GBT MEMO 218

# Comments On COMSAT's Alignment Survey Of The Subreflector Structure, As Erected Onto The GBT Telescope.

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December 23, 2000

See L0634 for additional materials.

Dec 29, 2006

To: David Parker

From: Mike Goldman

David,

I was not able to complete the document "Comments On Comsat's Alignment Survey Of The Subreflector Structure, As Erected ---"

I (not COMSAT) have a blunder somewhere in my analysis in Appendix B. I have been trying for a week to find it. Much of the document is correct. I have attempted to go through (in detail) the analysis of Comsats subreflector alignment + survey. I wanted to find the subreflector home position coordinates of COMSAT targets T1A, T2A, T3, T4, T5, T6A both theoretical and as-finally-aligned-and-surveyed. My goal was to obtain the subreflector orientation and displacement coordinates as the contractors left the subreflector after aligning it and measuring its final position.

I have set up the mathematical analysis to do this, but there is a bug in my analysis. I have looked for it for a week but haven't yet found it.

I hope that what portion of the effort has been done by me may help to complete the analysis of the subreflector alignment.

I believe that COMSAT did a good job. I tried to independently check all their steps (in Appendix C and Appendix B). I know the fault is an obvious blunder somewhere in my analysis. I checked and rechecked my coordinate transforms, coordinate basis vectors, and critical point coordinates in the various coordinate systems. Somewhere I overlooked the obvious.

The text file of "Comments..." has been recorded as a tex file on the accompanying 2 disks. (SRTARGn.Mcd)

The matrix transforms and numerical computations are mathcad files on the accompanying disk. Mathcad is on my computer in the Applications file. It is ~~at~~ the ~~[illegible]~~ windows icon "Applications" on my computer. I also include it on the disks.

Mike. G.

**Abstract**

The procedure for erecting the GBT subreflector into place on the telescope and surveying its position relative to the main reflector surface is included in COMSAT CORP. document "Procedure, GBT Optics Alignment, Revision C" by J.W. Gurney, October 09, 2000. The results for the alignment survey of the subreflector are also reported in that document.

In the present memo, the results of the COMSAT alignment survey are independently checked and analyzed to confirm the placement and orientation of the subreflector at its home position when the telescope tipping structure is at the rigging elevation angle.

Pages relating to the erection, alignment, and survey of the subreflector which appear in the document cited above are appended to the present memo, to allow comparison of the results of analysis presented here with COMSAT survey results.

**Introduction:**

Positioning the GBT subreflector optic to image radiation from the main dish prime focus to the phase center of a feed horn on the receiver house is a complicated task. The object point and the roof image point (the feed's phase center) vary with both telescope elevation and signal frequency. The command subreflector displacements and tilts needed to move the subreflector to its optimum imaging position are calculated by using an optical model which takes into account varying position of the object point feed's image point as antenna elevation and frequency vary, and also any lateral offset of the feed phase center in the turret focal plane.

The geometric parameters which define the subreflector position to achieve imaging are used as input variables to compute three displacement components and three tilt angle offsets of the subreflector from its home position. If these six offset parameters are known, the lengths of the six actuators which position the subreflector can be determined. Given the commanded actuator lengths, the subreflector servo system can be driven to orient the subreflector and bring its Gregorian focus point to its proper image position at the feed's phase center. To accomplish these objectives it is necessary to know the subreflector's location, when not electrically driven, relative to home position. Here, "home position" means the ideal design position of the subreflector for a geometric telescope (one with separately rigid tipping and alidade structures and having dimensions equal to the ideal values called out by the telescope design). In order to start observing with the GBT, we wish to confirm the undriven position of the subreflector surface at the telescope rigging elevation, as erected by COMSAT. As a first step we check out the Contractor's documented results describing the erection, alignment and survey of the subreflector.

The design telescope will set the subreflector to home position in a specified fixed place with respect to the telescope's parent paraboloid. To uniquely describe the subreflector position at arbitrary elevation and offsets, the following convention is chosen. The coordinate frame of reference for the main reflector is assumed to rotate rigidly with the commanded elevation angle of the telescope and to follow it. The subreflector frame remains rigidly fixed in position and orientation relative to the main reflector frame. That is, the two reference frames are postulated to be rigidly locked to one another, at all telescope elevations.

The positions of control points of survey targets attached to the subreflector structure are defined with respect to another coordinate reference frame, one which is rigidly fixed to the subreflector structure. This is the "Gregorian ellipsoid frame." This frame moves with respect to the subreflector frame when the subreflector is moved by driving its Stewart platform actuators. The geometric transformation between the ellipsoid and subreflector frames is given in [Goldman-1] in terms of the commanded subreflector offset parameters.

Before erecting the subreflector onto the GBT, COMSAT attached six total station survey targets, $T1$ to $T6$, rigidly to the subreflector and measured their center point positions with respect to six photogrammetry targets, $S1$ to $S6$, already on the subreflector. In this way the reference points (center points) of targets $T1$ to $T6$ were found relative to the Gregorian ellipsoid frame which was previously defined by a photogrammetric survey of the subreflector.

The subreflector was then erected by COMSAT onto the GBT antenna, and moved into position, while under survey observation and control. A total.station instrument located near the center of the main reflector surface was used. Six permanent total station targets, $R1$ to $R6$, at the rim of the main reflector structure supplied survey control points. Erection, alignment, and survey procedures and results are reported in [Gurney-1].

In this memo we will check out the reported location of the subreflector as erected into position by COMSAT. The alignment results were reported as follows. Main reflector coordinates for targets $T1$ to $T6$ are tabulated in Data Sheet W9 of [Gurney-1]. These coordinates are reported for the case of the telescope at rigging elevation during target survey. Theoretically-calculated locations for these targets are also tabulated. The subreflector location relative to its home position at rigging elevation is also reported. Given the survey information provided in [Gurney-1], we independently calculate the subreflector location with respect to its home position (at rigging elevation), and compare our calculated location to the survey location reported in [Gurney-1]. To perform these calculations we must first define the antenna geometry and its frames of reference and coordinate systems. We do this in the two sections following, and then analyze the survey results.

**Review Of The Subreflector's Intrinsic Geometry.**

The subreflector structure is quite rigid and does not flex or distort appreciably as it moves in space. Practically, it can be considered to have a rigid surface which is a surface patch on an ellipsoid of revolution (design parent ellipsoid). The surface patch has a single plane of symmetry. The ellipsoid's major axis lies in this plane. The parent ellipsoid is generated by an ellipse of eccentricity $e = 0.528$ and spacing $2f_e = 11.0$ meters $= 433.0787$ inches between foci. The design length of the semi-major axis of the parent ellipsoid is $a = 10.416667$ meter $= 410.105$ inches. The design length of each semi-minor axis of the ellipsoid is $b = 8.846296$ meter $= 348.2925$ inches. We call the two ellipsoid focal points: $F_0$ the "subreflector prime focus," and $F_1$ the "subreflector Gregorian focus."

The subreflector structure is defined geometrically by of a right-handed Cartesian coordinate reference frame which is considered to be rigidly embedded in the subreflector structure. We call this the "ellipsoid frame." The origin point of this reference frame is at the center of the parent ellipsoid. The unit basis vectors of the reference frame are denoted by $\widehat{X}_{ce}$, $\widehat{Y}_{ce}$, $\widehat{Z}_{ce}$. The plane of symmetry of the subreflector surface is the $(\widehat{X}_{ce}, \widehat{Y}_{ce})$-plane. The $\widehat{X}_{ce}$ basis vector points along the semi-major axis of the ellipse, from the ellipsoid center point towards the subreflector's $F_0$ (prime) focus. The $\widehat{Y}_{ce}$ vector points from the ellipsoid center point towards the subreflector support truss.

