Performance of the X-/Ka-/KABLE-Band Dichroic Plate in the DSS-13 Beam Waveguide Antenna

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The first Ka-band downlink demonstration was recently carried out by the Ka-Band Link Experiment (KABLE) in association with the Mars Observer spacecraft. In order to support the mission, a dichroic plate was required in the DSS-13 beam waveguide antenna to allow simultaneous X- and Ka-band operation. An X-/Ka-/KABLE-band dichroic plate was designed to transmit Ka-band downlink (31.8–32.3 GHz), Ka-band uplink (34.2–34.7 GHz), and KABLE (33.6–33.8 GHz) frequencies, while reflecting X-band (8.4–8.5 GHz). A computer program was developed for the analysis of a dichroic plate with rectangular apertures by using the mode-matching method. The plate was then fabricated and tested. The reflection, group delay, and noise temperature in the antenna system due to the dichroic plate were measured. The experimental results show good agreement with theoretical prediction.

I. Introduction

The DSN has a need for a dichroic plate that will simultaneously receive X- and Ka-bands on a beam waveguide antenna where an ultralow-noise receiver is used at Ka-band. The plate is required to pass a circularly polarized wave at (1) the Ka-band downlink (31.8–32.3 GHz) with a low insertion loss (as low as 0.04 dB), (2) a high-power Ka-band uplink (34.2–34.7 GHz), and (3) the Mars Observer spacecraft Ka-Band Link Experiment (KABLE) frequency (33.6–33.8 GHz), while at the same time reflecting the X-band downlink (8.4–8.5 GHz). A thin dichroic plate with apertures or patches is not mechanically suitable for these requirements; therefore, a thick metallic plate with rectangular apertures was designed and fabricated (Fig. 1). Mechanical constraints also require an oblique angle of incidence, while bandwidth considerations dictate the use of a skew grid.

II. X-/Ka-/KABLE-Band Dichroic Plate Design

The X-/Ka-/KABLE-band dichroic plate was designed using the thick, frequency-selective surface program based on the mode-matching method [1]. The cell size and pattern (D_x, D_y, and Ω), the aperture size (A_x, A_y), and the thickness of the plate (t) are adjusted to meet the requirements. The angle of incidence is $\theta = 30.0$ deg, and $\phi = 0.0$ deg (Fig. 2). The aperture wall thickness is limited to a 0.203-mm (0.008-in.) minimum due to mechanical constraints. The dichroic plate design was optimized with the following priority: (1) Ka-band downlink, (2) Ka-band uplink, and (3) KABLE frequencies.

The optimized design of the X-/Ka-/KABLE-band dichroic plate employs a rectangular aperture of size 5.080-mm (0.200-in.) A_x by 5.156-mm (0.203-in.) A_y, cell size of 6.198-mm (0.244-in.) D_x by 5.359-mm (0.211-in.) D_y

with a 60-deg skew angle (Ω), and plate thickness of 9.271-mm (0.365-in.) t; see Fig. 3(a). The computed reflection loss is about 0.007 dB at 32 GHz, 0.078 dB at 34.5 GHz, and 0.103 dB at 33.7 GHz [2]. The phase difference between the two linear polarizations is 3.4 to 4.0 deg at the Ka-band downlink, 1.8 to 3.8 deg at uplink, and –0.2 to 0.5 deg at KABLE. The phase shift can be corrected by adjusting the polarizer [2]. The overall size of the plate is 765.048 mm by 647.700 mm (30.12 in. by 25.50 in.), with the elliptical perforated area 561.848 mm by 444.50 mm (22.12 in. by 17.5 in.).[1] See Fig. 3(b).

III. Fabrication

The dichroic plate is made of copper for low conductivity loss. A tolerance study indicated that a ±0.0254-mm (±0.001-in.) tolerance on the dimensions of the apertures was acceptable in order to meet the RF requirements [2]. The plate was first drilled with an array of circular holes, then each hole was cut into a rectangular hole with a wire electrical discharge machine, producing higher accuracy and sharp rectangular corners. The walls of the rectangular apertures (waveguides) were then surface-treated with an extrude hone process. In the extrude hone process, two vertically opposed cylinders extrude abrasive media back and forth through the waveguide passages. The surface finish of the dichroic plate is 250μ mm (10μ in.). The average size of the finished apertures is 5.0607 mm by 5.1265 mm (0.19924 in. by 0.20183 in.) with 0.127-mm-radius (0.005-in.-radius) corners according to JPL fabrication. The discrepancy in one dimension of the aperture is thus 0.0193 mm (0.00076 in.), and in the other dimension it is 0.0297 mm (0.00117 in.); these are within the allowable tolerance. Figure 1 is a photograph of the X-/Ka-/KABLE-band dichroic plate.

