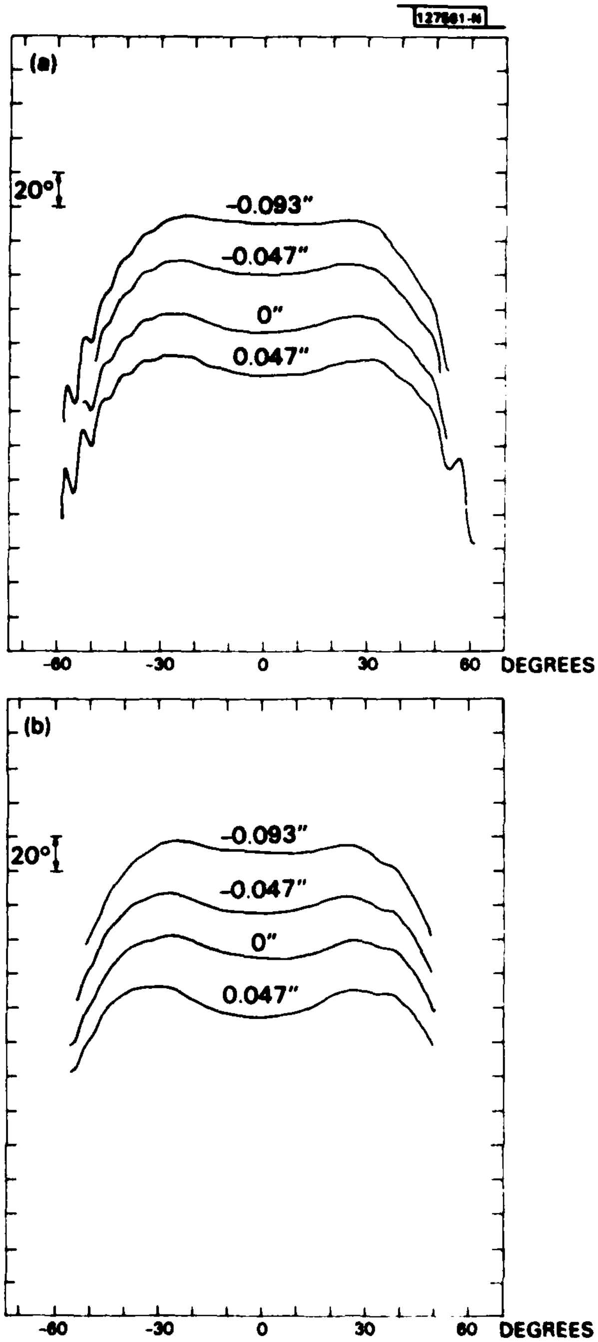

Fig. 9(a). E-plane phase pattern 20.7 GHz. (b) H-plane phase pattern 20.7 GHz.

