OVLBI-ES Memo 82

Notes on Optics of the Green Bank Earth Station

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Introductory Note to "Notes on Optics of the Green Bank Earth Station"

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This memo was completed in 1995 but never submitted to the NRAO Orbiting VLBI (OVLBI) memo series.[1] Having been recently "found" it is now being appended to that memo series. Two brief comments are made below to place the memo in some historical context.

Comment about the use of Dichroics

The memo documents among other things possibly the only instance of a dichroic mirror being used on an NRAO receiver installation to facilitate simultaneous dual-band operation. The use of a dichroic (called a frequency selective surface in the memo) adds noise temperature to both the transmitted and reflected beam which might be prohibitive in some instances for a radio astronomy receiver. However, the 45-foot antenna in Green Bank was outfitted for support of existing Orbiting VLBI missions and thus its main function was satellite communications rather than radio astronomy. In this use case, a 0.5 dB loss was perfectly acceptable.

Since the time of the OVLBI work in the 1990s, there are many examples of dichroics supporting simultaneous multi-band operation in radio astronomy, and very low losses have been demonstrated. Examples include room temperature dichroics used in the Korean VLBI network 21-m antennas [1], the Nobeyama 45-m antenna [2], and the Yebes 40m radio telescope [3]. Additionally, cryogenic dichroics for millimeter receivers are now being considered in the upgrade path for existing ALMA, SMA, and EHT arrays [4-6].

Comment about Beam Squint

It should be noted that in section 2.2 of the memo beam squint is addressed. In a circularly polarized system, beam squint is inevitably introduced when off-axis optics are used. It refers to the amount that the right (RCP) and left circularly polarized (LCP) beams are displaced from each other on the sky, The supported OVLBI programs (Japanese HALCA/VSOP [7] and the Russian RadioAstron [8]) did not require simultaneous use of RCP and LCP channels, but the beam squint was nevertheless analyzed because the 45-foot antenna was going to be concurrently used for targeted astronomical surveys [9]. The memo analysis predicted that pointing losses due to beam squint would be quite low (< 0. 1 dB), which was confirmed by later measurements [10].

References

[1] Han, Seog-Tae, et al. "Korean VLBI network receiver optics for simultaneous multifrequency observation: Evaluation." *Publications of the Astronomical Society of the Pacific* 125.927 (2013): 539

[2] Okada, Nozomi, et al. "Development of a 22/43 GHz-band quasi-optical perforated plate and dual-band observation system of the Nobeyama 45 m telescope." *Publications of the Astronomical Society of Japan* 72.1 (2020): 7

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[1] Note that nowadays "Space VLBI" is more commonly used than "Orbiting VLBI" to describe VLBI arrays with one or more array elements in orbit

[3] Tercero, F., et al. "Yebes 40 m radio telescope and the broad band Nanocosmos receivers at 7 mm and 3 mm for line surveys." *Astronomy & Astrophysics* 645 (2021): A37

[4] Montofré, D., et al. "Design of an optical beam combiner for dual band observation with ALMA." *2017 XXXIInd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*. IEEE, 2017

[5] Grimes, Paul K., et al. "Upgrading the submillimeter array: wSMA and beyond." *Ground-based and Airborne Instrumentation for Astronomy X*. Vol. 13096. SPIE, 2024.

[6] Montofre, Daniel, et al. "Single-layer dichroic filters for multifrequency receivers at THz frequencies." *IEEE Transactions on Terahertz Science and Technology* 10.6 (2020): 690-697

[7] Hirabayashi, Hisashi, et al. "The VLBI space observatory programme and the radio-astronomical satellite HALCA." *Publications of the Astronomical Society of Japan* 52.6 (2000): 955-965.

[8] Kovalev, Y. Y., et al. "The RadioAstron space VLBI project." *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*. IEEE, 2014

[9] G. Langton, “Astronomical Surveys with the Green Bank Earth Station,” Orbiting VLBI Earth Station (OVLBI-ES) Memo #45, May 20, 1994

[10] G. Langton, “GBES Antenna Pointing Offsets for 1994,” Orbiting VLBI Earth Station (OVLBI-ES) Memo #57, Jan 30, 1995

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1 Introduction

- Main Axis - Axis of 45-ft parabolic dish
- Prime Focus - Focal point of 45-ft parabolic dish
- Subreflector near/far focal point - The two focal points of the hyperboloidal subreflector, one behind it (near) and ideally colocated with the prime focus, the other (far) at the secondary focus.
- Secondary Focus - Far focal point of hyperboloidal subreflector, which should coincide with the phase center of whichever feed the subreflector is pointed at.
- Subreflector Axis - Axis containing the subreflector near and far focal points, and the subreflector vertex.
- Subreflector Vertex - Point where the subreflector crosses the subreflector axis, with slope perpendicular to the axis, indicated by a .500-inch drainage hole.
- Geometric Center - (of the subreflector) Point where the Main Axis intersects the subreflector surface, about 1.75 in. from the vertex. This is indicated by cross-hairs.

The primary reference for the design of the optics is GBES memo #27[1] and the purple OVLBI Critical Design Review Book[6]. Much of the work on the optics was done early in the project and the initial design was never changed.