IV. Reflection and Group Delay

In the experimental measurement of the reflection and group delay, the alignment between the transmit horn, dichroic plate, and receiving horn is very important. There are two kinds of experimental setups: the reflection setup for determining the reflection coefficients, especially the resonant frequencies, which is shown in Fig. 4(a), and the transmission setup for measuring the group delay, which is shown in Fig. 4(b). Both experiments were performed using an HP 8510C network analyzer. The reflection of the dichroic plate at 30 deg from the normal direction was measured at frequencies from 31 to 36 GHz. The measured and calculated reflection coefficients for transverse electric (TE) and transverse magnetic (TM) polarizations are shown in Figs. 5 and 6. There are two resonant frequencies between 31 and 36 GHz for both the TE and TM polarizations. The resonant frequencies of the dichroic plate are within 0.04 to 0.36 percent of the predicted values (Table 1). The combined transmitted power for TE and TM polarizations is shown in Fig. 7.

The group delay of the dichroic plate was measured using the transmission experiment setup. The calculated and the measured group delay versus frequency is shown in Figs. 8 and 9. The group delay is 0.074 to 0.115 nsec from 31.8 to 34.7 GHz for TE and TM polarizations. The group delay is about 0.002 nsec higher than predicted (Table 2).

V. Noise Temperature

In the antenna system, the dichroic plate is illuminated by a horn whose radiation pattern is considered to be a group of plane waves traveling with different amplitudes at different angles. These plane waves will not all strike the dichroic plate at the same angle. Since the dichroic plate is optimized for a 30-deg incident angle, the reflection is minimized at that angle. Therefore, the power reflected by the dichroic plate for horn illumination is larger than the reflection for pure plane wave incidence at 30 deg.

The conductivity loss (I^2R loss) for a rough surface, in addition to the reflected energy from the horn pattern, contributes to the overall noise temperature in the beam waveguide system. The noise temperature, which includes the reflection for plane wave incidence and the conductivity loss for a smooth surface, is calculated to be 1.34, 5.83, and 7.57 K minimum at 32.0 (downlink), 34.5 (uplink), and 33.7 GHz (KABLE), respectively. Measurements were made at the KABLE frequency of 33.7 GHz in the DSS-13 beam waveguide antenna using a corrugated horn. The measured noise temperature at 33.7 GHz was 11 K, which is 3.43 K higher than the calculation, due to the effects described above.

VI. Conclusion

The design of an X-/Ka-/KABLE-band dichroic plate has been presented. The theoretical and experimental results show good agreement in predicting the performance of the dichroic plate (Table 3). The X-/Ka-/KABLE-band dichroic plate is installed in the DSS-13 beam waveguide antenna at Goldstone, California (Fig. 10), for use in the KABLE experiment and future Ka-band operation.

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[1] W. Veruttipong and J. C. Chen, "New Optics Design of the X/Ka Basement Feed System for the DSS-13 Phase 2," JPL Interoffice Memorandum 3328-91-0103 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 14, 1991.

References

[1] J. C. Chen, "Analysis of a Thick Dichroic Plate With Rectangular Holes at Arbitrary Angles of Incidence," *The Telecommunications and Data Acquisition Progress Report 42-104, vol. October–December 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 9–16, February 15, 1991.

[2] J. C. Chen, "X-/Ka-Band Dichroic Plate Design and Grating Lobe Study," *The Telecommunications and Data Acquisition Progress Report 42-105, vol. January–March 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 21–30, May 15, 1991.

Table 1. The measured and calculated resonant frequencies of the X-/Ka-/KABLE-band dichroic plate. The calculations are based on 40 waveguide modes.