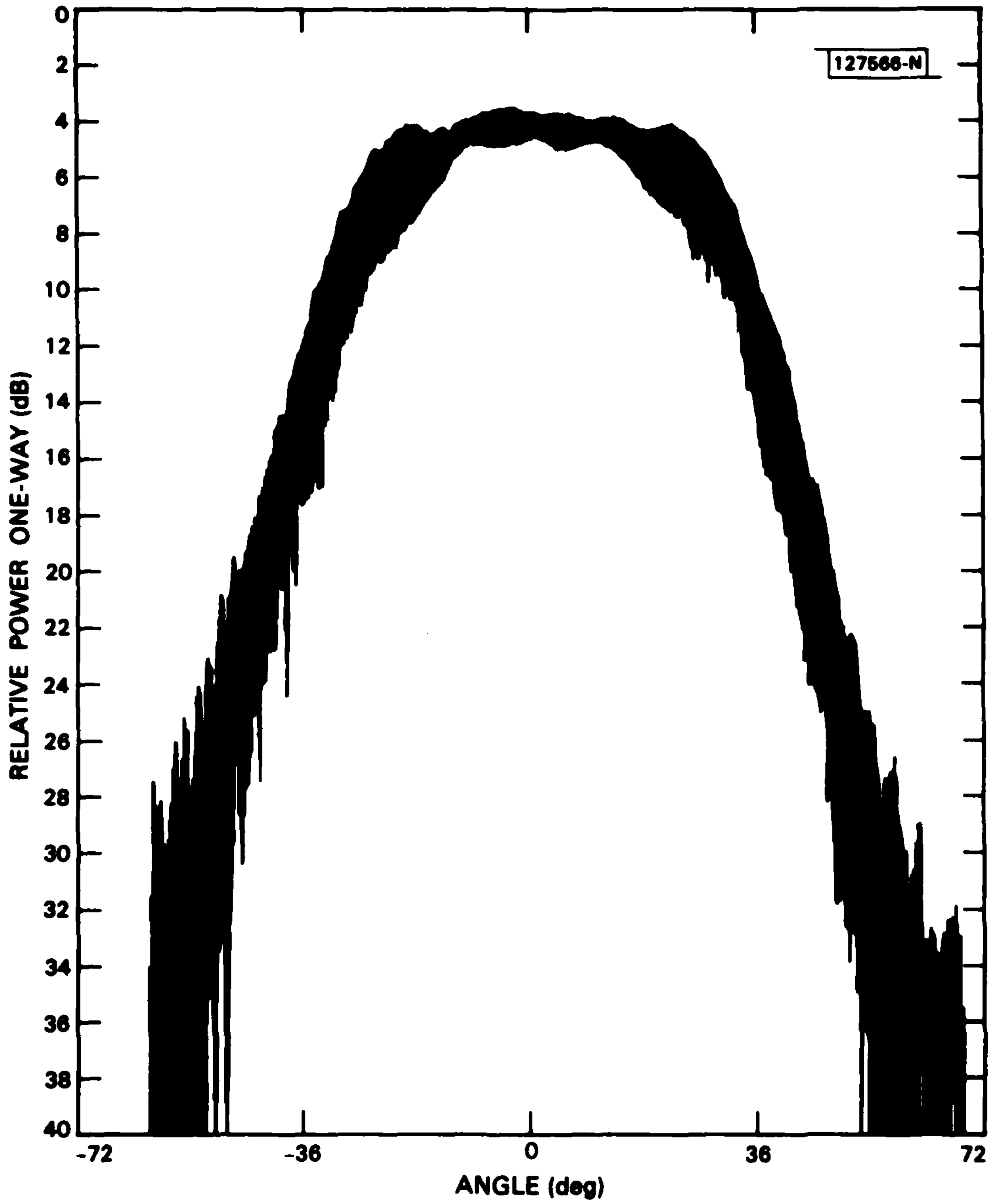

Fig. 10. Feed axial ratio pattern at 44.5 GHz.