2 Secondary Optics

2.1 Beam Squint

It is well-known that unless certain geometric properties exist, an offset geometry like that of the GBES leads to either crosspol or beam squint, for linearly or circularly polarized systems, respectively. (The Green Bank telescope, when used as a dual reflector, meets the criteria that allows one reflector to compensate for the other, thereby cancelling crosspol or beam squint.) The GBES uses circular polarization, and the expected beam squint is discussed here.

For X-band, the subreflector is illuminated directly by the feed. (Neglecting the FSS, which should introduce little additional crosspol, see GBES memo #26[2]). The Cassegrain system is only slightly offset, with the angle between the main axis and the subreflector axis equal to 3.7°. The beam squint introduced by the system is given by Napier[4]:

$$\theta_s = \mp \arcsin\left(\frac{\sin(\theta_b - \alpha)}{2 f_{eq} k}\right)$$

In the above equation, θ_b is the angle between the axis of the feed and the subreflector axis, α is the angle between the subreflector axis and the axis of the equivalent parabola, f_{eq} is the focal length of the equivalent parabola, and $k = \frac{2\pi}{\lambda}$ is the wavenumber. For the GBES, $\theta_b = 0$, $\alpha = 20.885°$.

f_{eq} is given by $M * f$ where M is the magnification and f is the 45-foot focal length (200 in.). M(=5.82) is in turn given by:

$$M = \frac{\tan\left(\frac{\theta_m}{2}\right)}{\tan\left(\frac{\theta_{sub}}{2}\right)}$$

where $\theta_m = 68.04°$is the half-angle to the main reflector, and $\theta_{sub} = 13.2°$is the half-angle to the subreflector. Thus $M = 5.82$ and $f_{eq} = 1164$ in.

Table 1 contains statistics on the antenna parameters for beam squint and beamwidth for four different frequencies. Note that the squint angle is a constant number of beamwidths as the frequency is changed. (The FORTRAN program squint.f does this calculation)

	Squint Angle		FHWM Beamwidth	Squint Angle
Freq (GHz)	Arc-min	Arc-sec	Arc-min	/ FWHM Beamwidth
7.2	.140	8.43	12.74	.022
8.5	.119	7.140	10.79	.022
14.2	.071	4.27	6.46	.022
15.3	.066	3.97	6.00	.022

Table 1: Beam Squint Resulting from Direct Illumination of the Subreflector, Bypassing the Ellipsoid-FSS

2.2 Beam Squint Induced by the Ellipsoid

To solve for the beam squint introduced by the ellipsoid-FSS combination is slightly more complicated. Generally speaking, the greater the offset angle, the larger is the beam squint. Some effort was taken to keep the secondary optics compact, so that the two feed horns were as close to the main axis as possible without being so close that the ellipsoid interfered with the X-band optics. This resulted in the ellipsoid offset angle being minimized. Nevertheless, the distorting effects of the offset ellipsoid are not negligible.

2.2.1 Beam Squint by the Equivalent Paraboloid Method

We refer again to the MMA memo #115 by P. Napier, which also contains several excellent additional references. Napier uses the equivalent paraboloid concept to solve for the beam squint of offset dual reflector antennas. The relevant equation is the same as it was for the case of direct illumination. However, this time $(\theta_b - \alpha)$ is given by the angle between the axis of the feed and the axis of the equivalent paraboloid. The axis of the feed is found by first removing the FSS from the geometry, that is, reflecting the feed and the ellipsoid through the mirror plane of the FSS. The axis of the equivalent paraboloid is defined by the line connecting the first focal point of the ellipse and the intersection of the ellipse with the subreflector axis. This is illustrated in Fig. 1. The angle $(\theta_b - \alpha)$ is then given by 90.55°as shown in the Figure. The equivalent focal length, f_{eq} is the same as it was above, 1164 in.

Table 2 shows the predicted results for beam squint from the offset ellipsoid:

Freq (GHz)	wavelength (in.)	θ_s
14.2	.832	11.73 arc-sec
15.3	.772	10.88 arc-sec

Table 2: Beam Squint Predicted by the Equivalent Paraboloid Method

2.2.2 Beam Squint Inferred From Linear Crosspol

The crosspol introduced by reflection from the ellipsoid was calculated from Gans, Bell Sys Tech Journal, 1976, p. 289. The equation is as follows:

$$C = \frac{2\gamma k_{perp}}{\sin\theta_i}$$

where γ is the beam waist size at the ellipsoid; k_{perp} is the ellipsoid curvature in the plane normal to the incidence plane; and θ_i is the incidence angle. The Ku-band horn has an aperture size of 3.96 in. and a standard relation for beam-waist size to feed aperture size is $w/a = .6435$, so that the beam waist size at the feed aperture is 2.55 in. The aperture is 11.9 in. from the phase center, and 12.1 in. in front of the ellipsoid. To calculate the beam-waist size at the ellipsoid, the following standard Gaussian beam equation is used:

$$w^2(z) = w_0^2 \left(1 + \frac{\lambda(z - z_0)}{\pi w_0^2}\right)$$

Knowing that $w(11.9) = 2.55$, one gets $w_0 = 1.85$ in., and $w(24) = 3.10$ in. This becomes γ in the first equation. The angle of incidence is $\theta_i = 28.8°$. It is difficult to tell exactly what the author meant by the ellipsoid curvature normal to the plane of incidence, but the ellipsoid major-and minor axes are 23.3 and 26.7 inches, so those values should bracket the value for k_{perp}. (k_{perp} is the curvature, and has units of $length^{-1}$, $1/24in^{-1}$ will be used for this calculation). The result for the maximum crosspol level in the crosspol lobe relative to the copolarized beam peak is C=.0756 or -22.4 dB.