Polarization	Resonant frequency	Measurement, GHz	Calculation, GHz	Error, percent
TE	First	32.03125	32.05	0.06
TE	Second	34.00625	34.08	0.22
TM	First	32.15625	32.17	0.04
TM	Second	35.95000	35.82	0.36

Table 2. Group delay of the X-/Ka-/KABLE-band dichroic plate for TE and TM polarizations.

Ka-band	Frequency, GHz	Group delay, nsec					
		TE polarization			TM polarization		
		Measured	Calculated	Δ	Measured	Calculated	Δ
Downlink	31.8	0.115	0.114	0.001	0.111	0.111	0.000
	32.0	0.108	0.107	0.001	0.105	0.105	0.000
	32.3	0.100	0.101	0.001	0.099	0.099	0.000
KABLE	33.6	0.085	0.083	0.002	0.077	0.074	0.003
	33.7	0.085	0.083	0.002	0.076	0.073	0.003
	33.8	0.085	0.083	0.002	0.075	0.073	0.002
Uplink	34.2	0.085	0.083	0.002	0.075	0.072	0.003
	34.5	0.085	0.083	0.002	0.074	0.072	0.002
	34.7	0.084	0.082	0.002	0.075	0.072	0.003

Table 3. Performance of the X-/Ka-/KABLE-band dichroic plate installed at the DSS-13 beam waveguide antenna.

Frequency characteristics	Downlink, 32 GHz		KABLE, 33.7 GHz		Uplink, 34.5 GHz	
	Calculated[a]	Measured	Calculated[a]	Measured	Calculated[a]	Measured
Reflection loss, dB	0.007	0.006	0.103	0.096	0.078	0.089
Conductivity loss,[b] dB	0.013 (approximate)	—	0.010 (approximate)	—	0.009 (approximate)	—
Ellipticity, dB	0.294	—	0.220	—	0.603	—
Group delay, nsec	0.106	0.102	0.078	0.080	0.078	0.080
Noise temperature, K	1.34 minimum[c]	TBD[d]	7.57 minimum[c]	11	5.83 minimum[c]	N/A

[a] Calculation is based on perfect plane-wave incidence.

[b] Conductivity loss is calculated for a dominant mode propagating in a rectangular waveguide 5.16 mm by 5.08 mm with a length of 9.27 mm. It does not include the effect of surface roughness.

[c] Calculated noise temperature only includes the reflection loss and conductivity loss.

[d] To be determined.

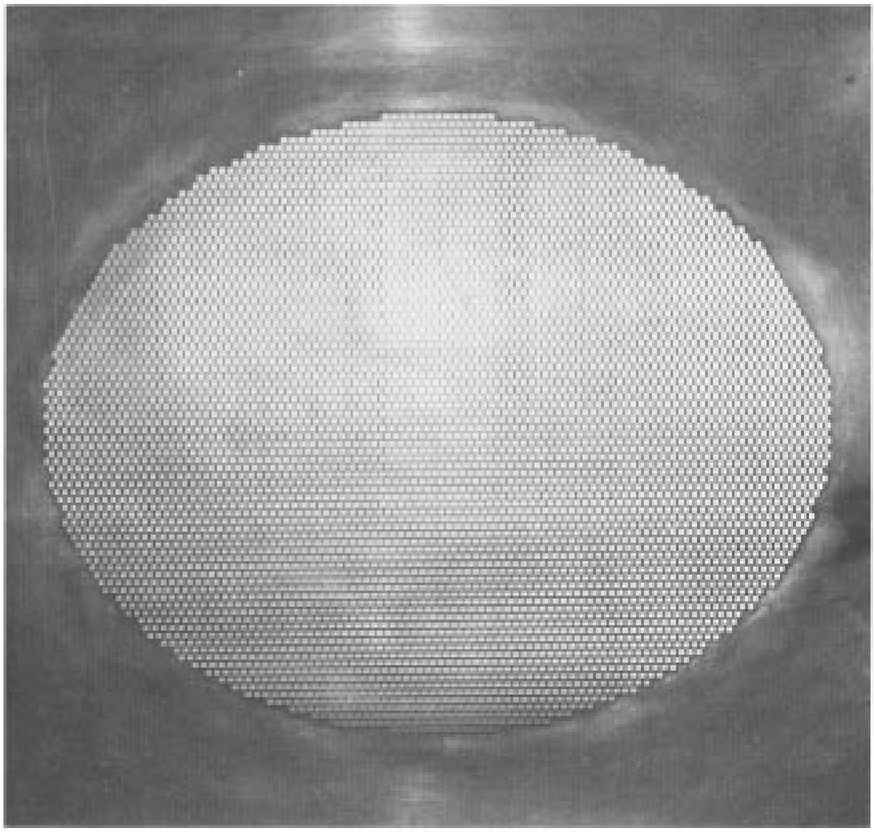

Fig. 1. The X-/Ka-/KABLE-band dichroic plate.

