OVLBI-ES MEMO NO. 27

Feed and Optics Design for the Green Bank OVLBI Earth Station

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April 27, 1992

1 Introduction

The Green Bank OVLBI Earth Station will be required to support satellite links in both X- and Ku-band in support of the Radioastron and VSOP missions. Covering a frequency range of 7.2–15.3 GHz is difficult to do with a single feed and receiver. During a preliminary design review in July, 1991, it was decided to use a two-feed approach, where the X- and Ku-band signals were split by means of a frequency-selective-surface (FSS). A preliminary design using this approach had been done earlier by S. Srikanth, and is described in OVLBI memo #5[1]. A key element to this approach is the FSS, which due to the Earth Station frequency assignments, must diplex frequencies separated by a ratio of 1.67:1 (14.2 GHz/8.5 GHz), and be extremely low-loss in both transmission and reflection bands. Much development effort has been given to the FSS, and results have been reported in OVLBI memo#18[2] and OVLBI memo#26[3]. Given the good results of the FSS measurements, we proceed here with a complete design and analysis of the optics of the Earth Station,.

2 Earth Station Links

As reported in OVLBI memo #4 [4], it is necessary for the Green Bank Earth Station to support the following space research allocation bands:

Frequency(GHz)	Direction	Space Research Allocation
7.190–7.235	uplink only	primary
8.450–8.500	downlink only	primary
13.40–15.35	both directions	secondary

Specifically, to support the VSOP and Radioastron projects, the following frequencies must be supported:

Frequency (GHz)	Satellite	Use	Link	Polarization
7.2000 GHz	Radioastron	CW	uplink	RCP
8.4720 GHz	Radioastron	CW	downlink	RCP
14.200 GHz	VSOP	data, 150 MHz	downlink	LCP
15.063 GHz	Radioastron	data, 150 MHz	downlink	RCP
15.300 GHz	VSOP	CW	uplink	LCP

3 Proposed Scheme

The proposed optics geometry is sketched in Figure 1. The primary reflector is a 45-foot parabola (M1), the secondary is a hyperbolic subreflector of approximately 6.5 foot diameter (M2). The first focal point of the subreflector coincides with the only focal point of the primary reflector (F1), 200 in. from the vertex of the primary. The phase-center of the feed horn should coincide with the second focal point of the subreflector

[1] S. Srikanth, "A Possible Optics Scheme for the 45-Foot Antenna in Green Bank," OVLBI-ES Memo #5, Nov. 27, 1990

[2] B. Shillue, "A Frequency-Selective Surface for the OVLBI Earth Station: Initial Design and Test Results," OVLBI-ES Memo #18, Nov. 20, 1991

[3] B. Shillue, "Measurement Results of Sandwich FSS," OVLBI Memo #26, April 24, 1992

[4] L.R. D'Addario, "Requirements for the Feed and Optics for the 45 ft. Antenna in Green Bank," OVLBI-ES Memo #4, Sept. 7, 1990

(F2) for best antenna illumination. Because we have two feeds, each is placed slightly (12 in) away from the axis of the primary reflector. The subreflector is then made to focus at this point so that the axis of the subreflector makes an angle of 3.71° with the axis of the primary. The X-band feed horn illuminates the subreflector directly; ideally all its energy passes through the tilted FSS(M3) which is placed in front of it. The Ku-band horn illuminates the subreflector via a double reflection off of an offset ellipsoid (M4) and the FSS. The geometry consisting of the two feed horns and their relative positions with respect to the offset ellipsoid and the FSS is subject to several design constraints, and will be discussed in detail. This will be called the vertex geometry, as all of the elements are in the vicinity of the vertex of the primary reflector.

Figure 2 shows a close-up of the vertex geometry. The Ku-band feed horn illuminates the offset ellipsoid, and its energy is reflected towards the FSS. The FSS is tilted so as to reflect the energy again to illuminate the subreflector. One of the design goals is that the doubly-reflected spherical wave incident on the subreflector from the FSS should have a virtual phase-center at or near the phase center of the X-band feed horn.