There is a distinguished point embedded in the subreflector surface, the subreflector reference point $I_1$. This point acts as an optical axis point for the design telescope. The *central ray* of the ray bundle, which leaves the prime focus point $F_0$ of the parent ellipsoid and hits the subreflector surface, passes through $I_1$ and arrives at the Gregorian focus point $F_1$ of the parent ellipsoid. The geometric details are given in [Goldman-1]. The design ideal ellipsoid coordinates of $I_1$ are:

$$
\begin{aligned}
(3.1) \qquad \widehat{X}_{ce}(I_1) &= 9.736366\,\mathrm{m} = 383.3215\,\text{inches}\,, \\
\widehat{Y}_{ce}(I_1) &= 3.144573\,\mathrm{m} = 123.8021\,\text{inches}\,, \\
\widehat{Z}_{ce}(I_1) &= 0.0\,\mathrm{m} = 0.0\,\text{inches}\,.
\end{aligned}
$$

The subreflector reference frame and coordinate system are defined so that when the subreflector is at home position at rigging elevation of the telescope, then the subreflector will be positioned so that $I_1$ lies at the origin of the subreflector coordinate system.

The ellipsoid frame is used to describe the locations of physical structures attached to the subreflector structure, in particular - surveyor's target control reference points. There are three classes of survey control targets attached to the subreflector structure. These are: photogrammetry targets which were used to generate and control the initial settings of the subreflector surface panels, Contractor's survey targets T1 to T6 used to provide subreflector survey control points for the COMSAT total station alignment survey of the GBT, and NRAO cube corner prism retroreflector targets used for laser rangefinder metrology of the subreflector.

The spatial locations of survey control targets attached to the subreflector structure are defined by reference to the ellipsoid frame of reference attached to the subreflector. The spatial locations of these same targets, when referenced to the main reflector structure are described by means of an intermediate reference frame, the "subreflector" frame of reference. The latter frame is fixed rigidly to the main reflector frame of reference at all elevation angles of the telescope. Motions of the subreflector with respect to the main reflector reference frame of the telescope can be specified by providing either the main reflector or subreflector frame coordinates of the subreflector target fiducial points, or providing the displacement and rotation offsets of the ellipsoid frame from its home position relative to the subreflector frame.

**Description Of The Subreflector Survey And Alignment.**

The unit basis vectors of the subreflector frame are rotated with respect to those of the main reflector frame by exactly 36.7° about the $\widehat{X}_{rg}$ basis vector. They can be expressed as linear combinations of the main reflector basis vectors:

$$
\begin{aligned}
\widehat{X}_s &= (\cos 36.7^\circ) \cdot \widehat{Y}_{rg} + (\sin 36.7^\circ) \cdot \widehat{Z}_{rg} \,, \\
\widehat{Y}_s &= -(\sin 36.7^\circ) \cdot \widehat{Y}_{rg} + (\cos 36.7^\circ) \cdot \widehat{Z}_{rg} \,, \\
\widehat{Z}_s &= \widehat{X}_{rg} \,.
\end{aligned}
\tag{4.1}
$$

When the subreflector lies at home position, the origin point for the subreflector coordinate system, $(I_1)_{hp}$ , has main reflector coordinates:

$$
\begin{aligned}
X_{rg}((I_1)_{hp}) &= 0.0\ \text{m} &&= 0.0\ \text{inches} \,, \\
Y_{rg}((I_1)_{hp}) &= \text{-4.291726 m} &&= -168.9656\,\text{inches} \,, \\
Z_{rg}((I_1)_{hp}) &= 63.802874\,\text{m} &&= 2511.9242\,\text{inches} \,.
\end{aligned}
\tag{4.2}
$$

Ellipsoid system coordinates for photogrammetry targets $S1 \cdots S6$ on the subreflector are listed in [Gurney-1] on the sheet entitled "GBT Subreflector Target Calculations 12/7/99." These coordinates were provided by Fred Schwab on 2/25/99. The origin for those tabulated coordinates is reported to be at the center of the design ellipsoid. Coordinates were also reported for the center of the ellipsoid, the prime focus of the ellipsoid and the Gregorian (M1) focus of the ellipsoid. (The M1 focus, in our notation, is the $F_1$ focus). We list these coordinates in Table 1. We will then calculate the main reflector coordinates of these targets for the case that the subreflector is at home position.

Coordinates of the total station survey targets $T1 \cdots T6$ (which lie near $S1 \cdots S6$) are determined by surveying them relative to $S1 \cdots S6$.

**Table 1. Coordinates Of Subreflector Photogrammetry Targets.**

| Point ($P$) | Point Type | $X_{ce}(P)$ inches | $Y_{ce}(P)$ inches | $Z_{ce}(P)$ inches |
|---|---|---|---|---|
| S1 | Photogrammetry Target Center | 407.8930 | 35.8260 | 4.0450 |
| S2 | Photogrammetry Target Center | 367.2150 | 102.5070 | −116.3350 |
| S3 | Photogrammetry Target Center | 288.2520 | 207.3260 | −135.5820 |
| S4 | Photogrammetry Target Center | 233.2590 | 286.4360 | 3.3000 |
| S5 | Photogrammetry Target Center | 288.3360 | 207.1530 | 135.7370 |
| S6 | Photogrammetry Target Center | 367.1090 | 102.6820 | 116.4130 |
| T10 | Ellipsoid Focus (Prime) | 216.5350 | 0.0000 | 0.0000 |
| T11 | Ellipsoid Center Point | 0.0000 | 0.0000 | 0.00000 |
| T12 | Ellipsoid M1 Focus (Greg.) | −216.5350 | 0.0000 | 0.00000 |

These coordinates appear in [Gurney-1]. They are for photogrammetry target centers on the subreflector, and were supplied to COMSAT by F.Schwab.

[Note: On the data sheet, the names of points T10 and T11 were interchanged. T11 lies midway between T10 and T12, which are 11 meters from one another.]

The transformation which gives the home position coordinates, in the main reflector coordinate system, of a point $P$ attached to the subreflector, in terms of the ellipsoid coordinates of that point, is the following:

$$
\begin{aligned}
X_{rg}((P)_{hp}) &= X_{rg}((CE)_{hp}) + Z_{ce}(P)\,, \\
Y_{rg}((P)_{hp}) &= Y_{rg}((CE)_{hp}) + (\sin 5.570^\circ)(X_{ce}(P)) - (\cos 5.570^\circ)(Y_{ce}(P))\,, \qquad (4.4) \\
Z_{rg}((P)_{hp}) &= Z_{rg}((CE)_{hp}) + (\cos 5.570^\circ)(X_{ce}(P)) + (\sin 5.570^\circ)(Y_{ce}(P))\,.
\end{aligned}
$$

When (4.4) is applied to the ellipsoid coordinates of points $S1 \cdots S6$, one obtains the **X**, **Y**, **Z** coordinates appearing in Data Sheet W2, Item 1. Those are main reflector system coordinates (inches) calculated for the home positions of $S1 \cdots S6$. This is confirmed by computations made in Appendix C.

Total station targets $T1 \cdots T6$ were fastened to the subreflector near photogrammetry targets $S1 \cdots S6$. An auxiliary set of total station targets (not named explicitly) were positioned over $S1 \cdots S6$. The two sets of total station targets were surveyed. The main reflector system coordinates (inches) of $T1 \cdots T6$ at home position, obtained from the survey, appear in Data Sheet W2, Item 2.

The subreflector alignment process is described in sections 7.2 and 9.2 of [Gurney-1]. During alignment, the subreflector is translated from its home position; subsequently the structure's gooseneck support is moved and shimmed at its connection to the vertical feed arm tip, to offset the subreflector to an optimal alignment position. The size of the offset translation components is discussed on pages 22-24 of [Gurney-1]. These sections are appended to this memo.

The first step in subreflector alignment is to bring the antenna to rigging elevation ($\simeq 50.29°$). The total station survey instrument near the main dish center is then oriented with respect to the main-reflector-rim control targets $R1 \cdots R6$ to establish the main reflector frame of reference. This procedure, also establishes the subreflector frame of reference, because the subreflector frame is rigidly tied to the main reflector frame.