A second reference (J.A. Murphy, "Distortion of a Simple Gaussian Beam on Reflection from Off-Axis Ellipsoidal Mirrors", Int. J. Infrared and Millimeter Waves, Vol. 8, No. 9, 1987) gives an equation that quantifies the amount of power lost into crosspolarization. This is given as:

$$\frac{1}{4}\tan\theta_i{}^2 (\frac{\gamma}{f})^2$$

where θ_i and γ are given as before, and f is the focal length of the ellipsoid. The focal length is given by $(1/R_1 + 1/R_2)^{-1}$ where R1 and R2 are the distances from the first and second focal point to the point where the beam center intersects the ellipsoid. In our case, we have R1=24, R2=29.5, and f=13.23. Thus we get that the fractional power that gets crosspolarized is .00416 or -23.8 dB. Both of the results, -22.4 dB for the peak crosspol referenced to the peak of the main beam, and -23.8 dB as the total power in crosspol mode versus copolarized mode, seem to be consistent.

There is a direct relation between the induced crosspol and the beam squint for any particular antenna geometry. The Napier paper[4] contains curves which relate crosspol level to beam squint, and if we use -23 dB for our linear crosspol level, these curves show a beam squint of $\frac{0.08\lambda}{D}$. the rsult is shown in Table 3.

Freq (GHz)	wavelength (in.)	θ_s
14.2	.832	24.7 arc-sec
15.3	.772	23.6 arc-sec

Table 3: Beam Squint Predicted by the Crosspol Method

There is a discrepancy by about a factor of two between the results using the equivalent parabola method and the results using the crosspol method. This discrepancy is not understood. The equivalent parabola method has been shown to be an accurate beam squint predictor, and may be a more accurate result.

The pointing loss comes as a result of having a beam separation of twice the beam squint, since LCHP and RHCP circluarly polarized waves squint in opposite directions. Assuming that the telescope is pointed between the two squinted beams so that they are both slightly off-source, the pointing loss due to beam squint can be calculated. These results are tabulated below, and include the beam squint due to the ellipsoid and the hyperboloid; assuming the total beam squint to be additive. A far-field power relation of $\exp \frac{-\theta^2}{\theta_0^2}$ is assumed, and the relation $\theta_0 = 1.70(\theta_{FWHM}/2)$ was used. Pointing loss due to beam squint is frequency-independent, so the result shown in Table 4is valid for 14-16 GHz. The pointing loss at X-band (7-9 GHz) is negligible.

Method	Pointing Efficiency	Pointing Loss (dB)
Equivalent Parabola	.995	-.02
Crosspol method	.984	-.07 dB

Table 4: Pointing Loss Due to Beam Squint

It should be noted that the pointing loss is only applicable when simultaneous left- and right-polarization channels are used simultaneously, which does not occur for either VSOP or Radioastron mode satellite tracking.

2.3 Feeds

The feeds were designed to satisfy several criteria: constant beamwidth versus frequency, good return loss ($\geq$ 25 dB) over the desired bands (7-9 GHz, 13-16 GHz), and to properly illuminate the subreflector. The VLBA X- and Ku-band feeds cover approximately the same frequency ranges, but were rejected for OVLBI use because they did not have the required beamwidth. The OVLBI Ku-band feed was designed however to taper to an opening waveguide size that would match the VLBA Ku-band dewar window size. It was necessry to make the X-band opening waveguide size slightly larger than the VLBA X-band dewar to accomodate the 7.2 GHz VSOP transmitter signal without the possibility of a cutoff mode in the waveguide. I this way, the VLBA dewar assemblies were adopted with as little modification as possible.

The main parameters of the feeds and how they fit into the overall optics design is covered in OVLBI-ES memo#27[1]. The dimensions of the the straight flare section of the feeds, the mode transformer section, and the circular waveguide tapers are given in the relevant OVLBI drawings.

Some measurement results are included here. Fig. 2 shows the Ku-band feed return loss measurement. The return loss was measured by a network analyzer one-port measurement, with coax-torectangular waveguide and rectangular waveguide to circular waveguide adapters preceding the horn taper and throat sections. Three offset shorts of lengths such that their impedances were well-spaced on the Smith Chart over the whole band were used as calibration terminations. Fig. 3 shows the X-band returm loss measurement result.

Fig. 4 shows the Ku-band horn feed patterns across the band for the E-plane. Fig. 5 shows the H-plane. Figs. 6 shows the X-band feed pattern for the E-plane, and Fig. 7 shows the X-band feed pattern for the H-plane.