The relevant property of the ellipsoid is that it has two focal points. Geometrical optics (GO) states that energy incident on any point of the ellipsoid from one focal point will be reflected through the second focal point, and any two such rays will have equal path length. If a feed horn is placed at one focal point (F4), its energy will appear to originate at the second focal point (F3). The portion of the ellipsoid that is illuminated (M4) determines the direction and beamwidth of the reflected field. Geometrical optics, however, describes the behavior of plane waves of very high frequency which are reflected from surfaces infinite in extent, while in our situation we have relatively spherical waves emitted from the feed horns illuminating finite mirrors at finite frequency. The result is the GO prediction that the incident field will be collimated at the second focal point is not true. We have used a physical optics (PO) computer program to analyze the reflected field, and found that it focusses to a point (F3′) that is well short of the second focal point (F3). After reflection from the FSS, the Ku-band reflected-field phase center has a virtual image at a point behind the FSS that should coincide with the subreflector focal point F2. In our final design, the virtual image is 3.9 in. from the X-band phase center. Since we are more concerned with the efficiency at Ku-band than at X-band, we place F2 between the two phase-centers, but much closer to the Ku-band phase center than the X-band phase-center.

4 Geometrical Constraints

The geometrical constraints placed upon the design of the optics mainly affect the vertex geometry. The basic antenna dimensions were given in OVLBI memo#4 [5], and are repeated here for convenience:

Basic Dimensions of the 45-Foot Antenna:

Primary Diameter D	540in.	13.7 m
Focal length f	200 in.	5.08 m (f/D=0.37)
Clear Access at Vertex	16 in	0.41 m radius
Inner Panels stop at	24 in	0.61 m radius
Center Blockage from focal package	54 in.	1.37 m radius

The magnification (M) parameter of a cassegrain antenna relates the focal length of the primary reflector to the equivalent focal length of the Cassegrain system. Either increasing the distance between the feed and the subreflector, or using narrower-beam feeds (and smaller subreflector) will increase M. In an offset-system such as ours, the undesirable beam squint effect of the offset is inversely proportional to M and proportional to the offset angle. However, the feed horn size must be made larger for smaller beamwidths, which can result in everything being too large to fit into the available space at the vertex.

It is of course desirable to keep the subreflector small for minimum blockage, but anything smaller than 54 in. radius contributes nothing to the existing blockage from the focal package. It is desirable to keep the horns spaced as closely as possible without having the ellipsoid interfere with the X-band beam. The field should be -20 to -25 dB from the beam peak at the edge of the ellipsoid. Smaller spacing of the horns reduces the offset angle and also usually results in a smaller incident angle on the FSS, which is desirable due to the good small-angle reflection properties of the FSS.

The geometrical constraints of the existing 45-foot antenna, listed above, and the benefit of larger M-factor, were considered along with the need for high antenna-efficiency at all frequencies of interest. The following

[5]L.R. D'Addario, "Requirements for the Feed and Optics for the 45 ft. Antenna in Green Bank," OVLBI–ES Memo #4, Sept. 7, 1990

table illustrates some of the design tradeoffs:

Parameter	Direction of Change	Desirable Effect
Subreflector Diameter	Smaller	Higher M, Lower Cost, Less Blockage
Distance F2 to F3	Larger	Lower beam squint and crosspol
Horn Separation	Larger	Low beam blockage
	Smaller	Lower offset angle, smaller FSS incident angle
Horn beamwidth	Smaller	Low beam interference, smaller FSS angle
	Larger	Smaller feed horns

5 Feed Design

Both feeds are corrugated horns. To keep the X-band horn reasonably small, and so that the phase center would be near the aperture, the 'narrow-band' horn type of horn[6] was selected. The parameter $\Delta = \frac{r}{\lambda} \tan \frac{\alpha}{2}$ was set at approximately 0.2. For values of Δ greater than 0.2, the beam efficiency is degraded, whereas for much lower values, the horn size becomes prohibitively large. The Ku-band horn was made a wide-band, or flare-angle-controlled design, so that the phase-center would be set back towards the throat and relatively stable as the frequency is changed. Table 1 gives the horn parameters at the lowest, highest, and mid-band frequency. The phase-center is measured from the horn aperture, positive direction away from the horn, and the beamwidth is the 12-dB half-beamwidth.