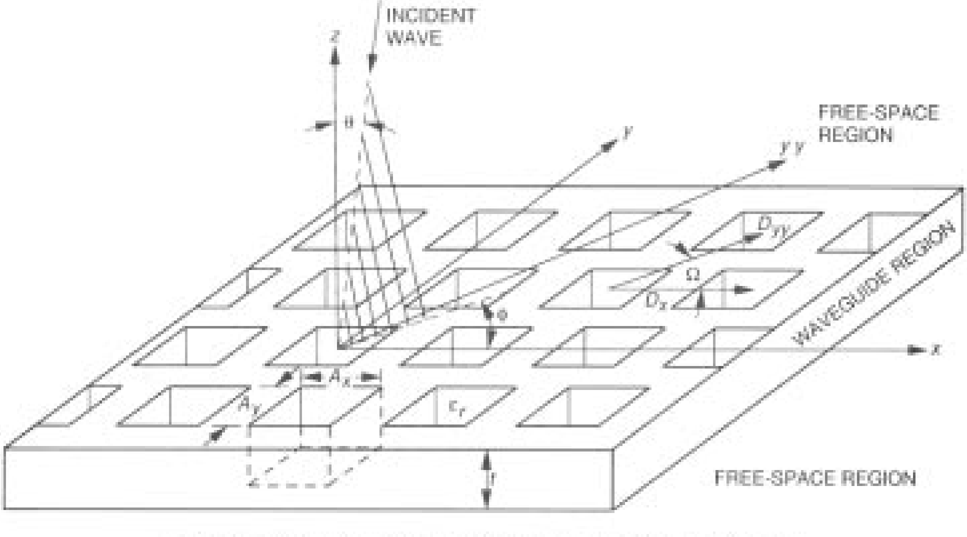

Fig. 2. Geometry of a dichroic plate with rectangular apertures.

