OPTIMIZED CASSEGRAIN FEED SYSTEM

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I. INTRODUCTION

The NRAO 11-Meter Telescope on Kitt Peak has been routinely used for over a decade for making millimeter-wavelength radio astronomical observations. In 1973 the telescope was adapted for use at the Cassegrain focus (f/13.8) as well as at the usual prime focus (f/0.800). The advent of cryogenically cooled receivers required more space and weight-carrying capability than were available at the prime focus. The addition of a removable 0.5 m diameter hyperbolic secondary mirror made it possible to mount larger and heavier receivers at the vertex of the primary mirror. Subsequent tests with several Cassegrain receivers showed that the telescope efficiency was significantly less than at the prime focus. Both the aperture and the beam efficiencies at several different frequencies were reduced by a factor of about 0.85 ± 0.04. Direct and indirect measurements made over a period of several years indicated that the basic problem was higher spillover loss. In principle the gain of an unshaped Cassegrain telescope should be almost equal to that of a prime focus instrument. Phase errors introduced by the secondary mirror were known to be quite small because of the accurate hyperbolic surface as determined by mechanical measurements. The secondary edge diffraction loss is also very small since even the subreflector is many wavelengths in diameter. The natural conclusion was that the feed was not efficiently coupling signal power from the antenna into the receiver. In fact several feeds were used at that time which differed in detail but not in basic structure.

A plastic converging lens collimated the spherical beam radiated by a corrugated horn antenna directly coupled to waveguide. The basic design critereon was that the gain of the radiated power pattern be down 10 dB from the axial value at the edge of the secondary mirror (2.07^{o} off the axis). Subsequent analysis reveals that this critereon is insufficient to guarantee high efficiency. Basically the lens is too small and the horn is too short. Some of the power radiated by the horn misses the lens because of aperture phase error and (because the lens aperture field distribution is not sufficiently tapered toward the edge) the beam efficiency of the feed itself is low. That is, a significant fraction of the power radiated by the horn is not collimated by the lens, and of the power which is collimated, a significant fraction appears in the sidelobes of the feed diffraction beam, which miss the subreflector.

In 1978 I began a more intensive study of lens-corrected horns used as Cassegrain telescope feeds. I have concluded that the basic feed configuration is indeed suitable and that adjustments of certain critical dimensions would result in improved and nearly optimum efficiency. My comparison feed (here called the JJG feed) was one designed for 80-120 GHZ operation by J. J. Gustincic and used in an existing cooled Cassegrain radiometer. I actually used the band from 72 to 115 GHz to produce a new design (here called the BLU feed) which optimized the signal-to-noise ratio of a point source when coupled to a cooled receiver with a DSB noise temperature of 200 K. The following sections in this report deal with the design, construction, and testing of this new feed system.

II. COMPUTER MODEL

A computer model was constructed which allowed the optimization of telescope efficiency to be carried out in an iterative fashion. This model first calculates the field radiated by the corrugated conical horn antenna using the diffracted field equations {Eq. (4) and (5)} given by Narasimhan and Rao (1970). The corrugation depth and spacing and the aperture phase error were chosen according to the curves given by MacA.Thomas (1978). Figure 1 is a cross-sectional construction drawing of the optimized (BLU) horn. For comparison purposes the horn designed by JJG is shown schematically in Figure 2. The new horn is larger in aperture and significantly longer with more slots. The greater length is necessary to reduce the aperture phase error to an acceptably low value.

Teflon was chosen as the lens material since it has lower loss at millimeter wavelengths than polystyrene or other common plastics. According to Jablonski (1978), Teflon has a relative dielectric constant of 2.00 and a loss tangent of about 2.2×10^{-4} at 73 GHz. The dielectric properties were assumed constant over the frequency range of interest (72-115 GHz). A convex-planar lens with two refracting surfaces was chosen over the somewhat simpler plano-convex shape for two reasons. First, neither of the surfaces is a contour of constant phase, and thus the reflections from imperfect surface matching will not increase the feed VWSR as much as for the plano-convex shape. Second, the different amplitude distribution across the lens results in a higher feed beam efficiency. The equation for the lens shape is given by Cohn (1961) in his Figure 14-4e. Basically the lens converts the spherical wave radiated by the horn into