Table 5 sumarizes some of the parameters of the feed horns and the predicted performance.

	Freq.	α^o	L(in)	r(in)	$\frac{r}{\lambda}$	$\frac{L}{\lambda}$	Δ	phase ctr(in)	Beam-width
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	12.0
	14.2				17.7	4.77	0.623	-11.4	12.3
	15.3				19.0	5.10	0.671	-11.9	12.4

Table 5: Parameters and Predicted Phase-Center and Beamwidth of X- and Ku-band Corrugated Feed Horns. α : horn semiflare angle, L: horn length, r: aperture radius

Table 6 and Table 7 represent the measured results for the two corrugated horns. Note that the measurements are pretty close to the design goals.

Freq.	Beamwidth			Xpol(max-dB)	Return	phase
(GHz)	E-plane	H-plane	45° plane	45° plane	Loss (dB)	ctr.(in)
13.8	11.8	12.0	12.0	-34	30	-12.4
14.2	11.6	11.8	11.9	-36	28	-11.8
15.0	11.7	11.9	11.8	-34	34	-12.1
15.3	12.5	12.5	12.2	-35	38	-12.3

Table 6: Results of Ku-band Horn Measurements. Beamwidth is 12 dB half-beamwidth.

2.4 Ellipsoid

The secondary optics design includes an offset ellipsoidal subreflector which refocuses the Ku-band beam between the FSS and the Ku-band horn. The specifications for the ellipsoidal subreflector have been set forth in NRAO specification A34221N002. The reflector was manufactured to this specification by Pacific Radomes of Santa Clara, CA.

Freq.	Beamwidth			Xpol(max-dB)	Return	phase
(GHz)	E-plane	H-plane	45° plane	45° plane	Loss (dB)	ctr.(in)
6.8	15.0	14.4	—	-37	–	—
7.2	13.8	13.8	—	-40	24	-4.30
7.6	13.1	13.1	—	-45	34	—
8.0	12.2	12.6	—	-43	¿40	-5.1
8.5	11.5	11.7	—	-38	31	-5.6
8.8	—	11.7	—	-30	18	—-

Table 7: Results of Ku-band Horn Measurements. Beamwidth is 12 dB half-beamwidth.

0.5dBTransmissionBandwidth

Angle	TE	TM
0°	7.2–8.6	7.2–8.4
15°	7.2–8.6	7.3–8.7
30°	7.2–8.4	7.2–8.4
40°	7.2–8.4	7.1–8.8
Common BW : 7.3–8.4		

20dBReflectionBandwidth

Angle	TE	TM
0°	13.9–15.7	14.0–15.8
15°	14.0–15.6	14.0–15.6
30°	13.8–15.5	13.9–15.3
40°	13.7–15.5	13.9-15.1
Common BW : 14.0–15.1		

Table 8: Bandwidth of Sandwich FSS

The ellipsoid was designed to inrtercept all of the transmitted energy from the Ku-band horn, or, equivalently, so that essentially zero spillover energy enters the horn from outside the edges of the ellipsoid. The ellipsoid reflects the incident wave from the Ku-band horn towards the FSS. Although the actual focal point of the FSS lies beyond the FSS surface, simulations showed that the wave was refocussed to a best fit phase center slightly in front of the FSS. Using image theory, then, looking from the subbreflector towards the FSS, one would 'see' the Ku-band phase center as being slightly behind the FSS.

The edge of the ellipsoid towards the center of the main dish actually extends a couple of inches beyond the main reflector axis and intercepts the X-band horn's transmission at an angle of 17°to the X-band horn, at a field level of 18-22 dB, depending on the frequency. Since the shadowing of the X-band beam by the FSS is an elliptical footprint intersecting a circular footprint at its edge, the total shadowing is very small. The possibility of this adversely affecting the X-band noise temperature is small, but finite.

2.5 FSS

The FSS consists of two 30-mil thick Teflon dielectric slabs [7], one unmetallized, the other with a copper pattern etched on one side. The two dielectric slabs, are bonded together using a 1-mil thick adhesive bonding film under thermal compression. For this reason, we have referred to this as the "Sandwich FSS." The result is a very sturdy and weatherproof reflector. The pattern mask was made in-house, and the etch and bond process done by a printed circuit-board manufacturer.

Measurement results of the present FSS have been presented in several places[2, 5, 6]. An outline of those results is summarized by Table 2.5.

In summary, the most conservative estimates of the FSS reflection loss and transmission loss have been made based on our measurements and included in our system link budgets. We have not yet met our specification of 0.2 dB maximum insertion loss, and the result is that the FSS increases the overall system temperature significantly, but a even in the worst case, ample link margins remain.

The FSS is a very inexpensive item to fabricate. The expense is in the time required to measure its characteristic. However, it should be noted that a swept frequency measurement setup was implemented on the outdoor antenna range in Green Bank which vastly increased the measurement time. A spare FSS does not exist, and should probably be fabricated.