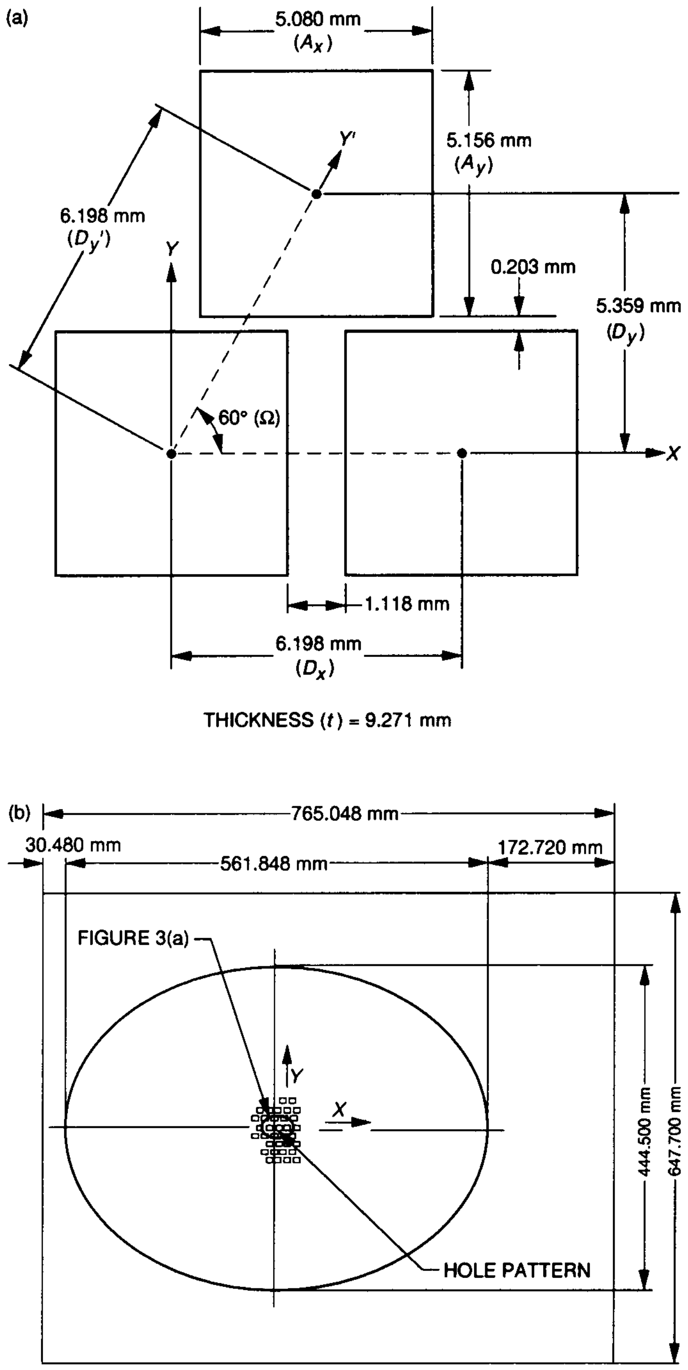

Fig. 3. Diagram of the X-/Ka-/KABLE-band dichroic plate: (a) dimensions and (b) overall size.