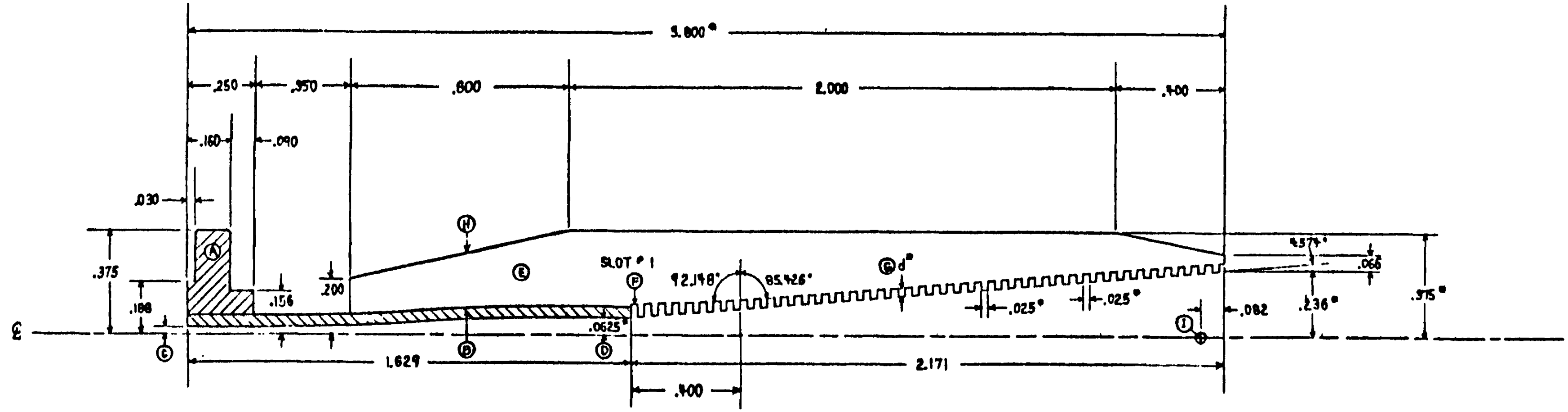


FIGURE 1

NOTES

- O QUANTITY: 2.
- O TOLERANCE ±.005, EXCEPT * DENOTES ±.002 INCH.
- O ONLY ONE SIDE OF CROSS-SECTION OF CIRCULARLY SYMMETRICAL HORN IS SHOWN ABOVE.
- (A) MIL-F-3922/67B-010 WAVEGUIDE FLANGE.
- (B) BAYTECH 3P-67/C RAW OFHC COPPER TRANSITION.
- (C) WR-10 INPUT WAVEGUIDE .050 × .100.
- (D) .125 DIA. OUTPUT CIRCULAR WAVEGUIDE.
- (E) ELECTROFORMED COPPER.
- (F) SLOTS ARE NUMBERED 1-44 FROM LEFT TO RIGHT.
- (G) SEE TABLE FOR SLOT DEPTHS.
- (H) GOLD PLATE ALL SURFACES.
- (I) PHASE CENTER LOCATION.

SLOT NUMBER	SLOT DEPTH d*
1	.050*
2	.048*
3	.046*
4	.044*
5	.042*
6	.039*
7	.037*
8	.035*
9-44	.033*

SLOT WIDTH = .025*
SLOT PERIOD = .050*

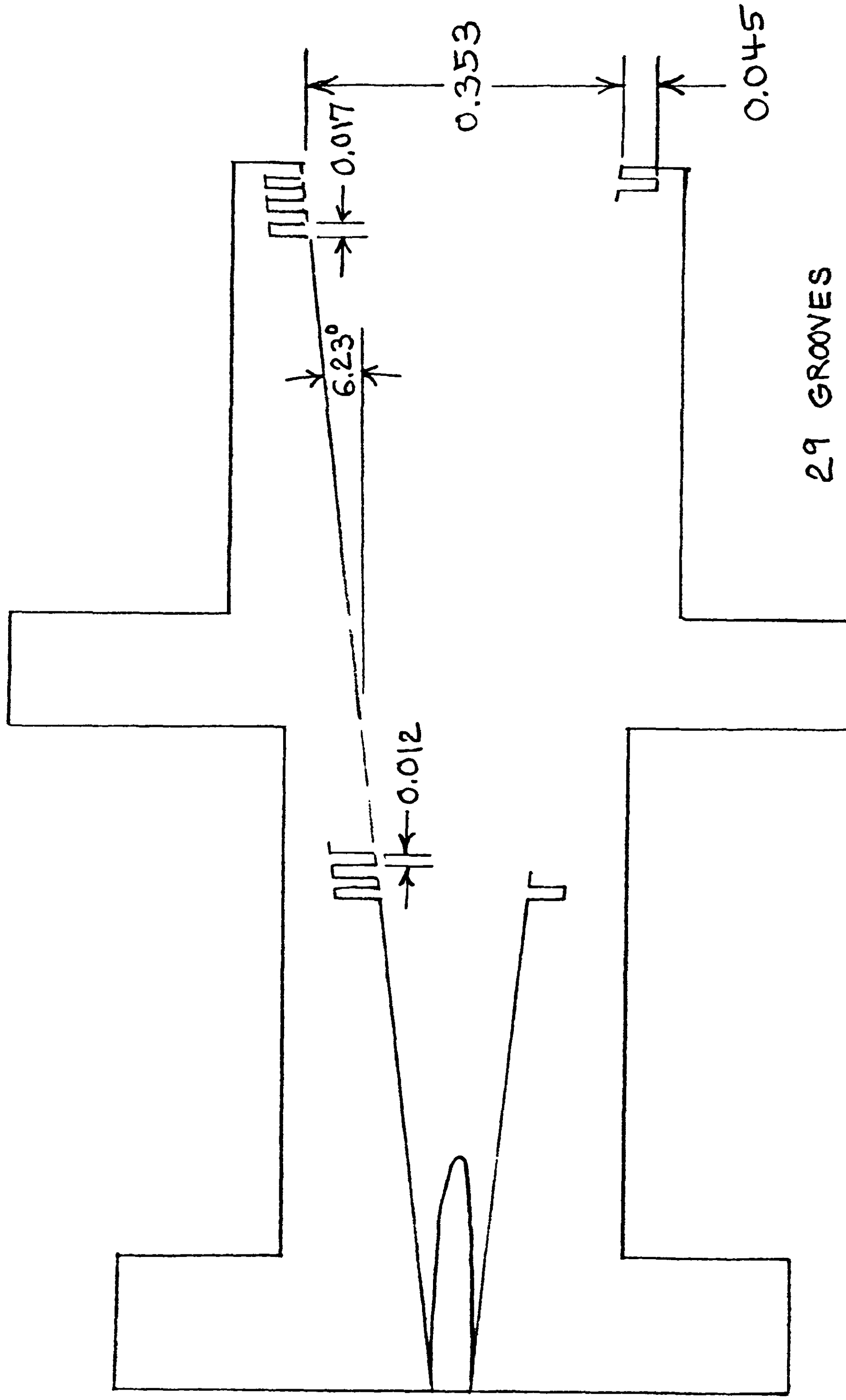
NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC.
GREEN BANK, W. VA.