2.6 Radome

A radome was installed over the secondary optics area. The primary reason was a motivation to reduce the loss associated with wet reflecting surfaces. By covering the optics, the radome gets wet but the ellipsoid, FSS, and feed horn windows do not. The radome is a Gore-Tex[8] canvas material stretched in a frame across the roof of a hexagonal-shaped frame. The walls of the radome housing are made in two sections, the bottom section called the 'tub', which is a 15-inch high by 45-inch diameter cylinder, and a top section which is about 40-in. high with the same hexagonal cross section as the frame. Access doors have been placed on two of the sides of this housing. All of the doors and seams of the radome housing assembly have been gasketed or sealed with RTV.

3 The Subreflector

The subreflector is a hyperboloid with its axis of symmetry offset from the Main Axis by 3.7°. The idea is for one of the focal points of the hyperboloid to coincide with the Prime Focus and the other with the secondary focus. The equation of the hyperboloid is: put eq'n here The primed coordinates here have origin at the Secondary Focus with Z' coinciding with the Subreflector Axis.

The subreflector has several points that are marked on its surface. The Subreflector Vertex is marked with a 1/2-inch drainage hole. The Subreflector Geometric Center is marked with pencilled cross-hairs. There are four marks on the perimeter, which have so far been of no use, but may have some conceivable use in alignment. These marks are at the 0, 90, 180, and 270 degrees points as you trace the perimeter of the subreflector. However, due to the nature of the offset system, the points are neither equally spaced on the perimeter of the subreflector, nor are they aligned with the cardinal planes of the main dish, nor is the plane that contains all four of the points perpendicular to the Subreflector Axis! Two of them fall on a line where the plane of symmetry cuts the subreflector and two fall on the plane of asymmetry. Refer to Specification A34221N006 for the full definition of these points.

The subreflector surface is very good; there should be no contribution to surface efficiency degradation from it. The surface was measured quite carefully in my presence, with a template rotated around the surface, and seven dial calipers equally spaced along the radius of the dish. The template was then carefully measured. Total surface RMS was .0035 inches, whereas the specification called for .008 inches. The results of these measurements are available as drawing ASI 001[7].

The subreflector bolt-plane was manufactured to be perpendicular to the main antenna axis, 3.7° from the subreflector axis. This was not measured in my presence, although I am assured by the manufacturer, ASI, that this was done extremely carefully. The distance from the vertex to the bolt-plane is $12.0 \pm .030$ inches. The nominal distance from the bolt-plane to the subreflector near-focus is 15.090 inches. These distances are shown on the sketch in Fig. 8.

3.1 Subreflector Support Structure

Fig. 8 shows a sketch of the subreflector with its support structure in the Sterling Mount. To get the subreflector focus to coincide with the main focus, the best focus position of the old prime focus holography receiver was used along with the measured length of the prime focus box. Details of that calculation are shown in the figure.

There has been some speculation as to how closely we can guarantee the tilt of the subreflector. The best indicator we have for the subreflector tilt is the bolt-plane. The six bushings on the bolt-plane should be level with respect to gravity when the antenna is truly pointed at zenith. Note that the fiberglass donut of the bolt-plane is NOT necessarily level, that part of it is sloppy. We have not made this leveling measurement, we merely bolted the subreflector to the support structure so that the bushings were equally spaced (about 1.8 inches) from the support structure mounting plate.

We are therefore trusting the subreflector support structure and the Sterling Mount itself to be level. Is this OK? An argument could be made that the Sterling Mount is tilted. As far as I know, the center of the Sterling Mount has been measured to coincide with the Main Axis, and this does not change when it is moved in focus and rotation, but that does not mean that it is not tilted.

The support structure was measured whilst standing upright in the machine shop, and it was level to within .062 inches. Of course, on the antenna, under cantilevered loading, some tilt and displacement will result, although this should not be too significant. While viewing the subreflector through a telescope during the feed alignment, the subreflector moved downward by about .500 in. as the antenna moved between zenith and 5° elevation. The feeds were aligned according to the position of the subreflector at 45° elevation. Thus a displacement of .250 inches of the subreflector is feasible. Of course, the effect that I witnessed could be caused all or in part by movement of the feed legs rather than movement of the subreflector support structure, but the effect is the same. The effect of this downward movement of the subreflector may be lessened if the best focus of the antenna also moves downward relative to a fixed line-of-sight from the vertex. This is in fact what you would expect to occur. If both the best focus of the parabola and the position of the subreflector move downward so that the subreflector focus and the prime focus track each other, then the only error would be an effective feed tilt, which would have a very small effect on overall gain. The worst case, then, is that the subreflector moves 0.25 inches from the prime focus.

If we assume a 0.25-inch subreflector worst case offset vs. elevation, and assume that there is a gravity induced tilted support structure causing the offset, the tilt would be $atan\frac{0.25inches}{40inches} = 22arcmin$ This would cause a substantial gain loss. However, the subreflector mounting structure was designed for a tilt of no more than 5 arc min, and a gain loss of 0.1 dB(.977). If, as seems likely, the movement of the subreflector is due to the feed leg movement, then the offset is mostly lateral rather than tilt. In this case, a lateral offset of .250 in. would result in a gain loss of about -0.4 dB.