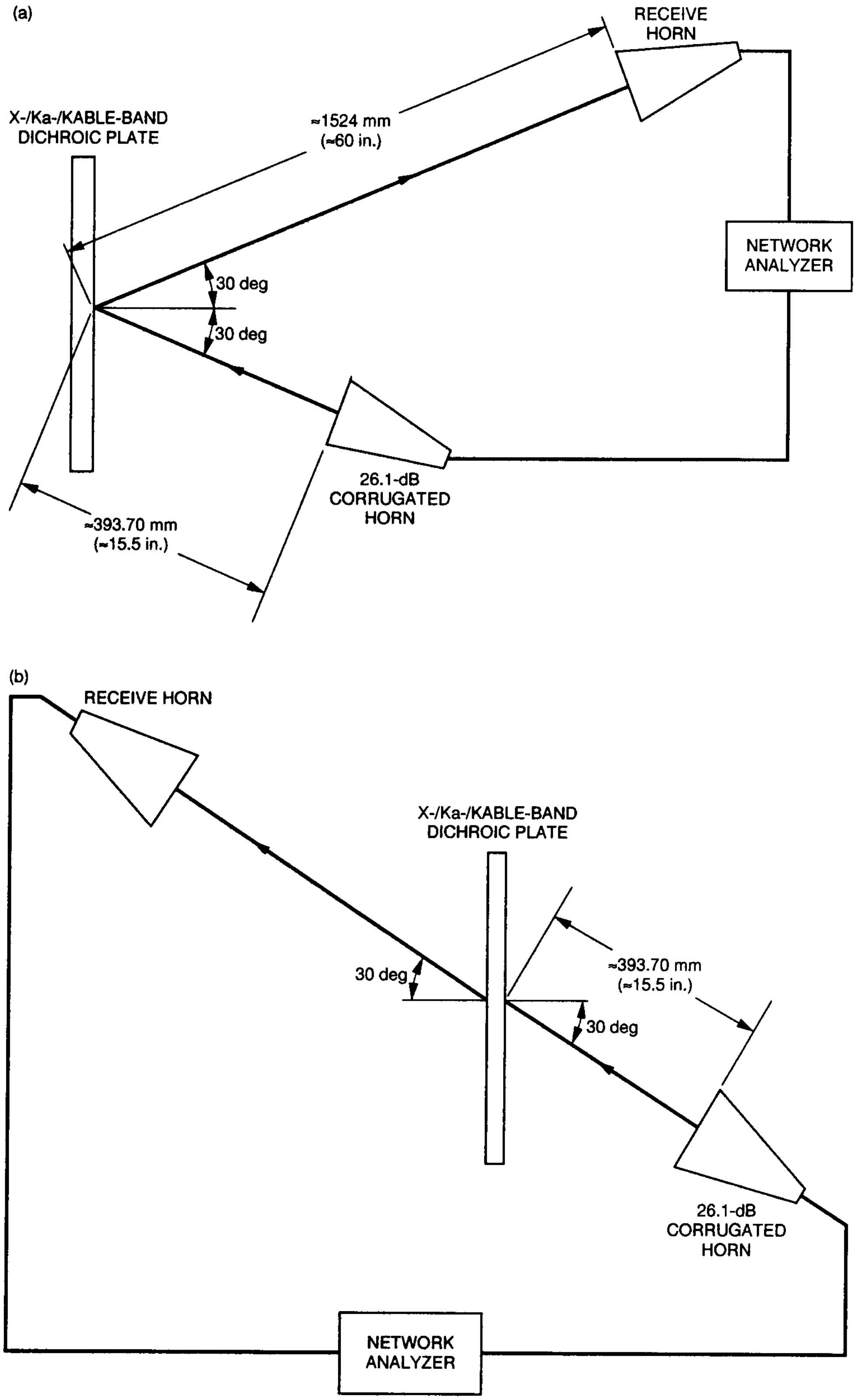

Fig. 4. Experiment setup for (a) reflection measurements and (b) group delay measurements.

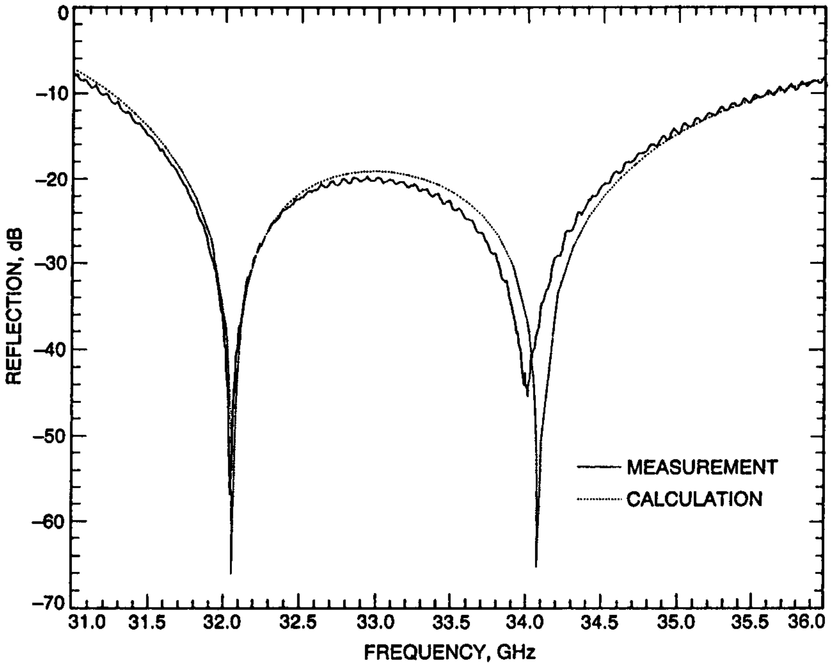

Fig. 5. Calculated and measured reflection coefficient versus frequency for the X-/Ka-/KABLE-band dichroic plate for TE polarizations.