3 MM CORRUGATED HORN

SCALE 5:1 | NO. T79-2

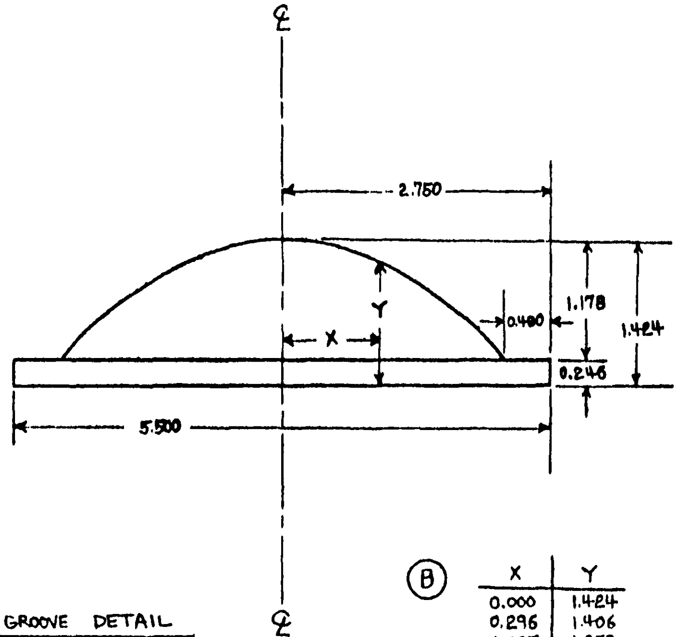
FIGURE 2

GUSTINCIC 80-120 GHz HORN

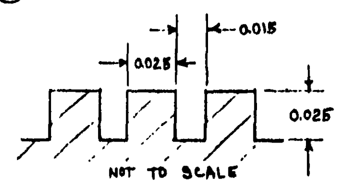


a plane wave. In addition, the angular amplitude distribution of the horn field is changed into a different radial amplitude distribution in the lens aperture. This distribution is used to calculate the far-field radiation pattern of the feed. The subreflector illumination is transformed into the aperture plane of the equivalent paraboloid. Then the radiation pattern of the telescope is calculated according to the Fraunhofer diffraction theory formulation given by Silver (1964) taking into account the central and spar blockage of the secondary mirror support structure. Optimization of the lens parameters to produce maximum telescope gain resulted in a focal length of 100 mm, a diameter of 140 mm and an axial thickness of 53.27 mm. The clear diameter of the metal cell holding the lens (rear stop) is 127.3 mm. Figure 3 is a drawing showing the new lens dimensions, and for comparison the JJG lens design is also shown. The new lens is clearly much larger in diameter and (necessarily) also thicker. The theory of Du and Scheer (1976) was used to design circular matching slots which are cut normal to both lens surfaces. Figure 3 also shows the slot dimensions. The lens surface contours were altered to account for the phase shift of the wave as it passes through the simulated quarter-wavelength matching section. Thus the presence of the matching layers does not perturb the focusing (or collimation) action of the lens. In practice the lens is quite well matched and does not contribute significantly to the overall feed VSWR. The phase center of the feed horn is 2.1 mm behind the horn aperture which should be located 97.5 mm behind the rear (planar) lens surface. Various feed and telescope efficiencies were calculated as a function of wavelength for both feeds, and the results are shown in Figure 4. The optimized feed is predicted to produce significantly higher telescope gain across the entire band.

A J J GUSTINCIC'S LENS DESIGN



Ⓐ GROOVE DETAIL



Ⓑ

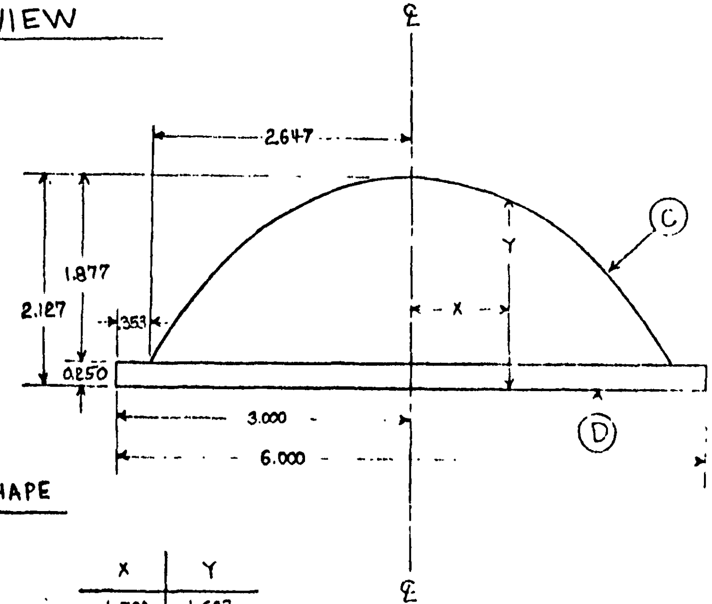
X	Y
0.000	1.424
0.296	1.406
0.587	1.353
0.870	1.266
1.142	1.149
1.400	1.006
1.643	0.839
1.869	0.655
2.078	0.456
2.270	0.246

NOTES

1. MATERIAL - TEFLON TFE.
2. QUANTITY - 1.
3. SHAPE OF CURVED SURFACE IS GIVEN BY TABLE Ⓑ.
4. CUT GROOVES PERPENDICULAR TO SURFACE ON BOTH FLAT AND CURVED FACES. SEE Ⓐ FOR DETAIL.
5. TOLERANCE ±0.002 INCH.

B. B.L. ULICH'S LENS DESIGN FOR 72-115 GHZ

SIDE VIEW



Ⓐ LENS SHAPE

X	Y	X	Y
0.000	2.127	1.500	1.603
0.100	2.125	1.600	1.526
0.200	2.118	1.700	1.441
0.300	2.107	1.800	1.352
0.400	2.092	1.900	1.256
0.500	2.072	2.000	1.151
0.600	2.046	2.100	1.037
0.700	2.018	2.200	0.918
0.800	1.984	2.300	0.788
0.900	1.945	2.400	0.645
1.000	1.900	2.500	0.495
1.100	1.852	2.600	0.332
1.200	1.798	2.647	0.250
1.300	1.738		
1.400	1.674		

Ⓑ GROOVE DETAIL

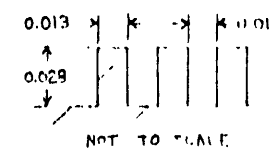


FIGURE 3

NOTES

1. MATERIAL — TEFLON TFE.
2. QUANTITY - 2.
3. SHAPE OF CURVED SURFACE IS GIVEN BY TABLE Ⓐ.
4. CUT GROOVES PERPENDICULAR TO SURFACE ON CURVED SURFACE Ⓒ AND ON FLAT SURFACE Ⓓ OUT TO 5.100 INCH DIAMETER. SEE Ⓑ FOR DETAIL.
5. TOLERANCE ±0.002 INCH.
6. GROOVES ARE CIRCULARLY SYMMETRIC ABOUT AXIS.