Trying to estimate optical losses due to elevation induced structural and alignment changes is very difficult without very careful measurements. Our approach was to design the optics support structures with adequate rigidity, aligning and setting distances as carefully as we could, and then looking into any potential problems only if the astronomical pointing and efficiency measurements indicated a problem.

3.2 Alignment

The secondary optics wre aligned in several steps. First, the main tilted mounting structure was built in the machine shop. The feeds and reflectors were mounted to this structure, and then all of the distances and angles were measured and adjusted to correspond to the nominal settings. The FSS and the ellipsoid were then removed and the rest of the structure was mounted on the antenna.

The feeds were then individually adjusted to point at the center of the subreflector. This is an important point. In all of the drawings and specifications on the optics, the axis of the feed is aligned with the subreflector axis. This is also the way that the feeds were initially set in the machine shop. However, due to the assymetry of the optics, pointing the feeds along the subreflector axis leads to an asymmetric main dish aperture distribution and a high level of spillover on the side of the subreflector that the feed is on. For this reason it was decided to point the feeds at the center of the subreflector. This is the point defined as the geometric center of the subreflector at the beginning of this report.

Two optical telescopes were used, one low power and one high power. They were both fit into a machined cylinder that snugly fit the outside of the telescope and prevented any movement of the cantilevered end of the telescope. This cylinder-piece was fitted to a flange that mated directly to the corrugated horns. One flange was made for each feed. Thus, the telescope was mounted coaxially with the feed, and within the feed, with the eyepiece below the feed and sighting on the subreflector. Due to the way that the optics were initially set, the sighting was on the vertex of the subreflector. (This was true for both feeds, and it was a little surprising; if the optics were not being re-pointed, then little or no alignment would have been required).

The lateral distance from the vertex to the geometric center of the subreflector is about 1.75 in. This corresponded to an angle of about 36 arcmin. To adjust the angle of the feed axis there is a threaded rod assembly consisting of three threaded rods which pass through the feed horn mounting plate. On each threaded rod was a nut on either side of the mounting plate which fixed the position and angle of the feed horn. To move a set point up, the top nut was loosened N number of turns, and then the bottom nut was tightened against it. To move a set point down the process was reversed.

On both horns, two of the rods were close to the horn, and one was further away. This meant that a single turn of the nut had a greater effect for the rod that was further away. Unless the ratio of turns matches the inverse ratio of the distance that the rod is from the horn, then you get a tilt and a lateral translation instead of a tilt. Since this ratio of distances was approximately 2:1, I made 2 turns on the inner nuts for every one turn on the outer nut. Knowing the distance of the nuts from the feed axis, it is a simple matter to calculate the required number of turns for a given angular displacement.

In this way, both of the feeds had their position adjusted to point at the geometric center of the ellipsoid. Note that the geometric center is the point on the sureflector that interects the main axis, so the subreflector does not have to be moved 180 degrees to align the Ku-band feed horn. Also, while sighting on the subreflector, you can rotate the subreflector and the telescop cross-hairs on the geometric center should not move. In fact, they moved enough to indicate that the center of the subreflector was about .150 inches South with the antenna stowed on 10-6-93. I am not sure if the subreflector was ever taken off of the telescope after that date.

There was another effect that the re-aligning had that was not noticed until much later. Because the feeds were tilted to point more towards the center of the subreflector, the feed throat regions and the dewar assemblies were rotated away from the main axis. Two critical areas for fit are the pregnant panel on the electronics box and the mating flange between the X-band feed horn and the X-band front end waveguide. The realignment caused the dewar to displace towards the pregnant panel. I don't remember if this caused a problem. If it did, then it just meant that more styrofoam had to be cut away from the inner pregnant panel. The aforementioned flange, however, had moved too close to the inner vertex ring, so that to get the quick-flange to connect, we had to machine down the clamp. A third problem caused by the realignment was the Ku-band dewar mounting assembly. This assembly was carefully built to mount the Ku-band dewar at the 3.7°optics angle. Increasing this angle by 0.6°made it very difficult to mate the Ku-band feed and waveguide. One of the steps taken to ease this problem was to convert the Ku-band waveguide to feed horn flange to a KF-type flange-clamp assembly. (See drawing A34221M008)

The final part of the alignment was the ellipsoid-FSS installation. The ellipsoid was installed and adjusted as closely as possible to the right height and angle by carefule tape measurements. Then a 0.5-inch diameter mirror was mounted with vacuum grease or double-sided tape on the ellipsoid at the drill hole point. The FSS was also mounted and adjusted to its nominal position. The FSS was then sighted optically through the Ku-band feed horn and reflecting off of the ellipsoid mirror. It was verified that the central ray, or the line-of-sight just described, brought the point of reflection on the FSS reasonably close to a point directly above the aperture center of the X-band horn. Then a second mirror was placed on the FSS, and the subreflector sighted through the entire optics assembly. The FSS has adjustment points at each corner that were used to bring the line-of-sight to the geometric center of the subreflector.