	Freq. (GHz)	$\alpha°$	L(in)	r(in)	$\frac{r}{\lambda}$	$\frac{L}{\lambda}$	Δ	phase-ctr(in)	Beamwidth
X-band horn	7.2	8.0	30.7	4.3	18.7	2.62	0.18	-3.3	14.0
	7.85				20.4	2.86	0.20	-4.3	12.9
	8.5				22.1	3.09	0.22	-5.5	12.0
Ku-band horn	13.4	15.0	14.7	3.94	16.7	4.47	0.588	-11.0	12.8
	14.2				17.7	4.77	0.623	-11.4	12.6
	15.3				19.0	5.10	0.671	-11.9	12.5

Table 1: Parameters of X- and Ku-band Corrugated Feed Horns. α : horn semiflare angle, L: horn length, r: aperture radius

6 Offset Geometry

The fact that the two feed horns are placed slightly off-axis results in the hyperbolic subreflector (M2) having an axis tilted by 3.7112° with respect to the axis of M1. Figure 3 shows the region of the subreflector in detail. Normally, with a symmetric Cassegrain, the angle at which the subreflector intercepts the feed pattern is the same all around the rim of the subreflector. For the assymetric case, this angle varies around the rim, although in both cases the rim is defined by the intersection of an imaginary line connecting F1 to the edge of the primary (M1). In our case, the vertex of the subreflector is off-axis, so that it points directly at the X-band feed horn. The subreflector half-angle is 68.04°, but the feed pattern is intercepted on one side at 12.59° and on the other side at 14.54°. Relative to the symmetric case, the subreflector is extended on one side and truncated on the other. In the plane of symmetry, perpendicular to the plane shown in Figure 3, the feed pattern is intercepted at 13.5°.

7 Design of the Vertex Geometry

The design of the vertex geometry was done iteratively, with a baseline design using the guidelines above, then small changes were made in order to improve the design. The parameters that could be varied include the horn spacing, the distance from the Ku-band horn to the ellipsoid, the focal length of the ellipsoid, and the position of the FSS. A horn spacing was chosen so that the feed horns and dewars fit within the access

[6] B. MacA. Thomas,"Design of Corrugated Conical Horns," IEEE Trans. Ant. and Prop., Vol. AP-26, No. 2, March, 1978, pp. 367– 372

Freq. (GHz)	η_{sp}	η_t	η_p	η_{BL}	η_{FSS}	η_x	η_{surf}	η_{TOTAL}
7.2	.865	.923	.995	.857	.870	.977	.877	.508
8.5	.907	.863	.994	.857	.955	.977	.835	.519
13.4	.831	.889	.980	.867	—	.977	.636	.390
14.2	.855	.878	.975	.867	—	.977	.602	.373
15.0	.861	.877	.970	.867	—	.977	.562	.349
14.2 w/FSS	.893	.894	.995	.867	.990	.955	.602	.392
15.0 w/FSS	.883	.890	.995	.867	.990	.955	.562	.360

Table 2: Computed beam efficiencies for OVLBI optics subsystem. Key: η_{sp}: spillover efficiency, η_t: taper efficiency, η_p: phase efficiency, η_{BL}: blockage efficiency, η_{FSS}: FSS efficiency, η_x: crosspolarization efficiency, η_{surf}: surface tolerance efficiency, η_{TOTAL}: total efficiency

area at the vertex, as shown in Figure 2. Then the ellipsoid was moved as far away from the Ku-band horn as possible while limiting the amount that it would block the X-band beam. Finally, the length to the second ellipsoid focal point was adjusted until the reflected Ku-band beam had the desired beamwidth and phase-center location. The reflected field from the ellipsoid was simulated with a rigorous physical optics scattering program.[7] The final design is shown in Figure 4.

8 Analysis and Results

Figure 5 shows the illumination patterns of the X- and Ku-band horns on the subreflector, with the Ku-band pattern shown for the doubly reflected case and also for the case of direct illumination with ellipsoid and FSS removed.