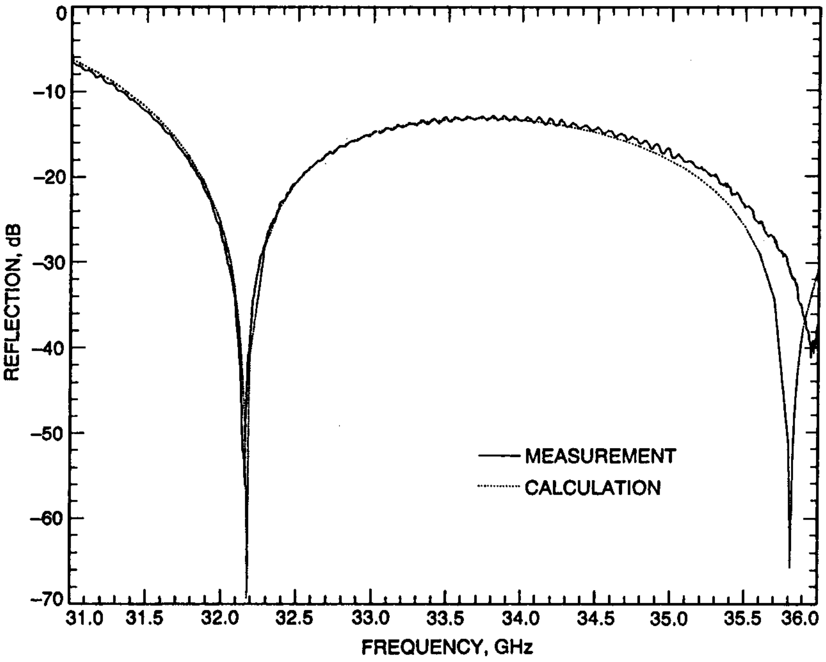

Fig. 6. Calculated and measured reflection coefficient versus frequency for the X-/Ka-/KABLE-band dichroic plate for TM polarizations.

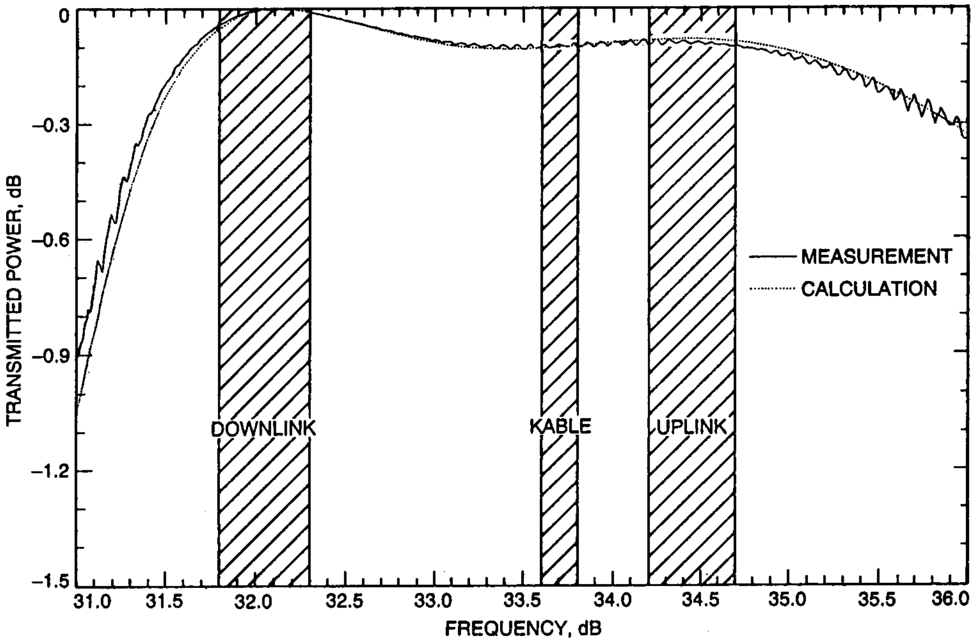

Fig. 7. Transmitted power for the X-/Ka-/KABLE-band dichroic plate.

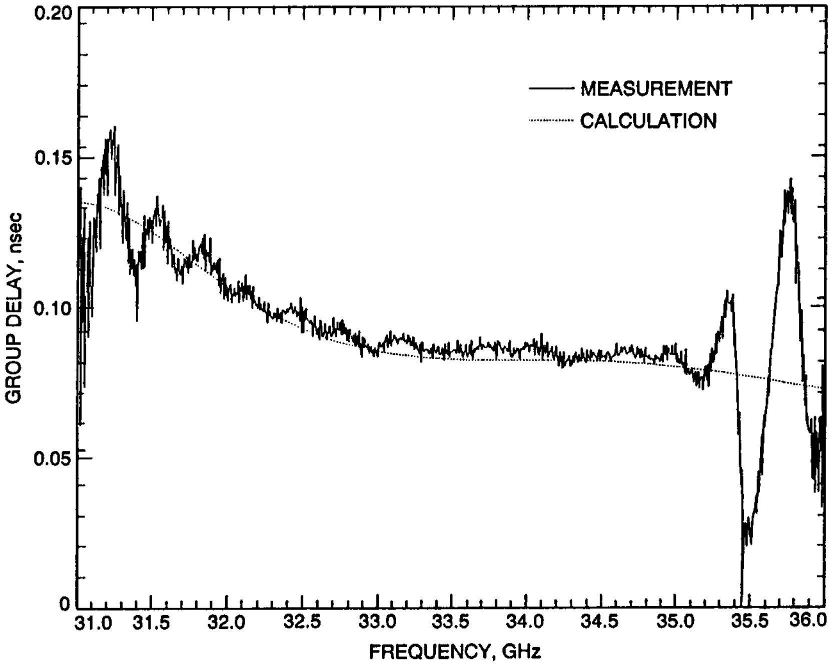

Fig. 8. Calculated and measured group delay versus frequency for the X-/Ka-/KABLE-band dichroic plate for TE polarizations.