Some care is required in placing the mirrors on the reflecting surfaces; and the procedure should be repeatable, so that nearly identical results are achieved after removeing the mirrors and telescope, and then remounting them. This eliminates the possibility of a biased optical element. In particular, it is possible to mount the telescope so that the flanges are not perfectly aligned, or to mount the small mirror so that its rear facet is not parallel with the ellipsoid surface.

The FSS is not perfectly flat, but rather seems to be slightly concave towards the sky. It has always been this way, and its reflection properties were measured with this same curvature, and the results looked OK.

3.2.1 Alignment vs. Elevation

The optics was aligned as follows for elevation: everything was lined up with the telescope at zenith, then the antenna was moved to about ten degrees elevation. Generally, the sighting on the subreflector drifted about 0.5-inches high on the subreflector, and this is thought to be due to feed leg sag. The drift of the sighting was noted and the zenith setting was then adjusted to to be half of this total drift, but in the opposite direction. This way the best alignment will occur at about 45°elevation, and total drift at zenith and 10°is approximately equal.

3.2.2 Alignment Tolerances

Two of the main references for the study of reflector alignment tolerance are by J. Ruze [9][10]. From these references, a study was made of the efficiency loss of the optics system as a result of axial motion of the subreflector and axial motion of the feed. A third reference[11] was used to solve for loss due to lateral motion of the feed. Fig. 9 is a graph of predicted phase efficiency as a function of axial motion of the subreflector, axial motion of the feed, and lateral motion of the feed. Axial motion means movement along the main axis, lateral motion means movement perpendicular to the main axis. From the figure, it is clear that subreflector offsets are the most critical. The predicted variation of gain with subreflector axial motion was measured, and was within 25% of what was predicted.

3.2.3 Subreflector Position Measurement

```
Measurement of the position of the subreflector
with respect to the vertex - 940415
----------------------------------------------

The subreflector to vertex distance was measured
with a tape measure while the antenna was in
Service position.  I held the end of the tape
at various points near the vertex and Dave held the
other end at the "geometric center" of the subreflector.
The geometric center is 27.09 inches in front of
the subreflector near focal point, leaving 172.91
inches from the subreflector to the vertex, nominally.

We measured:
1.Subreflector to Bottom of Tub Outside the Tub 179.75
2.Subreflector to Bottom of Feed Ring Outside the Tub  185.5
3.Subreflector to Bottom of the Top of the
Feed Ring Inside the Tub 179.8
4.Subreflector to Top of Feed Ring Inside the Tub 179.0
5.Subreflector to Panel Edge nearest vertex 174.06
6.Subreflector to Ku-Band Aperture - Outside Edge
furthest from Main Axis 146.5

Based on what we know about the dimensions of the
feed ring, and using the fact that top of the feed ring is 4.3
inches below the vertex (I measured about 4.5 inches
from the panel edge to the top of the feed ring, so this
gives confidence in the 4.3 inch figure), I compiled the
expected and measured distances.  All of the above measured values
are reduced by 1.3 inches, since they were measured
at 22 inches from the main axis.  The correction is arrived
at as follows:
Corrected distance = Measured distance -
Measured distance*cos(asin(22/Measured distance))
There may be a simpler way to express that, it's just
the projection of my measurement on the main axis.

Corrected measured dist Nominal distance  Delta
----------------------- ---------------- -----
1. 178.4 177.2 +1.2
2. 184.2  183.2 +1.0
3. 178.6 178.2 +0.4
4. 177.7 177.2 +0.5
5. 172.4* 172.9 -0.2
6. 146.5** 146.6 -0.1

* Used 24-inch radius projection correction
** No correction required, nominal distance is
```

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from AutoCad optics drawing

Of these measurements, 5 and 6 are probably better data
points than the others, because we did not have to bend the
tape around any obstructions.  Thus we appear to be
right on.  The Ku-band horn aperture measurement
being in agreement also is a good sign, as it rules
out the possibility of the secondary optics being
way too high or way too low.
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4 Drawings

The current list of drawings describing the GBES optics assemblies is included here. Updated versions of this list can be found in s3/bshillue/optdraw.list.