The next step is to translate the subreflector so that the position of its reference point $I$ is nominally at subreflector coordinates $X_s(I) = 1.91$, $Y_s(I) = -2.59$, $Z_s(I) = 0.0$ (inches). That is, the subreflector actuators are driven until the actuator readouts indicate that the subreflector has been driven upwards 1.91 inches along the $X$-actuator axis, and inwards 2.59 inches along the Y-actuator axis from the position whose readout corresponds to subreflector home position. Resolving these displacement components along the main reflector axes, the nominal offsets of the subreflector from home position are: 0.00 inches along the $X_{rg}$-axis, 3.079 inches along the $Y_{rg}$-axis, $-0.935$ inches along the $Z_{rg}$-axis. These component values (rounded to 2 places) are entered as Item 3 of Data Sheet W2. The nominal main reflector coordinates of $T1 \cdots T6$ , after driving the subreflector actuators to produce these displacement components, are found by adding the displacement components to the computed coordinates appearing in Data Sheet W2, Item 2. The nominal coordinates of $T1 \cdots T6$ after displacement are listed in Data Sheet W2, Item 4.

Coordinates of $T1 \cdots T6$ listed in Data Sheet W2, Item 4 are theoretical (ideal) values, and don't yet correspond to actual surveyed locations. The subreflector has not yet been aligned; the gooseneck support for the subreflector has not yet been shimmed to its proper position of attachment to the feed arm tip.

The next step of the alignment procedure, as stated in section 7.2, is to survey the subreflector from the instrument station on the main reflector, and determine current positions of $T1 \cdots T6$. The antenna sits at rigging elevation during this survey. Adjusted coordinates of $T1 \cdots T6$ found by this survey, are compared to the ideal coordinate values listed in sheet W2, Item 4. From the differences between the adjusted survey coordinates and their ideal values, correction adjustments are calculated to generate the translations and rotations of the subreflector needed to position it correctly at the calculated offset position.

The correction adjustments are made by shifting the attachment location of the gooseneck structure which joins the subreflector structure to the vertical feed arm tip. To reposition the gooseneck to the feed arm, the antenna must be brought to access elevation. The antenna is then raised to access elevation, to carry out the repositioning operations.

The attachment location of the gooseneck to the feed arm is moved until the computed target translation offsets have been reduced to within $\pm 0.25$ inch of theoretical. The subreflector support triangle's orientation is then determined, using a digital level to measure its front-to-back and sideways slopes. The gooseneck interface is then adjusted to reduce the orientation offset angles from home position to within $\pm 0.2°$. The gooseneck is then secured to the feed arm tip, and the telescope is returned to rigging elevation.

Targets $T1 \cdots T6$ are resurveyed at rigging elevation. Their adjusted survey coordinates are again compared to the ideal values of Item 4, Data Sheet W2. Translation and orientation angle adjustments are recalculated and, if necessary, the telescope is returned to access elevation and the gooseneck attachment is again shifted. The procedure is repeated until the survey at rigging elevation gives surveyed target position departures from their theoretical values to within the error bounds stated above.

The actual subreflector alignment procedure differed slightly from the procedure outlined in section 7.2 of [Gurney-1]. (Section 9.2 is merely a restatement of 7.2.) Visibility of targets $T1$, $T2$, $T6$ was not adequate for the surveys. Three additional total station targets: $T1A$, $T2A$, $T6A$ were fastened to the subreflector near $T1$ , $T2$ , $T6$ and were used in the alignment and survey procedure. In the manner described previously, coordinates for $T1A$, $T2A$, $T6A$ were found relative to $S1 \cdots S6$. Ideal main reflector coordinates for these three targets were computed corresponding to the offset position of the subreflector. The alignment surveys were actually made using the six targets: $T1A$, $T2A$, $T3$, $T4$, $T5$, $T6A$. The final alignment results are given in Data Sheet W9.

Item 1a of sheet W9 lists the computed ideal main reflector coordinates of the survey targets actually used during the alignment procedure. These coordinates correspond to the ideal coordinates listed in Data Sheet W2, Item 4 but with targets $T1$, $T2$, $T6$ replaced by $T1A$, $T2A$, $T6A$.

Item 1b of Data Sheet W9 lists the target coordinates measured by the final survey, at rigging elevation, after the gooseneck positioning adjustments were completed. These are the final measured main reflector system target coordinates for the subreflector.

The differences, measured-minus-ideal coordinate, are listed in Item 1c of sheet W9. These coordinate differences vary from -0.240 inch to 1.342 inch. The survey standard errors are expected, a-priori, to be near 1 millimeter. This indicates that most of the coordinate difference is due to translation and rotation of the as-aligned subreflector from its ideal position.

A simple check can be made to distinguish survey measurement errors from coordinate differences due to the subreflector's final alignment offset from the ideal. Point-pair distances calculated for pairs of points whose ideal positions are listed in Item 1a of sheet W9 are expected to agree (with about 95% probability) with corresponding point-pair distances calculated from the measured coordinates in Item 1b, to within twice the survey standard distance measurement error (which should be nearly the same for each of the six target points). We compute the 15 pairs of target distances using coordinates listed in Item 1b and compare them with the distances computed using coordinates listed in Item 1a. Differences between corresponding point-pair distances are due to survey error alone. They may be used to estimate an a-postiori survey standard error for distance measurement. This is done in Appendix B. The standard error computed from the two sets of coordinate differences is 0.020 inches. This result confirms that the coordinate differences listed in Item 1c, sheet W9 are essentially due to departure of the as-aligned subreflector from its ideal to-be-aligned location.

Using measured target coordinates, in Item 1b, together with the calculated a-postiori survey standard error, it is possible to least-squares calculate the translation and rotation offsets of the subreflector from home position, when the antenna is at rigging elevation and the subreflector drive is commanded to be at home position. To do this we require, first, two additional coordinate transformations.

The inverse of (4.4) transforms main reflector system home position coordinates of subreflector targets to ellipsoid system coordinates:

(4.5)

$$X_{ce}(P) = (\cos 5.570°)((Z_{rg}((P)_{hp}) - Z_{rg}(CE)_{hp}) + (\sin 5.570°)((Y_{rg}((P)_{hp}) - Y_{rg}(CE)_{hp}) ,$$

$$Y_{ce}(P) = -(\sin 5.570°)(Z_{rg}((CE)_{hp}) - Z_{rg}(P)_{hp}) + (\cos 5.570°)((Y_{rg}((CE)_{hp}) - Y_{rg}(P)_{hp}) ,$$

$$Z_{ce}(P) = X_{rg}((P)_{hp}) - X_{rg}((CE)_{hp}) .$$

The transformation giving the subreflector system coordinates, at subreflector home position, for subreflector survey targets, in terms of their ellipsoid system coordinates is:

$$X_{shp}(P) = (\sin 42.27°)(X_{ce}(P) - X_{ce}(I_1)) - (\cos 42.27°)(Y_{ce}(P) - Y_{ce}(I_1)) ,$$

$$\text{(4.6)} \quad Y_{shp}(P) = (\cos 42.27°)(X_{ce}(P) - X_{ce}(I_1)) + (\sin 42.27°)(Y_{ce}(P) - Y_{ce}(I_1)) ,$$

$$Z_{shp}(P) = Z_{ce}(P) - Z_{ce}(I_1) .$$

## Discussion.

The subreflector has been aligned by using a total station survey instrument near the center of the main reflector surface, which has been referenced to six permanent survey control targets around the periphery of the main reflector. The aligned position of six survey targets on the sbreflector has been checked at rigging elevation. The six subreflector targets: $T1A$, $T2A$, $T3$, $T4$, $T5$, $T6A$, were surveyed at the rigging angle both before and after alignment, and their main reflector system coordinates after alignment were checked with their theoretical positions at rigging elevation. Theoretical positions for the survey targets at rigging elevation, when the subreflector is at home position, are obtained by known coordinate transformations of their ellipsoid system coordinates. Their ellipsoid system coordinates are obtained by surveying and comparing their center points with respect to the center points of six photogrammetry targets ($S1 \cdots S6$) whose ellipsoid system coordinates were obtained by a photogrammetric survey of the subreflector.