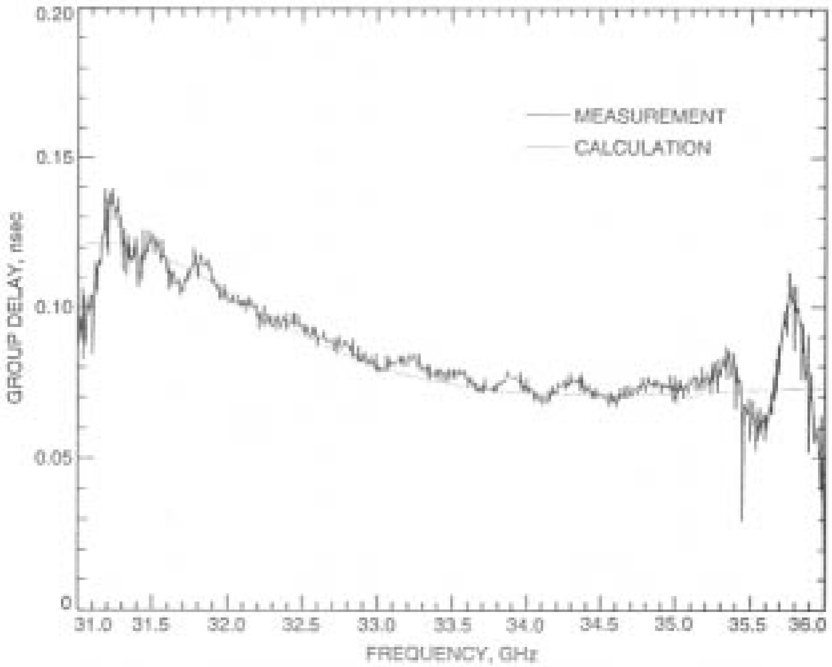

Fig. 9. Calculated and measured group delay versus frequency for the X-/Ka-/KABLE-band dichroic plate for TM polarizations.

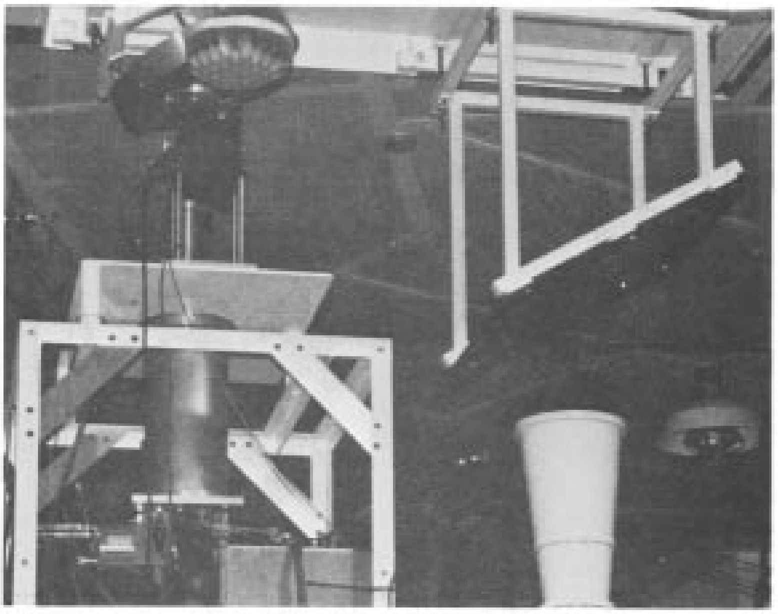

Fig. 10. The X-/Ka-/KABLE-band dichroic plate installed at the DSS-13 beam waveguide antenna at Goldstone, California.