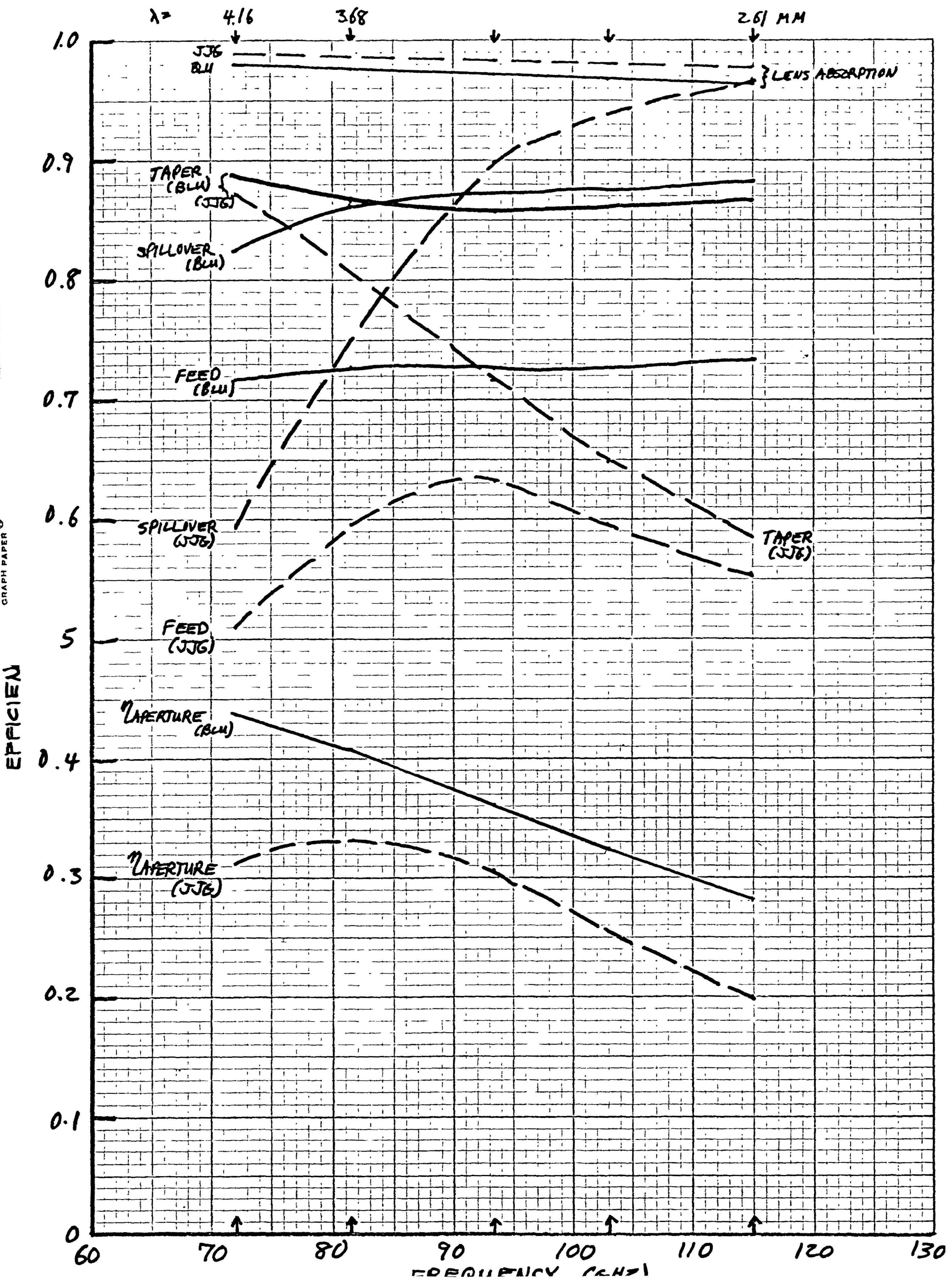
	DATE	BY
REVISIONS		

NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC
GREEN BANK W. VA

TITLE: CASSEGRAIN FEED LENS DESIGN

	NAME	DATE	RECOMMENDED BY	SIGNATURE	DATE
DESIGN	B.L. ULICH				
DRAWN	B.L. ULICH		ENGINEER		
CHK'D	B.L. ULICH		APPROVED		

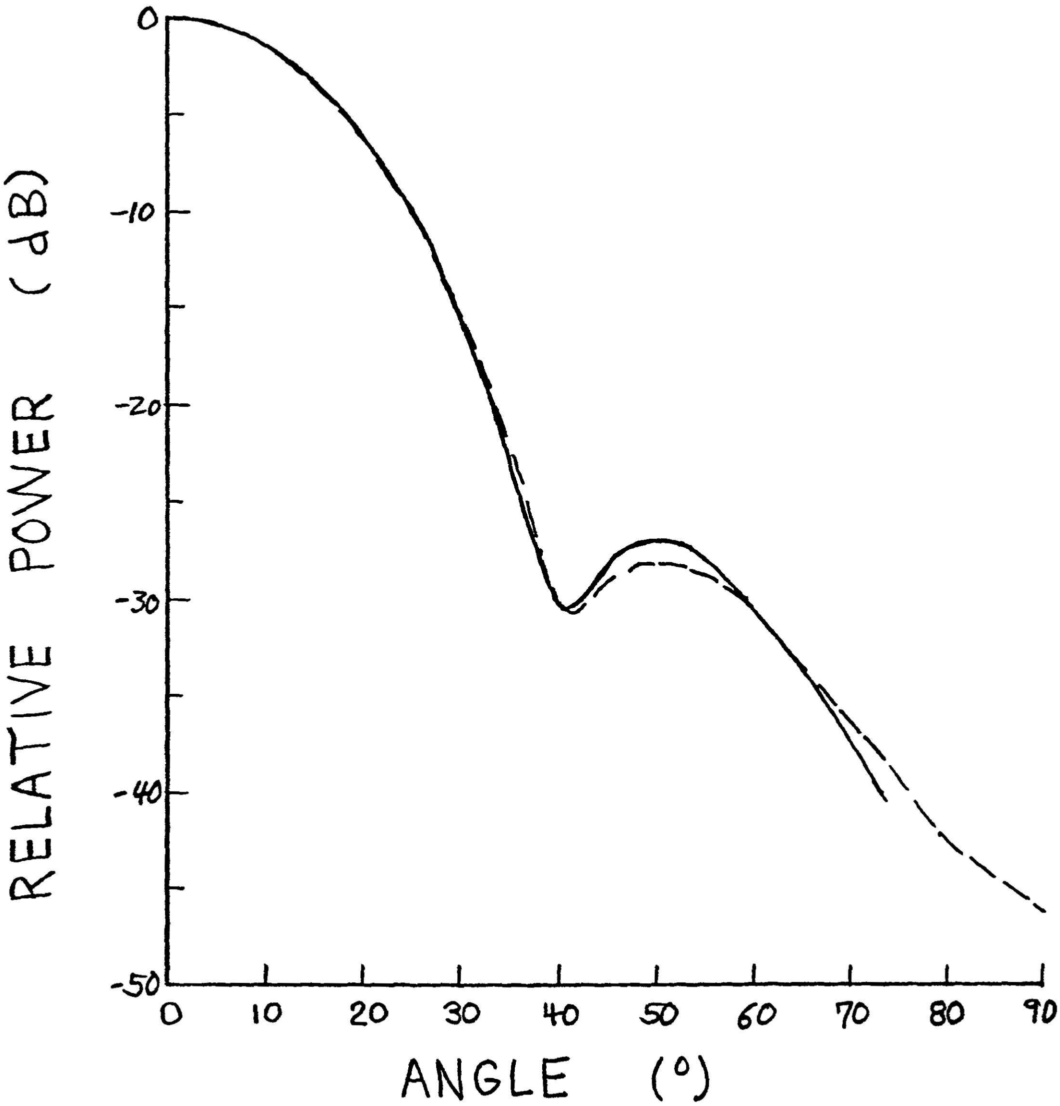
SCALE FULL | NO. T79-1


λ= 4.16 3.68 2.61 MM
JJG
BLU
LENS ABSORPTION
TAPER (BLU)
(JJG)
SPILLOVER (BLU)
FEED (BLU)
SPILLOVER (JJG)
FEED (JJG)
TAPER (JJG)
ηAPERTURE (BLU)
ηAPERTURE (JJG)
EFFICIEN
1.0
0.9
0.8
0.7
0.6
5
0.4
0.3
0.2
0.1
0
60
70
80
90
100
110
120
130
FREQUENCY (GHZ)

III. POWER PATTERN MEASUREMENTS

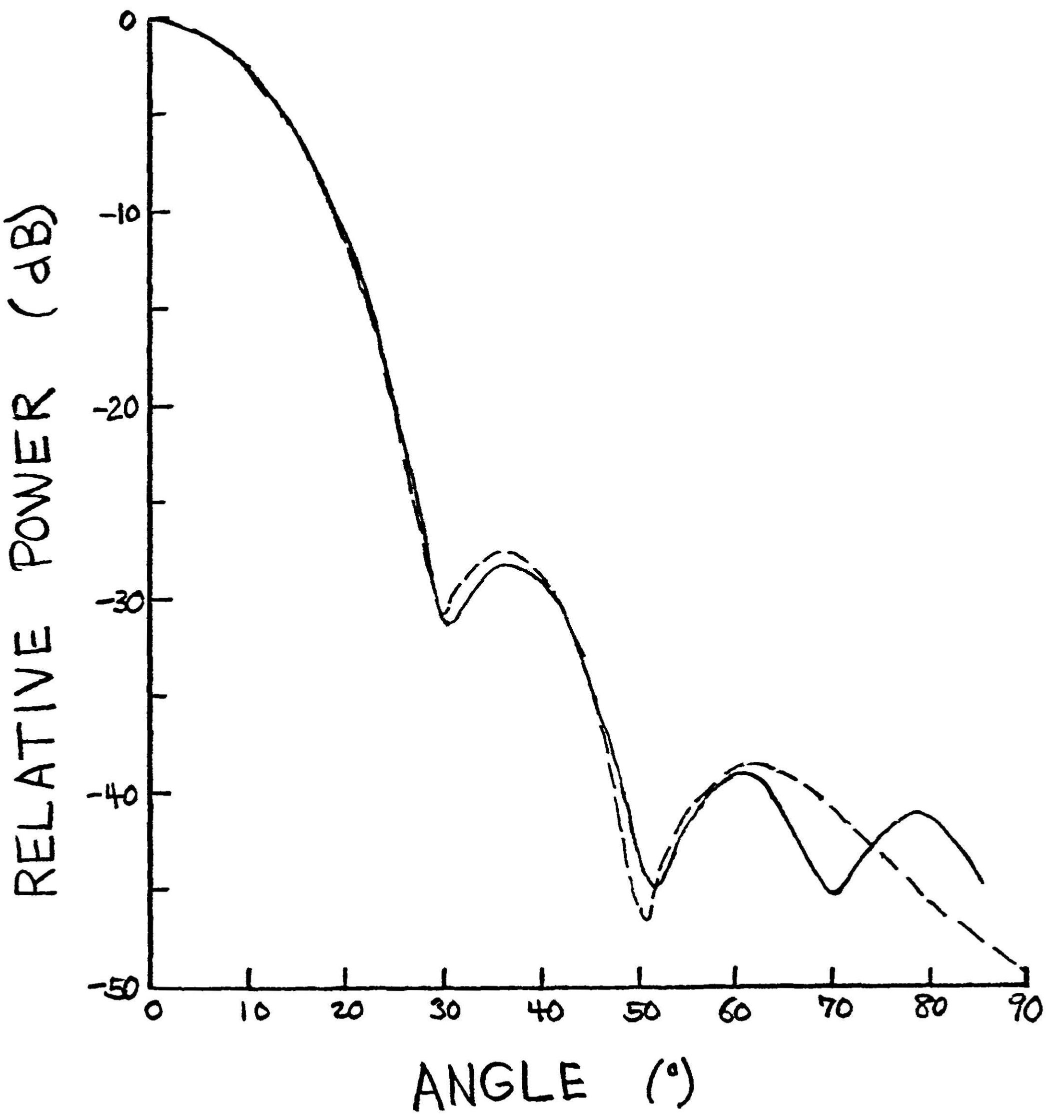
The computer model was used to calculate the power patterns of the horn and of the horn/lens combination. Measurements were made at one frequency near the center of the band (88.8 GHz) to confirm the computations. Comparisons of the measured and calculated patterns for the two horns are shown in Figure 5 and in Figure 6. Very close agreement is apparent down to -28 dB. The larger aperture of the optimized horn results in a narrower beam. Measured and calculated patterns for the two feed assemblies are shown in Figure 7 and in Figure 8. Again, the agreement between theory and experiment is quite satisfying, being better than 1 dB down to -30 dB. The first sidelobe of the pattern of the new feed is about 6 dB lower than for the JJG feed, indirectly indicating that a higher beam efficiency has been achieved.