Once the calculated home position and as-erected positional coordinates have been obtained in the main reflector system, by means of the alignment final survey, their coordinates can be converted to the subreflector system. Once on is in possession of both the home position subreflector system coordinates of the subreflector targets and their as-aligned subreflector system coordinates at rigging elevation, it is possible to find the displacement and rotation parameters of the subreflector by using the methods of [Goldman-1].

An estimate for the accuracy of the alignment procedure was obtained by computing the 15 survey distances of the subreflector target center points before and after the alignment procedure (shifting the gooseneck attachment and orientation). The details are given in Appendix B. The distances agreed to a sample standard error of 0.020 inches. This indicates that the measurement accuracies are good within one millimeter, and the coordinate differences before and after are due to an offset of the as-aligned subreflector from its to-be-aligned position.

## Appendix A. Coordinate Reference Frames.

- **Main Reflector Frame:**

Unit frame basis vectors: $\widehat{X}_{rg}$, $\widehat{Y}_{rg}$, $\widehat{Z}_{rg}$; $\widehat{\mathbf{X}}$, $\widehat{\mathbf{Y}}$, $\widehat{\mathbf{Z}}$ (Contractor's notation).

Coordinates of a point $P$ : $X_{rg}(P)$, $Y_{rg}(P)$, $Z_{rg}(P)$;
$\widehat{\mathbf{X}}(P)$, $\widehat{\mathbf{Y}}(P)$, $\widehat{\mathbf{Z}}(P)$. (Contractor's notation).

Frame Origin Point: $R_g$ , $X_{rg}(R_g) = 0$, $Y_{rg}(R_g) = 0$, $Z_{rg}(R_g) = 0$.

Point $R_g$ is the vertex of the parent paraboloid.

Design Prime Focus Point of the Parent Paraboloid: $F_p$ ,

$X_{rg}(F_p) =$ 0.0 m = 0.0 inches,

$Y_{rg}(F_p) =$ 0.0 m = 0.0 inches,

$Z_{rg}(F_p) =$ 60 m = 2362.2047 inches.

*Home position* of optical axis reference point $I_1$ embedded in the subreflector surface coincides with the point $(I_1)_{hp}$ having main reflector coordinates:

$X_{rg}(I_1)_{hp} =$ 0.0 m = 0.0 inches,

$Y_{rg}(I_1)_{hp} =$ $-4.291726$ m = $-168.9656$ inches,

$Z_{rg}(I_1)_{hp} =$ 63.802874 m = 2511.9242 inches.

*Home position* of the ellipsoid center point $CE$ considered embedded rigidly to the subreflector frame, coincides with the point $(CE)_{hp}$ having main reflector coordinates:

$X_{rg}(CE)_{hp} =$ 0.0 m = 0.0 inches,

$Y_{rg}(CE)_{hp} =$ $-0.533840$ m = $-21.0173$ inches $(-5.5\,\mathrm{m} \cdot \sin 5.570°)$,

$Z_{rg}(CE)_{hp} =$ 54.525969 m = 2146.6917 inches $(60\,\mathrm{m} - 5.5\,\mathrm{m} \cdot \cos 5.570°)$.

- **Ellipsoid Frame:**

Unit frame basis vectors: $\widehat{X}_{ce}$, $\widehat{Y}_{ce}$, $\widehat{Z}_{ce}$.

In this document we assume that $\widehat{X}_{ce}$ is directed from the ellipsoid center point towards the subreflector's prime focus point $F_0$ and $\widehat{Z}_{ce}$ is $\perp$ to the midplane of the subreflector surface.

Coordinates of a point $P$ : $X_{ce}(P)$, $Y_{ce}(P)$, $Z_{ce}(P)$.

Frame Origin Point: $CE$ (Ellipsoid Center Point) .

$X_{ce}(CE) = 0$, $Y_{ce}(CE) = 0$, $Z_{ce}(CE) = 0$.

Point $I_1$ is the optical axis reference point of the subreflector surface. It has coordinates:

$$X_{ce}(I_1) = 9.736366\,\text{m} = 383.3215 \text{ inches},$$
$$Y_{ce}(I_1) = 3.144573\,\text{m} = 123.8021 \text{ inches},$$
$$Z_{ce}(I_1) = 0.0 \text{ m} = 0.0 \text{ inches}.$$

Note on the coordinate frame and coordinates used to describe the ellipsoid frame:

The ellipsoid frame has been defined in this document to agree with the definitions given in the document "Geometry And Conventions For Subreflector Metrology" [Goldman-1]. Here, the $(\widehat{X}_{ce}, \widehat{Y}_{ce})$-plane is the symmetry plane of the subreflector surface, the $\widehat{X}_{ce}$ basis vector is along the ellipsoid's major semi-axis from the ellipsoid's center towards its prime focus point, the $\widehat{Y}_{ce}$ points in the general direction towards the feed arm, and the $\widehat{Z}_{ce}$ vector points in the general direction of the telescope elevation axis in the sense from telescope midplane towards the man-lift. This differs from the convention adopted in the document "GBT Coordinates And Coordinate Transformations' [Goldman-2]. The coordinate transformations given in [Goldman-2] should be used with caution

We also note that our notation uses the symbol $F_0$ to represent the prime focus of the subreflector ellipsoid and the symbol $F_1$ to represent the Gregorian focus of the subreflector ellipsoid. This differs from the notation used by D. Wells in his document "GBT Gregorian Focus Tracking in C," GBT Memo 183, June 1998. Wells uses $F_1$ to denote the prime focus point and $F_2$ to denote the Gregorian focus point in that memo.

- **Subreflector Frame:**

Unit frame basis vectors: $\widehat{X}_s$, $\widehat{Y}_s$, $\widehat{Z}_s$.

Coordinates of a point $P$ : $X_s(P), Y_s(P), Z_s(P)$ .

Home position coordinates of point $P$ : $X_{shp}(P), Y_{shp}(P), Z_{shp}(P)$ .

The home position coordinates apply only when the subreflector is stationed at its home position relative to the main reflector frame.

Frame Origin Point: $(I_1)_{hp}$ , $X_{shp}((I_1)_{hp}) = Y_{shp}((I_1)_{hp}) = Z_{shp}((I_1)_{hp}) = 0.$

Point $I_1$ is the optical axis reference point embedded into the subreflector surface.

The unit basis vectors for the subreflector are found by rotating the main reflector frame by 36.7° about $\widehat{X}_{rg}$ :

$$
\begin{aligned}
\widehat{X}_s &= (\cos 36.7°) \cdot \widehat{Y}_{rg} + (\sin 36.7°) \cdot \widehat{Z}_{rg} \, , \\
\widehat{Y}_s &= -(\sin 36.7°) \cdot \widehat{Y}_{rg} + (\cos 36.7°) \cdot \widehat{Z}_{rg} \, , \\
\widehat{Z}_s &= \widehat{X}_{rg} \, .
\end{aligned}
\tag{A1.1}
$$

We use the symbol $I$ to denote the point in space which temporarily coincides with the reference point $I_1$ embedded in the subreflector surface, when the subreflector is not at home position. When the subreflector structure is in a general position (away from home position) the subreflector system coordinates of the subreflector's reference point are $X_s(I)$, $Y_s(I)$, $Z_s(I)$ .

We note that our definition of the subreflector frame of reference and coordinate system follows the convention given in GBT Drawing C35102M081, Sheet 1, Rev. B; G. Morris, 12/93. It also follows the convention for the subreflector actuator directions given in COMSAT RSI Drawing 121038, "GBT Subreflector Positioner Data Package."