Table 2 shows the various components of the aperture efficiency for the optics system at 7.2 GHz, 8.5 GHz, 14.2 GHz, and 15.0 GHz. In cases for which the Earth Station were to be used as a ground-VLBI telescope, the efficiency has also been computed at 13.4 GHz, 14.2 GHz, and 15.0 GHz for direct illumination without the ellipsoid and FSS. For direct illumination, the Ku-band horn is out-of-focus by from 3.7 to 4.2 wavelengths, which results in a degraded phase efficiency as shown in the fourth column. For the OVLBI uplink and downlink frequencies, and use of the ellipsoid-FSS combination, we expect reasonably good phase, illumination, and crosspol-efficiency. The performance of the system as a whole will be limited by the FSS efficiency and the surface-tolerance efficiency. The numbers that are used for these two columns are based on prior measurement reported in OVLBI memos #14 [8] and #26.[9] There still exists the possibility that the FSS performance can be improved, or that the surface efficiency can be improved by purchasing new panels for the primary-reflector.

[7] James R. Lyons, "JPL Physical Optics Scattering Program", NRAO Electronics Division Internal Report#221, September, 1981; Addendum - August, 1982

[8] L.R. D'Addario, "Performance Measurementds of the Green Bank 45-Foot (13.7 M) Antenna," OVLBI-ES Memo#14, June 13, 1991

[9] B. Shillue, "Measurement Results of Sandwich FSS," OVLBI Memo #26 April, 1992