FIGURE 5



0
-10
-20
-30
-40
-50
RELATIVE POWER (dB)
0
10
20
30
40
50
60
70
80
90
ANGLE (°)

FIGURE 6



0
-10
-20
-30
-40
-50
RELATIVE POWER (dB)
0
10
20
30
40
50
60
70
80
90
ANGLE (°)

FIGURE 7

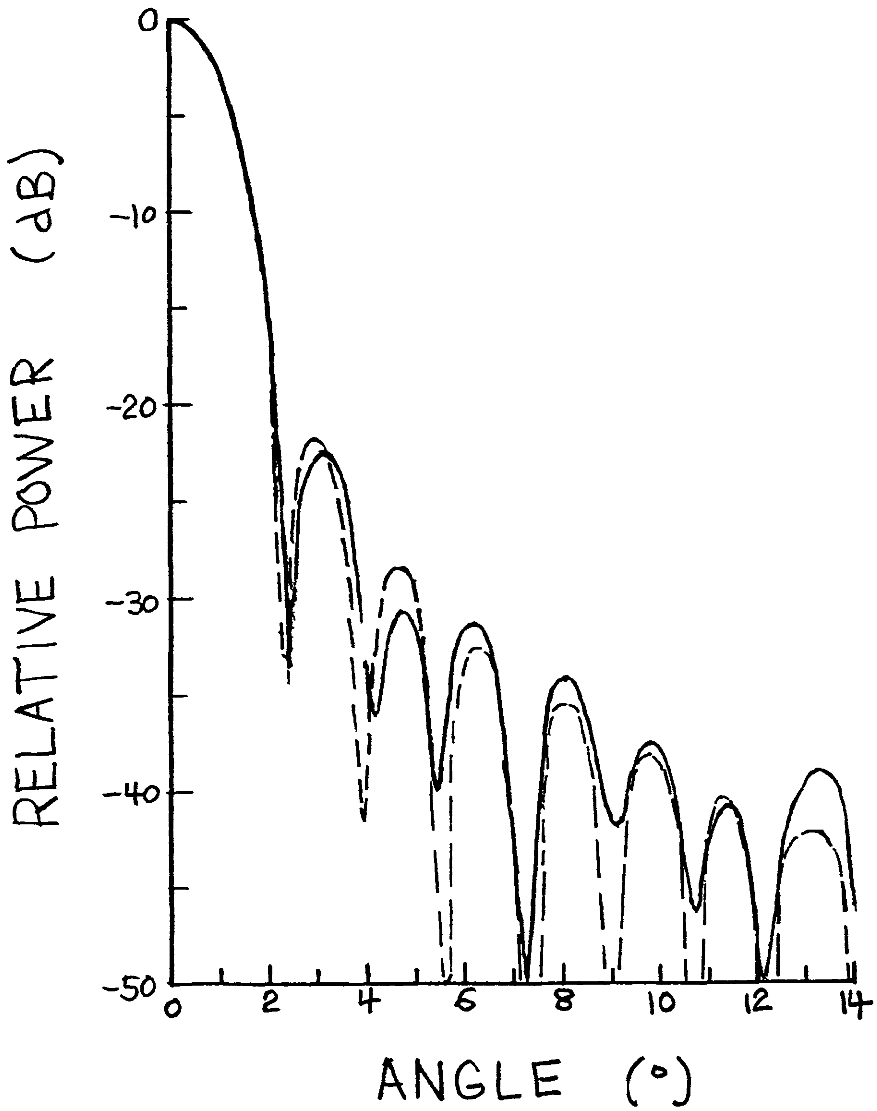
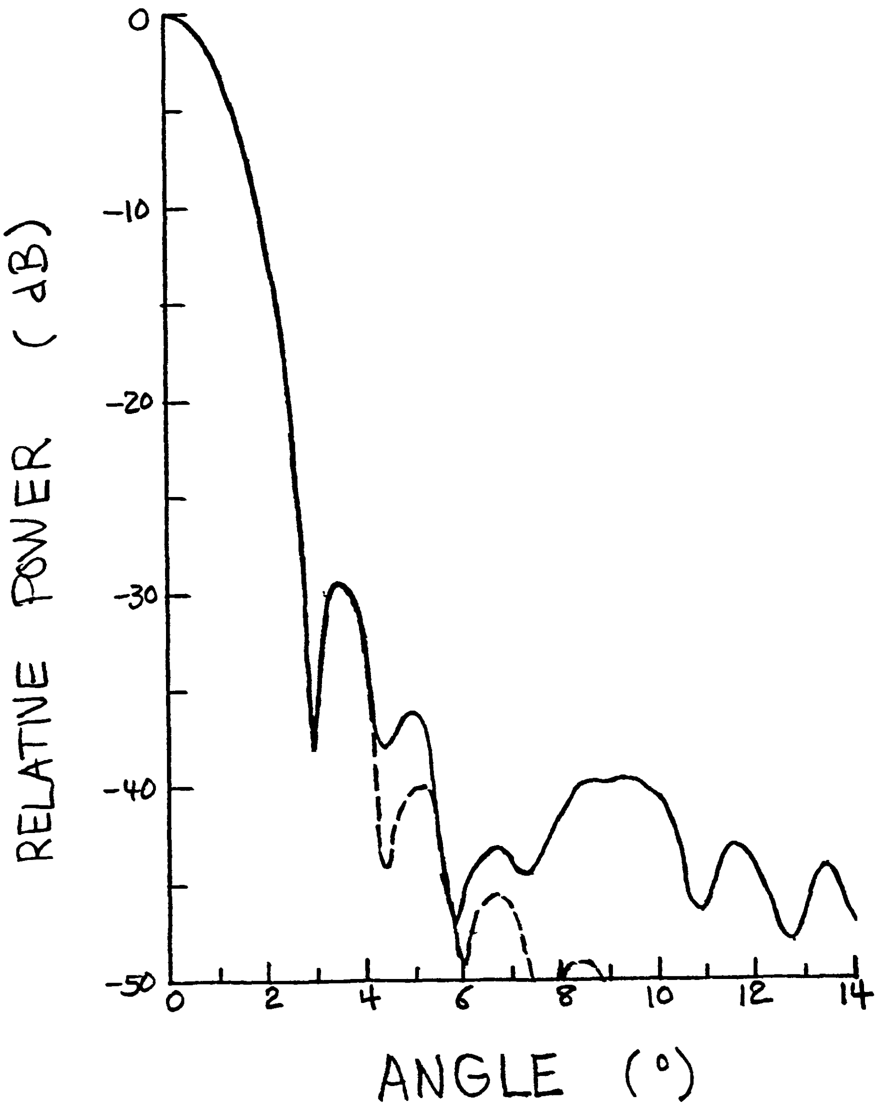