In [Gurney-1] a different convention was used for the subreflector reference frame; the convention is illustrated in Figure B of that document (appended). There, subreflector frame unit basis vectors $\widehat{\mathbf{X}}_s$, $\widehat{\mathbf{Y}}_s$, $\widehat{\mathbf{Z}}_s$ were used. The correspondence between the subreflector frame basis vectors in [Gurney-1] and those in this memo is:

$$\widehat{\mathbf{Y}}_s \Longleftrightarrow \widehat{X}_s \,,$$

$$\widehat{\mathbf{Z}}_s \Longleftrightarrow \widehat{Y}_s \,,$$

$$\widehat{\mathbf{X}}_s \Longleftrightarrow \widehat{Z}_s \,.$$

The subreflector system coordinates of a point $P$ can be found in terms of its main reflector system coordinates by using the transformation:

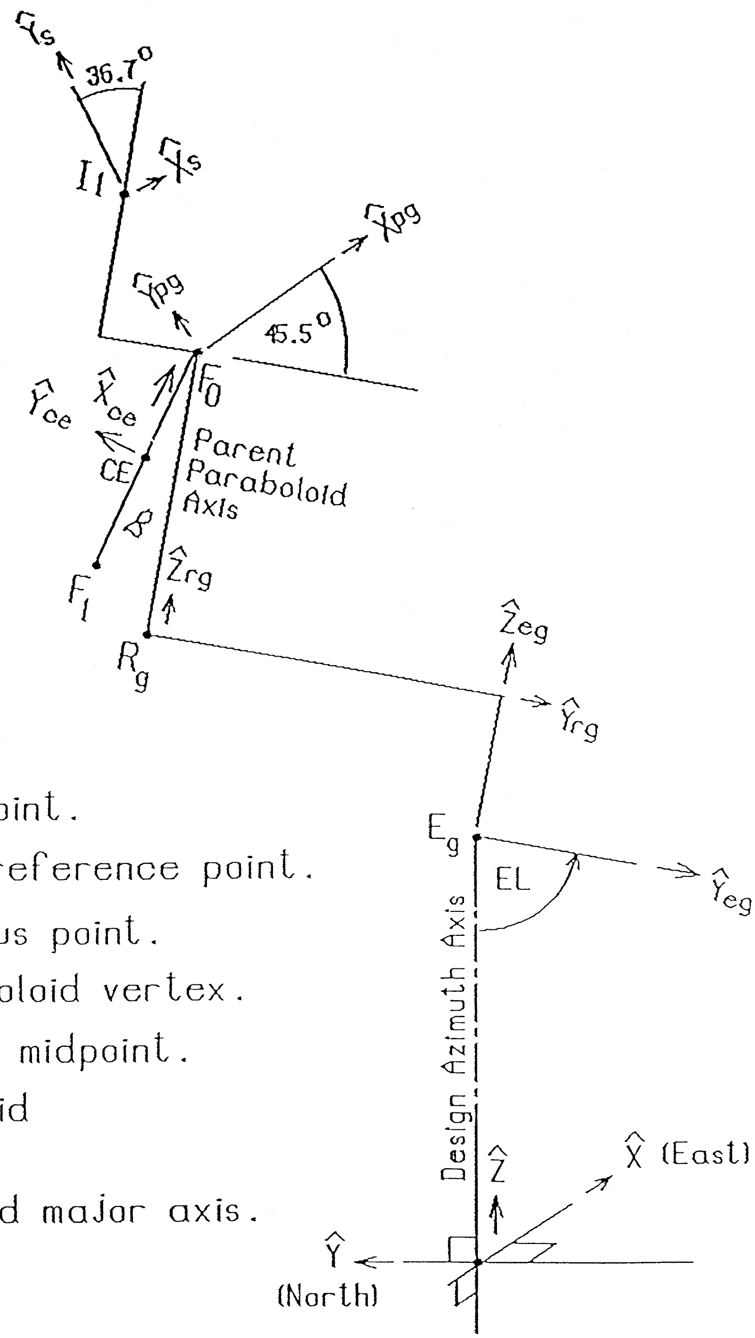
$$\begin{aligned} X_s(P) &= \phantom{-}(\cos 36.7^\circ)(Y_{rg}(P) - Y_{rg}(I_1)_{hp}) + (\sin 36.7^\circ)(Z_{rg}(P) - Z_{rg}(I_1)_{hp}) \,, \\ Y_s(P) &= -(\sin 36.7^\circ)(Y_{rg}(P) - Y_{rg}(I_1)_{hp}) + (\cos 36.7^\circ)(Z_{rg}(P) - Z_{rg}(I_1)_{hp}) \,, \\ Z_s(P) &= \phantom{-}X_{rg}(P) \,. \end{aligned} \tag{A1.2}$$

## References

[Goldman-1]
M.A. Goldman, *Geometry And Conventions For Subreflector Metrology.* GBT Memo (To be issued). April 09, 2000.

[Goldman-2]
M.A. Goldman, *GBT Coordinates And Coordinate Transformations.* GBT Memo 165. February 15, 1997.

[Gurney-1]
J.W. Gurney, *Procedure, GBT Optics Alignment*, GBT. Revision C. COMSAT Corp. Specification No. 121960, Contract No. AUI-1059, October 09, 2000.




EL is the antenna elevation angle.

$F_0$ is the prime focus point.

$I_1$ is the subreflector reference point.

$F_1$ is the gregorian focus point.

$R_g$ is the parent paraboloid vertex.

$E_g$ is the elevation axle midpoint.

CE is the parent ellipsoid center point.

$\hat{X}_{ce}$ is along the ellipsoid major axis.

Figure 1. Geometric Telescope Unit Base Vectors.

# Appendix B.

## Calculation Of Target Pair Distances For Subreflector Survey Targets, And Survey Target Coordinates In Several Coordinate Systems.

Table B1. Names of Ellipsoid System Coordinates Of Survey Target Centers.

$T := 1, 2 .. 6$

| | | | Survey Target |
|---|---|---|---|
| $Xce_1$ | $Yce_1$ | $Zce_1$ | T1A |
| $Xce_2$ | $Yce_2$ | $Zce_2$ | T2A |
| $Xce_3$ | $Yce_3$ | $Zce_3$ | T3 |
| $Xce_4$ | $Yce_4$ | $Zce_4$ | T4 |
| $Xce_5$ | $Yce_5$ | $Zce_5$ | T5 |
| $Xce_6$ | $Yce_6$ | $Zce_6$ | T6A |

Table B2. Main ReflectorCoordinates (inches) of Survey Targets.

Calculated main reflector system ideal coordinates of survey target centers for subreflector translated from home position, antenna at rigging elevation. ( Listed in Data Sheet W9, Item 1a).

Note that listed coordinates in Table B2, below, for targets T3, T4, T5 also agree with the coordinates for these targets in Item 4 of Data Sheet W2.

| | | | Survey Target |
|---|---|---|---|
| $Xrg_1 := -11.754$ | $Yrg_1 := -7.105$ | $Zrg_1 := 2569.413$ | T1A |
| $Xrg_2 := -142.704$ | $Yrg_2 := -96.199$ | $Zrg_2 := 2513.744$ | T2A |
| $Xrg_3 := -128.871$ | $Yrg_3 := -211.681$ | $Zrg_3 := 2443.517$ | T3 |
| $Xrg_4 := -19.124$ | $Yrg_4 := -280.072$ | $Zrg_4 := 2405.279$ | T4 |
| $Xrg_5 := 125.640$ | $Yrg_5 := -215.949$ | $Zrg_5 := 2441.406$ | T5 |
| $Xrg_6 := 144.863$ | $Yrg_6 := -98.957$ | $Zrg_6 := 2512.000$ | T6A |

Table B3.