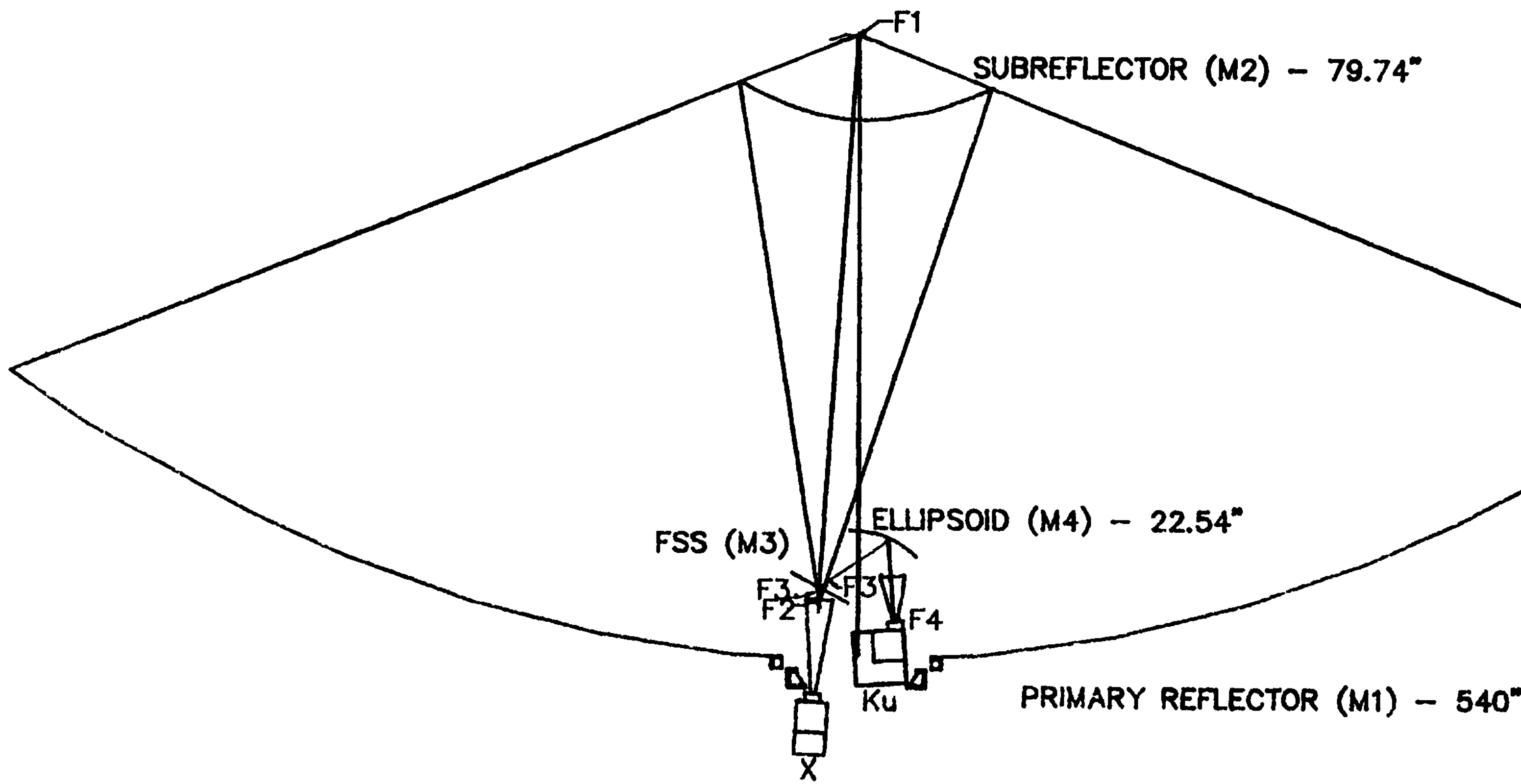

Fig. 1: Proposed X,Ku-band Feed and Optics Geometry for OVLBI Earth Station