FIGURE 8



IV. TELESCOPE TEST RESULTS

The good agreement of the measured and the calculated power patterns indicated no significant computational problems existed in the computer model. Thus (at least at the center frequency of the band) the predictions concerning improved telescope gain were judged to be reliable. Accordingly, a special receiver was constructed to allow a direct side-by-side comparison of the two feeds on the telescope. This receiver was an uncooled broadband continuum radiometer with a ΔT_{RMS} of about 0.08 K. A remote-controlled waveguide switch was used to select either of the two feeds, which were mounted symmetrically about the telescope axis. A second switch was used to select one of three local oscillators at 72, 89, and 115 GHz. In this way the ratio of telescope gain with each feed could be measured at the band edges and at the center of the band. In August 1979 this system was installed on the NRAO 11-Meter Telescope on Kitt Peak. Several days of testing produced the results summarized in Table I. With the new feed both the aperture efficiency and the beam efficiency referred to the feed output flange are increased by from 7% to 19%. In addition, the telescope beamwidth is reduced at the high end of the band, resulting in improved angular resolution. An explicit comparison between the predicted and the measured improvement in the aperture and the main beam efficiencies is shown in Figure 9. At the band center the agreement is excellent. At 89 GHz the aperture efficiency with the optimized Cassegrain feed is in fact slightly higher than at prime focus. Thus the primary goals of this study have been met. The reasons for the low efficiency are now understood and a new feed has been designed, fabricated, and tested which overcomes these difficulties. At the band edges, how-

TABLE I

FEED TEST DATA SUMMARY

Item	71.8 GHz			88.8 GHz			115.2 GHz[a]		
	BLU	JJG	BLU/JJG	BLU	JJG	BLU/JJG	BLU	JJG	BLU/JJG
T (Zenith) (K)	91	93	—	57	56	—	163	169	—
τ (Neper)	0.31	0.31	—	0.12	0.12	—	0.45	0.45	—
T (Spillover) (K)	33	36	—	34	33	—	87	93	—
T (NoiseTube) (K)	11.5	11.7	—	15.5	21.0	—	6.4	11.4	—
η (Sun)[b,c] at Input	0.75	0.70	1.07±0.02	0.79	0.78	1.01±0.02	0.62	0.61	1.01±0.01
HPBW (")	96	94	1.02±0.02	79	84	0.94±0.02	62	68	0.91±0.03
η [illegible] Input	—	—	1.08±0.03	0.38	0.34	1.12±0.02	—	—	1.09±0.04
Feed Transmissivity	—	—	1.10±0.01	0.95	0.90	1.06±0.01	—	—	1.06±0.01
η_A^d at Output	—	—	1.19±0.03	—	—	1.18±0.02	—	—	1.15±0.05
η_B^d at Output	—	—	1.17±0.03	—	—	1.07±0.02	—	—	1.07±0.02
VSWR (Horn)	1.29	1.22	—	1.13	1.22	—	1.12	1.20	—
VSWR (Feed)	1.28	1.27	—	1.15	1.31	—	1.12	1.14	—

Notes:

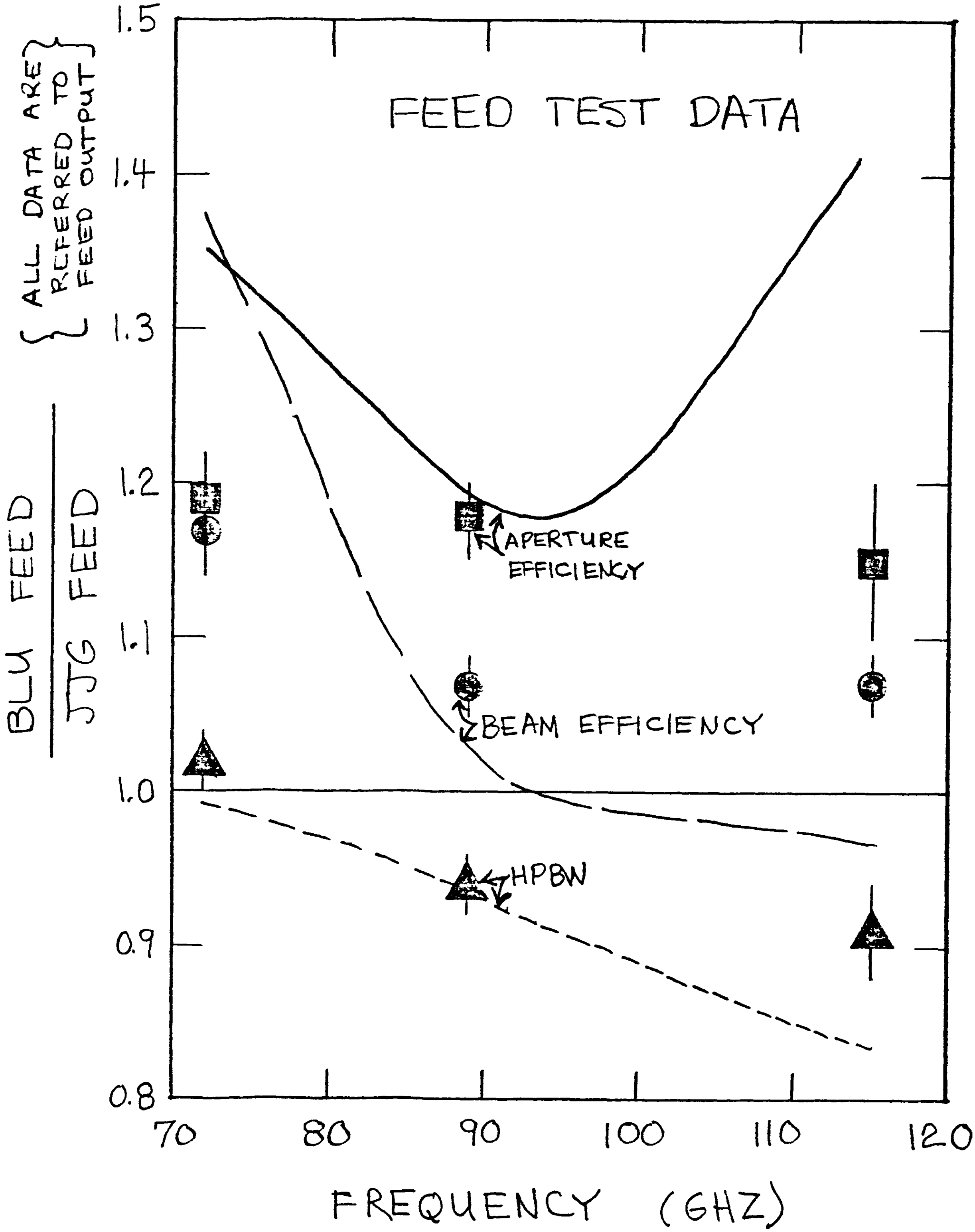
[a]Sunscreen installed.

[b]Assuming T (Sun)=8200 K at 72 GHz, 7800 K at 89 GHz, and 7200 K at 115 GHz.

[c]Referred to plane between feed lens and subreflector.

[d]Referred to plane between waveguide flange of horn and receiver input.

FIGURE 9


FEED TEST DATA
APERTURE EFFICIENCY
BEAM EFFICIENCY
HPBW
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
70
80
90
100
110
120
FREQUENCY (GHZ)
BLU FEED / JJG FEED
{ALL DATA ARE REFERRED TO FEED OUTPUT}

ever, the agreement of the model predictions with the measurements is poor. The new feed is clearly superior at all frequencies, but not by the predicted amount at the band edges. The reason for the poor agreement is not clear. The lens itself and the overall feed geometry should be quite broadband, but achieving good performance over a frequency range of 1.6 is certainly not a trivial task. The slots in the corrugated horn are exactly resonant only near the band center. Possibly the horn pattern is degraded at frequencies near the band edges, and the difference in degradation results in the disagreement between the predicted and the measured gain ratios.

V. RECOMMENDATIONS

The feed design presented here will improve the signal-to-noise ratio of astronomical sources by about 7-19% compared to the feed currently used. This means that the length of integration time required to produce a given signal-to-noise ratio will be reduced by 13-29%, which is clearly a significant improvement. The new feed can and should be retrofitted into all NRAO recievers using the f/13.8 Cassegrain system. Some mechanical modifications will be necessary to accomodate the longer horn and the larger lens.

It should also be noted that this design can be scaled very simply to other wavelengths. To very high precision all dimensions should be scaled directly with wavelength. That is, at twice the frequency an exact half-scale model of the horn and of the lens will produce the same feed radiation pattern and thus the same telescope illumination. At grossly different wavelengths (more than an order of magnitude), the relative dielectric constant of Teflon may be slightly different, and the lens thickness must be appropriately modified.

ACKNOWLEDGMENTS

It is a pleasure to thank M. A. Gordon for his continued support and encouragement. I am also grateful to W. Luckado for manufacturing the horns and lenses used in this study.

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