Survey measurement main reflector system coordinates of survey target centers for subreflector translated from home position, antenna at rigging elevation. (Listed in Data Sheet W9, Item 1b).

| | | | Survey Target |
|---|---|---|---|
| $Xmrg_1 := -11.146$ | $Ymrg_1 := -7.166$ | $Zmrg_1 := 2570.420$ | T1A |
| $Xmrg_2 := -142.384$ | $Ymrg_2 := -96.146$ | $Zmrg_2 := 2515.086$ | T2A |
| $Xmrg_3 := -128.798$ | $Ymrg_3 := -211.387$ | $Zmrg_3 := 2444.362$ | T3 |
| $Xmrg_4 := -19.364$ | $Ymrg_4 := -279.750$ | $Zmrg_4 := 2405.551$ | T4 |
| $Xmrg_5 := 125.724$ | $Ymrg_5 := -215.821$ | $Zmrg_5 := 2441.243$ | T5 |
| $Xmrg_6 := 145.199$ | $Ymrg_6 := -98.919$ | $Zmrg_6 := 2512.026$ | T6A |

Reflector offset values used during alignment (inches):

$\Delta Xrg := 0.00$ $\Delta Yrg := 3.079$ $\Delta Zrg := -0.935$

Table B4.

Calculated main reflector system ideal coordinates of survey target centers for subreflector, returned to home position, antenna at rigging elevation. ( Translation of Data Sheet W9, Item 1a Coordinates).

$Xrhp_T := Xrg_T - \Delta Xrg$ $Yrhp_T := Yrg_T - \Delta Yrg$ $Zrhp_T := Zrg_T - \Delta Zrg$

| | | | Survey Target |
|---|---|---|---|
| $Xrhp_1 = -11.754$ | $Yrhp_1 = -10.184$ | $Zrhp_1 = 2570.348$ | T1A |
| $Xrhp_2 = -142.704$ | $Yrhp_2 = -99.278$ | $Zrhp_2 = 2514.679$ | T2A |
| $Xrhp_3 = -128.871$ | $Yrhp_3 = -214.76$ | $Zrhp_3 = 2444.452$ | T3 |
| $Xrhp_4 = -19.124$ | $Yrhp_4 = -283.151$ | $Zrhp_4 = 2406.214$ | T4 |
| $Xrhp_5 = 125.64$ | $Yrhp_5 = -219.028$ | $Zrhp_5 = 2442.341$ | T5 |
| $Xrhp_6 = 144.863$ | $Yrhp_6 = -102.036$ | $Zrhp_6 = 2512.935$ | T6A |

Table B5.

Survey measurement main reflector system coordinates of survey target centers for subreflector translated from home position, antenna at rigging elevation. (From Data Sheet W9, Item 1b, translated back).

$Xmr_T := Xmrg_T - \Delta Xrg$ $\quad$ $Ymr_T := Ymrg_T - \Delta Yrg$ $\quad$ $Zmr_T := Zmrg_T - \Delta Zrg$

| | | | Survey Target |
|---|---|---|---|
| $Xmr_1 = -11.146$ | $Ymr_1 = -10.245$ | $Zmr_1 = 2571.355$ | T1A |
| $Xmr_2 = -142.384$ | $Ymr_2 = -99.225$ | $Zmr_2 = 2516.021$ | T2A |
| $Xmr_3 = -128.798$ | $Ymr_3 = -214.466$ | $Zmr_3 = 2445.297$ | T3 |
| $Xmr_4 = -19.364$ | $Ymr_4 = -282.829$ | $Zmr_4 = 2406.486$ | T4 |
| $Xmr_5 = 125.724$ | $Ymr_5 = -218.9$ | $Zmr_5 = 2442.178$ | T5 |
| $Xmr_6 = 145.199$ | $Ymr_6 = -101.998$ | $Zmr_6 = 2512.961$ | T6A |

Computations of point pair distances.

$i := 1, 2 .. 6 \qquad j := 1, 2 .. 6$

Ideal Distances:

$$Di_{i,j} := \sqrt{\left(Xrg_i - Xrg_j\right)^2 + \left(Yrg_i - Yrg_j\right)^2 + \left(Zrg_i - Zrg_j\right)^2}$$

Survey Measurement Distances:

$$Dm_{i,j} := \sqrt{\left(Xmrg_i - Xmrg_j\right)^2 + \left(Ymrg_i - Ymrg_j\right)^2 + \left(Zmrg_i - Zmrg_j\right)^2}$$

Matrix listings of ideal and measured target pair distances:

$$Di\_ij := \begin{bmatrix} 0 & Di_{1,2} & Di_{1,3} & Di_{1,4} & Di_{1,5} & Di_{1,6} \\ 0 & 0 & Di_{2,3} & Di_{2,4} & Di_{2,5} & Di_{2,6} \\ 0 & 0 & 0 & Di_{3,4} & Di_{3,5} & Di_{3,6} \\ 0 & 0 & 0 & 0 & Di_{4,5} & Di_{4,6} \\ 0 & 0 & 0 & 0 & 0 & Di_{5,6} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Dm\_ij := \begin{bmatrix} 0 & Dm_{1,2} & Dm_{1,3} & Dm_{1,4} & Dm_{1,5} & Dm_{1,6} \\ 0 & 0 & Dm_{2,3} & Dm_{2,4} & Dm_{2,5} & Dm_{2,6} \\ 0 & 0 & 0 & Dm_{3,4} & Dm_{3,5} & Dm_{3,6} \\ 0 & 0 & 0 & 0 & Dm_{4,5} & Dm_{4,6} \\ 0 & 0 & 0 & 0 & 0 & Dm_{5,6} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta L\_ij := Dm\_ij - Di\_ij$$

$$Di\_ij = \begin{bmatrix} 0 & 167.8829 & 267.2406 & 318.5989 & 280.8536 & 190.4256 \\ 0 & 0 & 135.8649 & 246.6697 & 302.6241 & 287.5855 \\ 0 & 0 & 0 & 134.8476 & 254.5555 & 303.8535 \\ 0 & 0 & 0 & 0 & 162.3993 & 266.6154 \\ 0 & 0 & 0 & 0 & 0 & 137.9861 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Dm\_ij = \begin{bmatrix} 0 & 167.9366 & 267.2804 & 318.6712 & 280.9929 & 190.4527 \\ 0 & 0 & 135.8932 & 246.6622 & 302.7487 & 287.6126 \\ 0 & 0 & 0 & 134.7427 & 254.5797 & 303.8122 \\ 0 & 0 & 0 & 0 & 162.5157 & 266.6791 \\ 0 & 0 & 0 & 0 & 0 & 138.042 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Matrix listing of differences between measured and ideal target pair distances, and their sample standard error.

$$\Delta L\_ij = \begin{bmatrix} 0 & 0.0537 & 0.0398 & 0.0723 & 0.1393 & 0.0271 \\ 0 & 0 & 0.0282 & -0.0075 & 0.1246 & 0.0271 \\ 0 & 0 & 0 & -0.1049 & 0.0242 & -0.0413 \\ 0 & 0 & 0 & 0 & 0.1164 & 0.0638 \\ 0 & 0 & 0 & 0 & 0 & 0.0559 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$S1 := 0.0537^2 + 0.0398^2 + 0.0723^2 + 0.1393^2 + 0.0271^2 + 0.0282^2 + 0.0075^2 + 0.1246^2 + 0.0271^2 + 0.1049^2$$

$$S2 := 0.0242^2 + 0.0413^2 + 0.1164^2 + 0.0638^2 + 0.0559^2$$

$$S3 := S1 + S2$$

$$S3 = 0.081$$

Sample standard error:

$$\left(\frac{1}{14}\right)\cdot\sqrt{S3} = 0.0203 \qquad 25.4\cdot\left[\left(\frac{1}{14}\right)\cdot\sqrt{S3}\right] = 0.5163$$

The sample standard error for the difference between survey measurement values and theoretical values, of the 15 distances between pairs of survey target center points, is 0.020 inches (0.52 millimeters).

This is approximately the standard error in measured distance which is to be expected using the total station instrument to measure survey path distances of order 100 meters.

This standard error is small compared to differences in coordinates found in Item 1c of Data Sheet W9. This indicates that the coordinate differences between the theoretical and actual measured survey coordinates are due to positional offset of the subreflector, as aligned, from the theoretical position which is the desired position for the aligned subreflector.