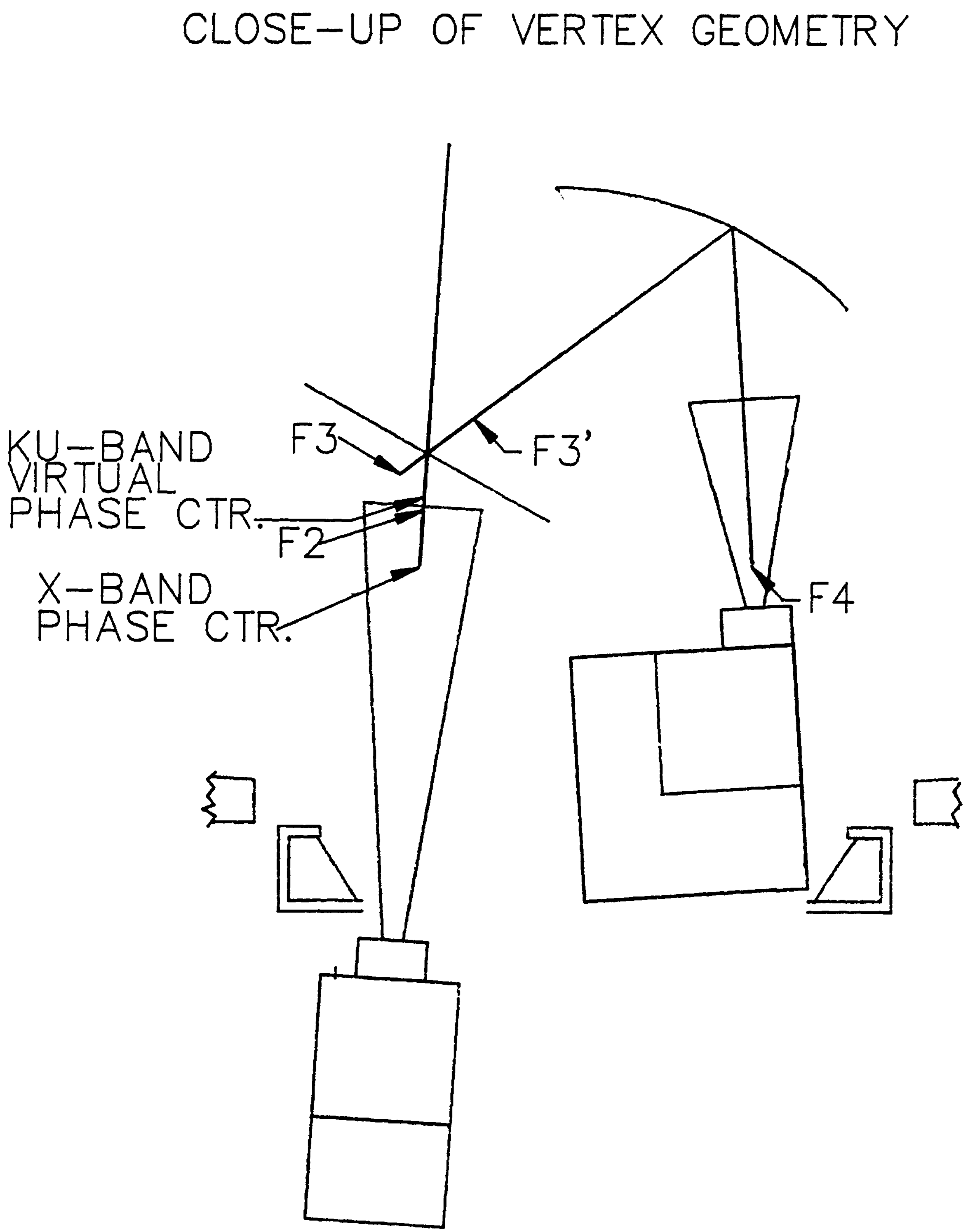

Fig. 2: Geometry of Vertex Region of 45-Foot Antenna

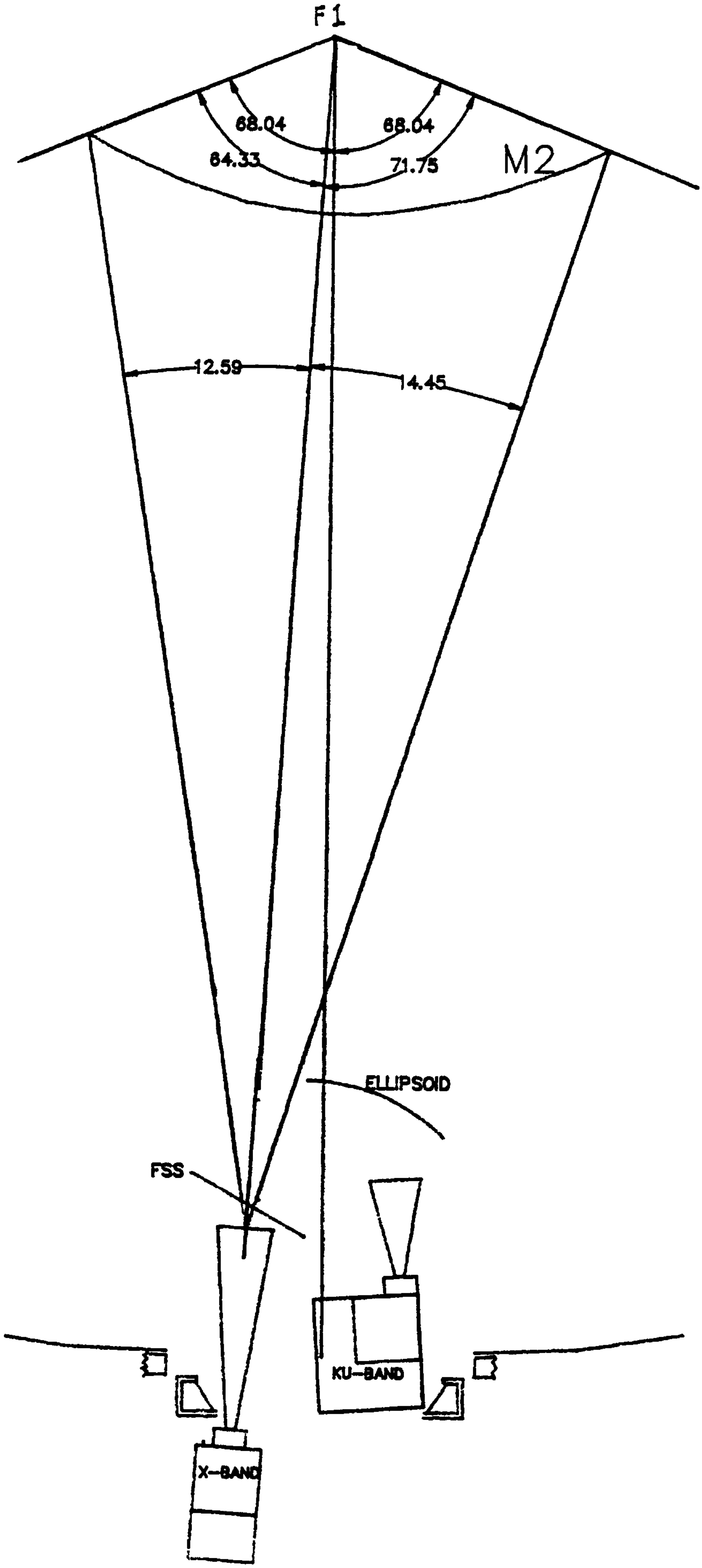