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********************************************************************
221A001   Optics Assembly
********************************************************************
221A002  Hyperboloid Assembly
221B001  Hyperboloid BOM
221N001  Hyperboloid Specification
D221M001 920904 y    hypvar.dwg  Hyperboloid, Asymmetric Plane
A221M002 920910 y    hypcuta.dwg Hyperboloid, Principal Plane Cuts
A221M002 920910 y    hypcutb.dwg  Sheet2
A221M004 920910 y    hypprime.dwg Hyperboloid, X'-Y' Plane
221D001   Hyperboloid, Coordinates
non-OVLBI:
ASI001          y    hardcopy    Hyperboloid Surface Measurement Results
********************************************************************
221A003  Ellipsoid Assembly
221B002  Ellipsoid BOM
221N002     Ellipsoid Specification
A221M003 920701  y   ellip.dwg   Ellipsoid, Mechanical
         920701  y   ellip2.dwg
221D002    hardcopy  Ellipsoid, Surface and Rim Coordinates
221M005    hardcopy  Ellipsoid, Rim Contour Projection
other: not OVLBI dwg's
PACRAD2    hardcopy  Ellipsoid, Mechanical, Manufacturer
PACRAD2    hardcopy-13sh Ellipsoid, Surface Measurement Results
********************************************************************
221A004  Freq. Selective Surace Assembly
221B003  FSS BOM
221Q001    tefss.dwg  FSS, Artwork
221M006  FSS, Frame
********************************************************************
221A005  Ku-band Corrugated Horn Assembly
221B004  Ku-band Corrugated Horn BOM
D221M007 920527  y kuhorn.dwg  Ku-band Corrugated Horn, Mechanical
A221D003 920528  y hardcopy  Ku-band Corrugated Horn, Coordinates
A221M008 940602  y kufdflg.dwg  Ku-band Corrugated Horn,
    Throat Section Flange Modification
A221D005 920609  y hardcopy      Ku-band Corrugated Horn, Waveguide
Taper Coordinates
********************************************************************
221A006  X-band Corrugated Horn, Assembly
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221**  X-band Corrugated Horn, BOM
D221M010 920803  y xhorn.dwg  X-band Corrugated Horn, Mechanical
D221M009 920807  y xtaperb.dwg   X-band Corrugated Horn, Taper Section
   and Waveguide Test Pieces
A221D004  y hardcopy  X-band Corrugated Horn, Coordinates
D221M025 920817  y  xfewg.dwg  X-band Corrugated Horn,
Front End Waveguides
B221M026 931130  y  xfewgrv.dwg  X-band Corrugated Horn, Front End
                                   Waveguide Extension
A221D006 920803  y hardcopy     X-band Corrugated Horn, Waveguide
Taper Coordinates
*********************************************************************
221A007      Radome Assembly
221**  Radome BOM
221M011    radhex.dwg    Radome Hexagonal Frame
D221M013 931004 y  radbotfl.dwg  Radome Bottom Flange
D221M014 931004 y  radmidfl.dwg  Radome Middle Flange
D221M015 941207 y  radfrmrv.dwg  Radome, Canvas Frame
D221M015 940114 y  radframe.dwg  Radome, Canvas Frame ** obsolete **
*********************************************************************
221A008  Optics Mounting Structure, Assembly
B221M012 941128 y  optmtdim.dwg  Optics Mounting Structure, Dimensions
B221M016 ?????? y  optframe.dwg  Optics, Main Tilted Frame Mount
221M017 n  Ku-band Horn Brackets
221M018 n  X-band Horn Brackets
221M019 n  FSS Brackets
221M020 n  Ellipsoid, Brackets
*********************************************************************
B221A009 y   hypassy.dwg  Hyperboloid Mount. Struct. Assembly
221**      Hyperboloid Mount. Struct. BOM
B221M020 930507 y  sterlflg.dwg   Hyperboloid Mount. Struct.,
                                   Sterling Mount Mating Flange
B221M021 930507 y  hypflg.dwg  Hyperboloid Mount. Struct.,
    Subreflector Mating Flange
B221M023 930507 y  sidesek.dwg   Subreflector Mounting Structure,
 930507 y  sidesek2.dwg     Side View - 2 sheets
*********************************************************************
D203M015 y  pregbox.dwg  Pregnant Box, Mechanical
B203M014 940709 y  helwrmv.dwg   Helium Wrap, Moving End Fixture
B203M016 ?????? y  compress.dwg  Compressor Housing, Side View
```

References

[1] B. Shillue, "Feed and Optics Design for the Green Bank OVLBI Earth Station, OVLBI ES-Memo #27, 5/92

[2] B. Shillue, "Measurement Results of Sandwich FSS," OVLBI-ES memo #26, 5/92

[3] B. Shillue, " Measurement Resuls: Corrugated Horns and FSS," OVLBI-ES memo #41, 5/93

[4] P. Napier, "Polarization Properties of an Open Cassegrain Antenna," MMA memo #115, 5/94

[5] T.K. Wu, W.P. Shilue, "Dichroic Design for the Orbiting VLBI Earth Station Antenna," IEE Proc.-Microw. Antennas Propag., Vol. 141, No. 3, June, 1994, pp. 181-184

[6] L. D'Addario, R. Hudson, E. Meinfelder, B. Shillue, and D. Varney, "The Green Bank OVLBI Earth Station: Report on the Detailed Design Phase," Oct. 9, 1992

[7] Antenna Systems Inc., 672 Commercial St., San Jose, CA 95112

[8] RA7943 Laminate, Gore and Associates, Inc., PO#20961

[9] J. Ruze, "Lateral Feed Displacements in a Paraboloid," IIII Trans. on Antennas and Prop., Sept. 1965, pp. 660-665

[10] J. Ruze, "Small Diplacements in Parabolic Reflectors," MIT Lincoln Lab Tech Rpt, Feb. 1969

[11] J.A. Murphy and R. Padman, "Focal-Plane and Aperture-Plane Receivers for Millimeter-Wave Radioastronomy- A Comparison," Int. Journal of Infrared and Millemeter-Waves, Vol. 9, No. 8, 1988, pp. 667-704