We now calculate the ideal ellipsoid coordinates of the six survey targets from their theoretical main reflector system coordinates at home position. We apply the inverse of transformation (4.4) to the coordinates listed in Table B4. We also need the main reflector coordinates of the ellipsoid center at home position at rigging elevation. These are listed on page 12 of this memo. In inches, the main reflector system coordinates of the ellipsoid's center point are, when the subreflector is at home position:

$XrghpCE := 0.0$ $\qquad$ $YrghpCE := -21.0173$ $\qquad$ $ZrghpCE := 2146.6917$

Let Sn = sin 5.570 degrees, Cn = cos 5.570 degrees.

$Sn := 0.0970617$ $\qquad$ $Cn := 0.9952783$

The inverse transform of (4.4) is:

$$Xce_j := Cn \cdot \left(Zrhp_j - ZrghpCE\right) + Sn \cdot \left(Yrhp_j - YrghpCE\right)$$

$$Yce_j := Sn \cdot \left(Zrhp_j - ZrghpCE\right) + Cn \cdot \left(YrghpCE - Yrhp_j\right)$$

$$Zce_j := Xrhp_j - XrghpCE$$

Table B6. Computed Ideal Values of Ellipsoid System Coordinates Of Survey Target Centers.

| | | | Survey Target |
|---|---|---|---|
| $Xce_1 = 422.7074$ | $Yce_1 = 30.3387$ | $Zce_1 = -11.754$ | T1A |
| $Xce_2 = 358.6537$ | $Yce_2 = 113.6086$ | $Zce_2 = -142.704$ | T2A |
| $Xce_3 = 277.5494$ | $Yce_3 = 221.729$ | $Zce_3 = -128.871$ | T3 |
| $Xce_4 = 232.8538$ | $Yce_4 = 286.0857$ | $Zce_4 = -19.124$ | T4 |
| $Xce_5 = 275.0341$ | $Yce_5 = 225.772$ | $Zce_5 = 125.64$ | T5 |
| $Xce_6 = 356.6502$ | $Yce_6 = 116.1844$ | $Zce_6 = 144.863$ | T6A |

From the ideal ellipsoid system coordinates of the survey targets given in Table B6 we calculate their ideal home position subreflector coordinates. The transformation equations (4.6) are:

$Ssce := 0.6726251$ $\qquad$ $Csce := 0.7399833$

$Xcel1 := 383.3215$ $\qquad$ $Ycel1 := 123.8021$ $\qquad$ $Zcel1 := 0.0$

$$Xshp_i := \left(Xce_i - Xcel1\right)\cdot Ssce - \left(Yce_i - Ycel1\right)\cdot Csce$$

$$Yshp_i := \left(Xce_i - Xcel1\right)\cdot Csce + \left(Yce_i - Ycel1\right)\cdot Ssce$$

$$Zshp_i := Zce_i$$

Here: Ssce = sin (36.7 + 5.570) deg = sin 42.27 deg = 0.6726251 ,
and Csce = cos (36.7 +5.570) deg = cos 42.27 deg = 0.7399833 .

Table B7. Computed Ideal Values of Subreflector System Home Position Coordinates (inches) of Survey Target Centers.

| | | | Survey Target |
|---|---|---|---|
| $Xshp_1 = 95.6533$ | $Yshp_1 = -33.7209$ | $Zshp_1 = -11.754$ | T1A |
| $Xshp_2 = -9.0492$ | $Yshp_2 = -25.1102$ | $Zshp_2 = -142.704$ | T2A |
| $Xshp_3 = -143.6093$ | $Yshp_3 = -12.4015$ | $Zshp_3 = -128.871$ | T3 |
| $Xshp_4 = -221.2955$ | $Yshp_4 = -2.1876$ | $Zshp_4 = -19.124$ | T4 |
| $Xshp_5 = -148.2928$ | $Yshp_5 = -11.5434$ | $Zshp_5 = 125.64$ | T5 |
| $Xshp_6 = -12.3028$ | $Yshp_6 = -24.8602$ | $Zshp_6 = 144.863$ | T6A |

As a final step, we calculate the subreflector system coordinates of the survey targets for the as-erected subreflector, by converting the main reflector coordinates, measured by the alignment survey, to subreflector system coordinates (inches). The transformation equations (A1.2) are:

$XrghpI1 := 0.0$ $\qquad$ $YrghpI1 := -168.9656$ $\qquad$ $ZrghpI1 := 2511.9242$

$Ss := 0.5976251$ $\qquad$ $Cs := 0.8017756$

Ss = Sin 36.7 degrees $\qquad$ Cs = cos 36.7 degrees.

$$Xs_i := \left(Ymrg_i - YrghpI1\right)\cdot Cs + \left(Zmrg_i - ZrghpI1\right)\cdot Ss$$

$$Ys_i := -\left(Ymrg_i - YrghpI1\right)\cdot Ss + \left(Zmrg_i - ZrghpI1\right)\cdot Cs$$

$$Zs_i := Xmrg_i$$

Table B8. Computed Alignment Survey Values of Subreflector System Coordinates (inches) of Survey Target Centers on the Subreflector As-Erected.

| | | | Survey Target |
|---|---|---|---|
| $Xs_1 = 164.6855$ | $Ys_1 = -49.795$ | $Zs_1 = -11.146$ | T1A |
| $Xs_2 = 60.2745$ | $Ys_2 = -40.9838$ | $Zs_2 = -142.384$ | T2A |
| $Xs_3 = -74.3893$ | $Ys_3 = -28.8176$ | $Zs_3 = -128.798$ | T3 |
| $Xs_4 = -152.3955$ | $Ys_4 = -19.0799$ | $Zs_4 = -19.364$ | T4 |
| $Xs_5 = -79.8084$ | $Ys_5 = -28.6685$ | $Zs_5 = 125.724$ | T5 |
| $Xs_6 = 56.2225$ | $Ys_6 = -41.78$ | $Zs_6 = 145.199$ | T6A |

We now tabulate the differences between the survey values calculated for the subreflector system coordinates of the survey targets and their calculated home position survey system coordinates.

Table B9.

Survey System Coordinates of the Displacements of the Subreflector Survey Targets from their Home Positions.

| | | | Survey Target |
|---|---|---|---|
| $Xs_1 - Xshp_1 = 69.0322$ | $Ys_1 - Yshp_1 = -16.0741$ | $Zs_1 - Zshp_1 = 0.608$ | T1A |
| $Xs_2 - Xshp_2 = 69.3238$ | $Ys_2 - Yshp_2 = -15.8736$ | $Zs_2 - Zshp_2 = 0.32$ | T2A |
| $Xs_3 - Xshp_3 = 69.22$ | $Ys_3 - Yshp_3 = -16.4161$ | $Zs_3 - Zshp_3 = 0.073$ | T3 |
| $Xs_4 - Xshp_4 = 68.9$ | $Ys_4 - Yshp_4 = -16.8923$ | $Zs_4 - Zshp_4 = -0.24$ | T4 |
| $Xs_5 - Xshp_5 = 68.4845$ | $Ys_5 - Yshp_5 = -17.1251$ | $Zs_5 - Zshp_5 = 0.084$ | T5 |
| $Xs_6 - Xshp_6 = 68.5253$ | $Ys_6 - Yshp_6 = -16.9198$ | $Zs_6 - Zshp_6 = 0.336$ | T6A |

As a check we compute the subreflector system coordinates of the calculated (not measured) subreflector targets from their main reflector system coordinates, using transformation equations (A1.2):

$$Xscalc_i := \left(Yrg_i - YrghpI1\right)\cdot Cs + \left(Zrg_i - ZrghpI1\right)\cdot Ss$$

$$Yscalc_i := -\left(Yrg_i - YrghpI1\right)\cdot Ss + \left(Zrg_i - ZrghpI1\right)\cdot Cs$$

$$Zscalc_i := Xrg_i$$

Table B10. Computed Theoretical Values of Subreflector System Coordinates (inches) of Survey Target Centers on the Subreflector. This is a transform of the calculated main reflLector coordinates listed in Item 4 of Data Sheet W2.