Fig. 3: Detail of Subreflector Region

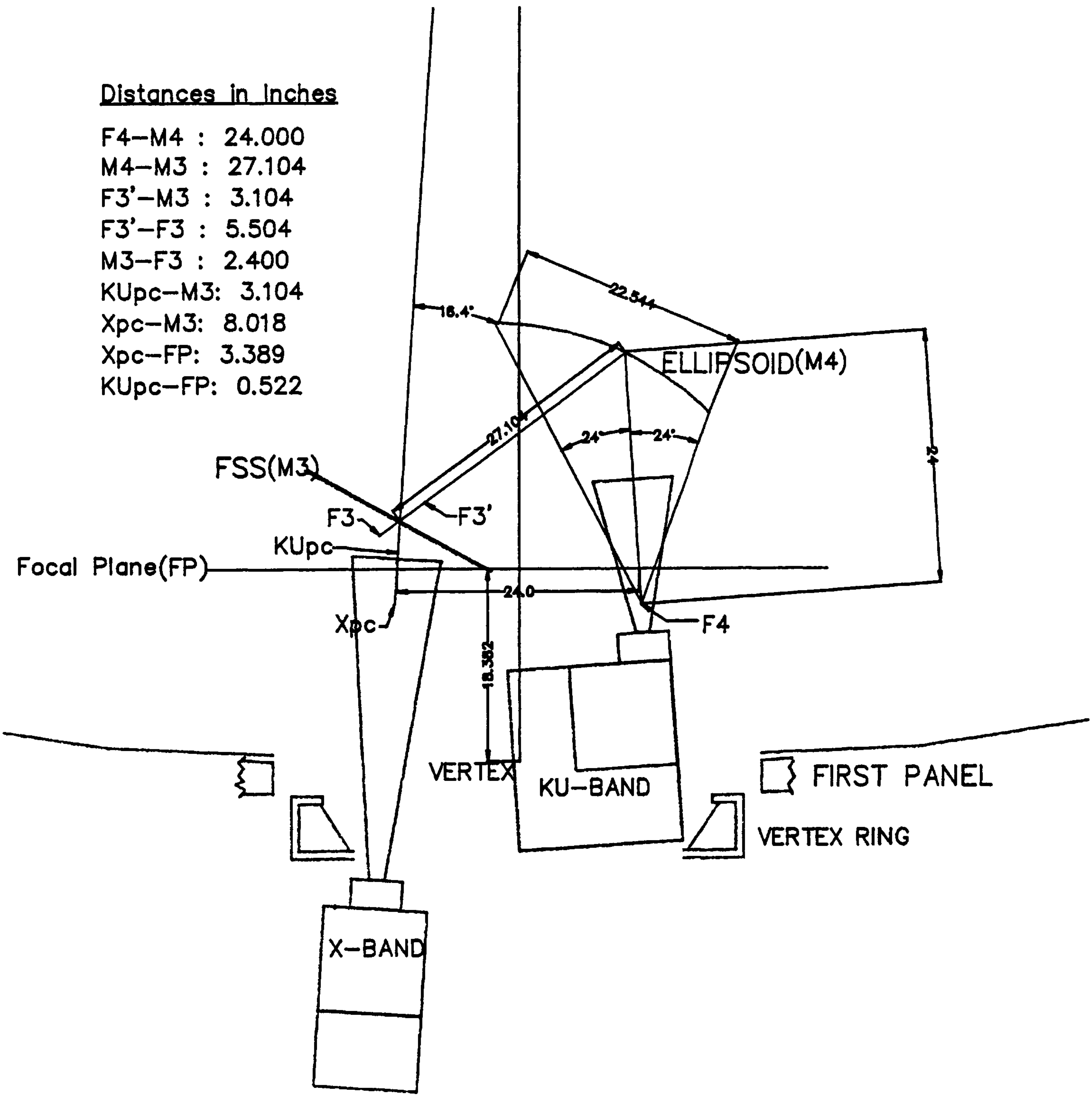

Fig. 4: Final Design