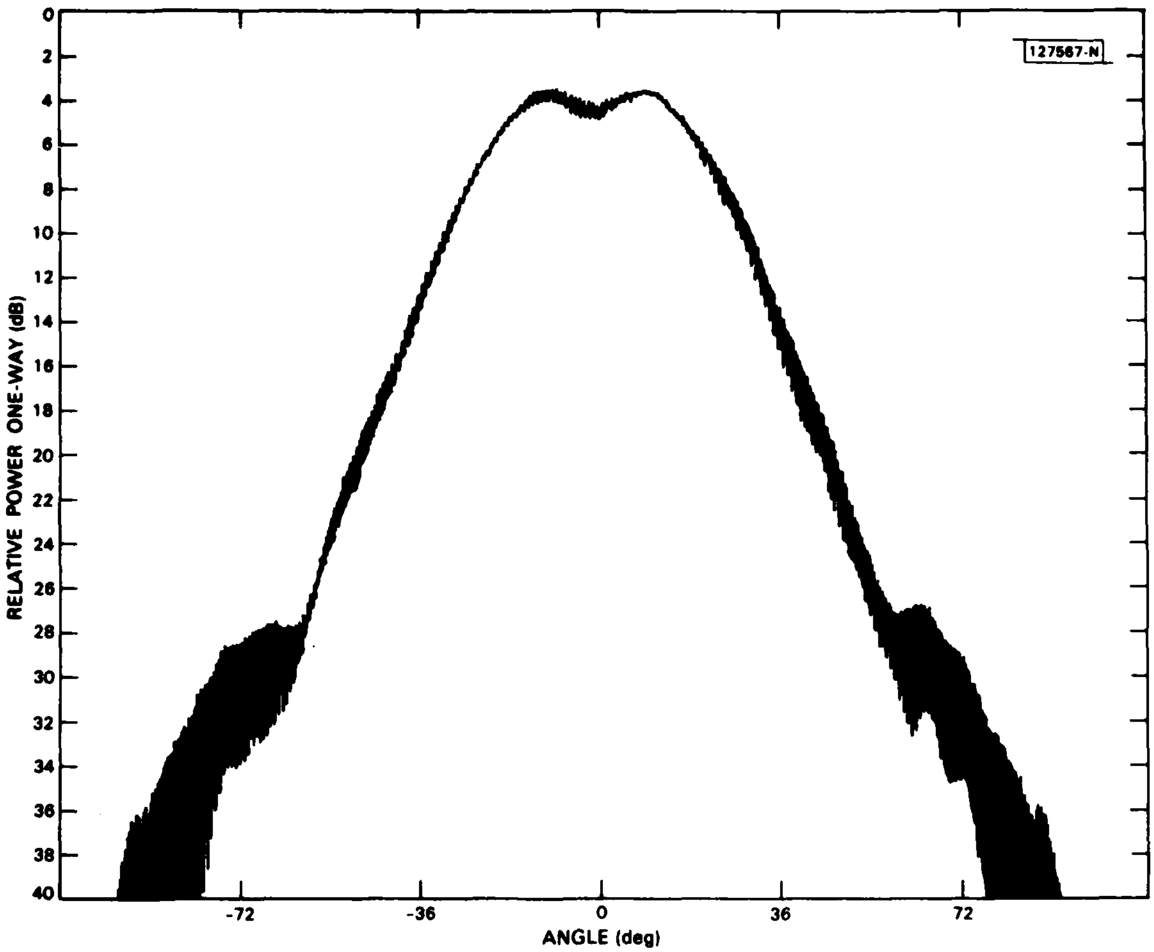

Fig. 11. Feed axial ratio pattern at 20.7 GHz.

for both frequency bands, the optimum phase center locations for E- and H-planes are between 0 and -0.047 inches from the horn throat.

Military standard environmental tests (MIL-STD-810C) were carried out to see if the feed can be qualified for tracked vehicle applications. Positive results were obtained from such tests. The temperature range of the tests was -40°C to +50°C for operation and -50°C to 60°C for survival. During the tests, signal levels at the transmit frequency were continuously monitored for insertion and return losses. Very small changes in return and insertion losses were observed as temperature was changed. At certain intervals, the feed under test was returned to room temperature, taken out of the thermal chamber, and tested on a bench at the transmit frequency for axial ratio and at the receive frequency for insertion and return loss and axial ratio. Negligible changes were noted in the course of the test.

A vibration test using a sine waveform, with 4.2 g peak and a frequency range of 3 to 500 Hz for three hours per axis and a shock test at a level of 40 g for 11 ms per axis were used. No measurable change was obtained from RF tests of the feed before and after each test.

The feed assembly was also tested for leakage under pressure. No leakage was detected for pressure less than 9 psi.

V. CONCLUSIONS AND REMARKS

In conclusion, a compact dual-frequency feed with rugged construction was designed, fabricated, and measured. A high-performance feed operating in two mm-wave bands of relatively low cost was demonstrated. With this feed, overall aperture efficiency of 60% to 70% has been achieved feeding both offset reflectors and center-fed lenses.[15] Other dual-frequency applications such as satellite spot-beam antennas and super-compact reflector with splash plate added to the feed are being investigated.

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A mm-wave dual-frequency (Q- and K-bands) circularly polarized feed for an offset reflector antenna is being developed for a portable satellite ground terminal. The chosen feed design consists of a single corrugated horn designed for the two separate frequency bands with two circular waveguide concentric openings at the horn throat. Separate circular polarizers, orthomode transducers, and impedance matching elements for each frequency band are designed and integrated in a compact with good performance in both frequency bands. Detailed design considerations and measured performance data are presented.

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