of Feed and Optics in Vertex Region

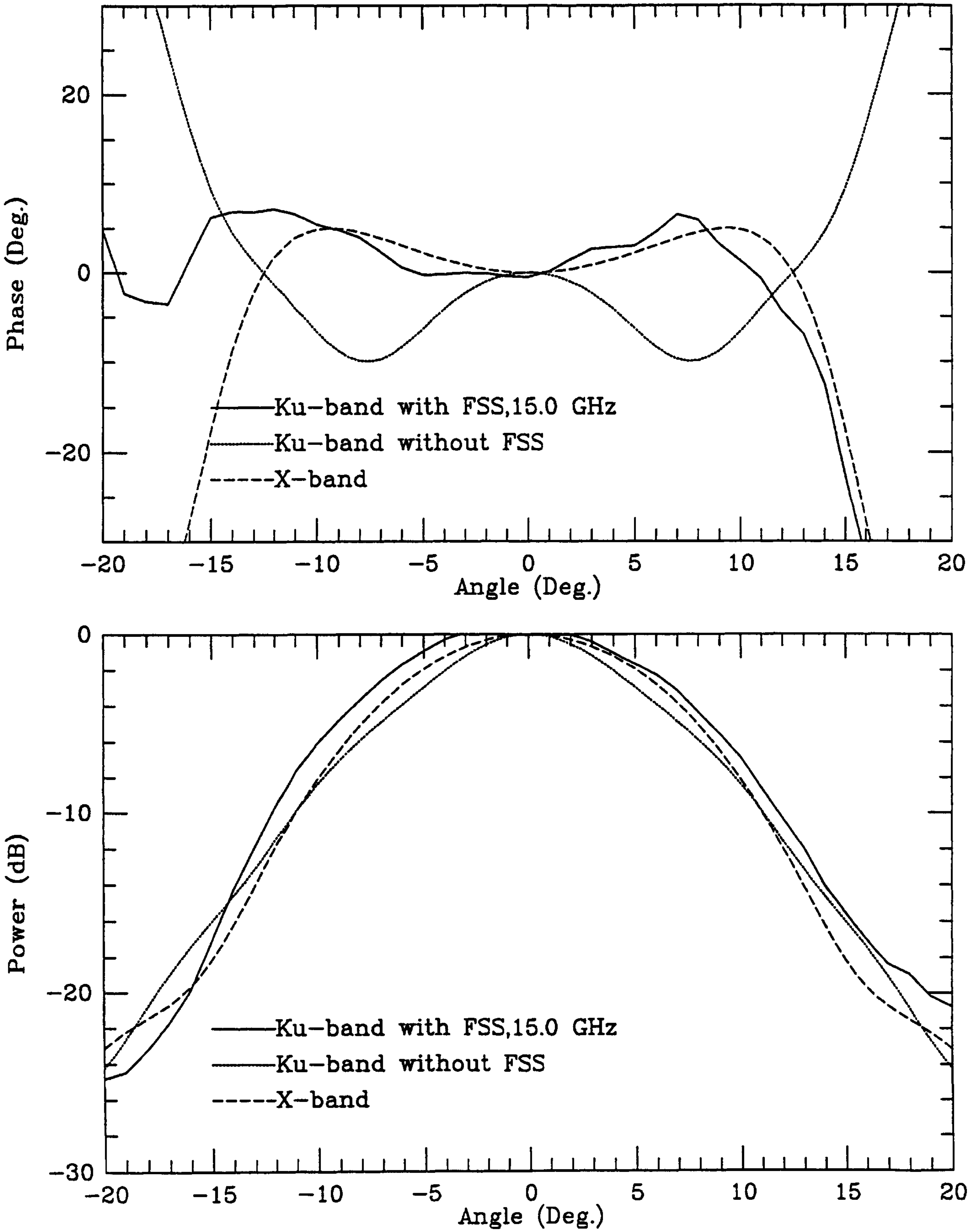

Fig. 5: Subreflector Illumination Patterns