| | | | Survey Target |
|---|---|---|---|
| $Xscalc_1 = 164.1326$ | $Yscalc_1 = -50.6388$ | $Zscalc_1 = -11.754$ | T1A |
| $Xscalc_2 = 59.43$ | $Yscalc_2 = -42.0281$ | $Zscalc_2 = -142.704$ | T2A |
| $Xscalc_3 = -75.13$ | $Yscalc_3 = -29.3194$ | $Zscalc_3 = -128.871$ | T3 |
| $Xscalc_4 = -152.8162$ | $Yscalc_4 = -19.1055$ | $Zscalc_4 = -19.124$ | T4 |
| $Xscalc_5 = -79.8136$ | $Yscalc_5 = -28.4613$ | $Zscalc_5 = 125.64$ | T5 |
| $Xscalc_6 = 56.1765$ | $Yscalc_6 = -41.7781$ | $Zscalc_6 = 144.863$ | T6A |

Table B11. Computed Main Reflector System Coordinates (inches) of Survey Target Centers on the Subreflector from the ellipsoid system coordinates listed in Table B6, to the Main Reflector Coordinate System, assuming that the Sub-reflector is at home position. The transform equations (4.4) are:

$$Xr_j := XrghpCE + Zce_j$$

$$Yr_j := YrghpCE + Sn \cdot Xce_j - Cn \cdot Yce_j$$

$$Zr_j := ZrghpCE + Cn \cdot Xce_j + Sn \cdot Yce_j$$

Table B11. Computed Main Reflector System Coordinates System Coordinates (inches) of Survey Target Centers on the Subreflector. This is a transform of ellipsoid system coordinates listed in Table B6, assuming the subreflector is at home position. The transformation equations are (4.4).

| | | | Survey Target |
|---|---|---|---|
| $Xr_1 = -11.754$ | $Yr_1 = -10.184$ | $Zr_1 = 2570.3479$ | T1A |
| $Xr_2 = -142.704$ | $Yr_2 = -99.278$ | $Zr_2 = 2514.679$ | T2A |
| $Xr_3 = -128.871$ | $Yr_3 = -214.76$ | $Zr_3 = 2444.452$ | T3 |
| $Xr_4 = -19.124$ | $Yr_4 = -283.151$ | $Zr_4 = 2406.214$ | T4 |
| $Xr_5 = 125.64$ | $Yr_5 = -219.028$ | $Zr_5 = 2442.341$ | T5 |
| $Xr_6 = 144.863$ | $Yr_6 = -102.036$ | $Zr_6 = 2512.935$ | T6A |

These reproduce the ideal home position coordinates of Table B4.

## Appendix C. Conversion Of Target Coordinates From The Ellipsoid System To The Main Reflector System, For The Subreflector Photogrammetry Targets S1 To S6, When The Subreflector Is At Home Position.

The following ellipsoid coordinates have been provided provided for subreflector photogrammetry targets S1 to S6 (Calculation Sheet 12/7/99). All values are in inches.

$XceS_1 := 407.893$ $\quad$ $YceS_1 := 35.826$ $\quad$ $ZceS_1 := 4.045$

$XceS_2 := 367.215$ $\quad$ $YceS_2 := 102.507$ $\quad$ $ZceS_2 := -116.335$

$XceS_3 := 288.252$ $\quad$ $YceS_3 := 207.326$ $\quad$ $ZceS_3 := -135.582$

$XceS_4 := 233.259$ $\quad$ $YceS_4 := 286.436$ $\quad$ $ZceS_4 := 3.300$

$XceS_5 := 288.336$ $\quad$ $YceS_5 := 207.153$ $\quad$ $ZceS_5 := 135.737$

$XceS_6 := 367.109$ $\quad$ $YceS_6 := 102.682$ $\quad$ $ZceS_6 := 116.413$

Also,

$XrghpI1 := 0.0$ $\quad$ $YrghpI1 := -168.9656$ $\quad$ $ZrghpI1 := 2511.9242$

$XrghpCE := 0.0$ $\quad$ $YrghpCE := -21.0173$ $\quad$ $ZrghpCE := 2146.6917$

Let C = cos 5.570 degrees , S = sin 5.570 degrees.

$C := 0.9952783$ $\quad$ $S := 0.0970617$

$j := 1, 2 .. 6$

The main reflector system coordinates for these targets, when the subreflector is at home position are given by the transformation equations (4.4):

$$XrghpS_j := XrghpCE + ZceS_j$$

$$YrghpS_j := YrghpCE + XceS_j \cdot S - YceS_j \cdot C$$

$$ZrghpS_j := ZrghpCE + XceS_j \cdot C + YceS_j \cdot S$$

Numerical evaluation of the transformation gives:

| $j$ | $XrghpS_j$ | $YrghpS_j$ | $ZrghpS_j$ |
|---|---|---|---|
| 1 | 4.045 | -17.0834 | 2556.1361 |
| 2 | -116.335 | -87.3978 | 2522.1223 |
| 3 | -135.582 | -199.3861 | 2453.7061 |
| 4 | 3.3 | -283.4603 | 2406.6513 |
| 5 | 135.737 | -199.2058 | 2453.7729 |
| 6 | 116.413 | -87.5822 | 2522.0338 |

as the main reflector system home position coordinates of photogrammetry targets S1 to S6.

These values agree with the computed values listed for Item 1 on Data Sheet W2.

We next calculate the home position subreflector system coordinates of the six photogrammetry targets, by transforming coordinates from the ellipsoid to the subreflector system. The transformation equations are:

Ssce=0.6726251 = sin 42.27 deg Csce = 0.7399833 = cos 42.27 deg

$Ssce := 0.6726251$ $Csce := 0.7399833$

$XceI1 := 383.3215$ $YceI1 := 123.8021$ $ZceI1 := 0.0$

$$XshpS_j := \left(XceS_j - XceI1\right)\cdot Ssce - \left(YceS_j - YceI1\right)\cdot Csce$$

$$YshpS_j := \left(XceS_j - XceI1\right)\cdot Csce + \left(YceS_j - YceI1\right)\cdot Ssce$$

$$ZshpS_j := ZceS_j$$

The home position subreflector system coordinates (inches) of the photogrammetry targets S1 ... S6 are:

| | $j$ | $XshpS_j$ | $YshpS_j$ | $ZshpS_j$ |
|---|---|---|---|---|
| $S_1$ | 1 | 81.6283 | -40.9924 | 4.045 |
| $S_2$ | 2 | 4.9244 | -26.2422 | -116.335 |
| $S_3$ | 3 | -125.7524 | -14.1696 | -135.582 |
| $S_4$ | 4 | -221.2822 | -1.6521 | 3.3 |
| $S_6$ | 5 | -125.5679 | -14.2238 | 135.737 |
| $S_6$ | 6 | 4.7236 | -26.2029 | 116.413 |

## 7.2 Initial Alignment of Subreflector

The following steps are used to perform the initial alignment of the subreflector positioner:

(1) Move the reflector to rigging angle ($\approx$ 50.29°). Set up the total station in the center of the reflector and orient the coordinate system to the six targets R1-R6 distributed near the reflector periphery that were measured previously in 6.0.

**CAUTION:** The panels are designed to support the weight of a 250 lbs. person walking carefully anywhere on the surface. All personnel who may be working on the panel surface shall wear clean, light-colored sole shoes to prevent marring of the surface finish.

(2) Adjust the subreflector positioner to the location of Xs = 0.00, Ys = 1.91, and Zs = -2.59 inches which corresponds to the optimum offset position for the $\approx$ 50.29° rigging angle.

(3) Use the total station to measure the six targets T1-T6 on the subreflector. Compare these measurements to those listed in Data Sheet W2 to calculate the error relative to the best fit focal point.

(4) Rotate the antenna to the 77.67° access position. Adjust the gooseneck at its interface with the feed arm tip structure to reduce the errors determined in Data Sheet W5 to within ± 0.25 inches of theoretical.

(5) Use a digital level to determine the sideways and front-to-back slopes of the subreflector support triangle. Note that the front-back slope is $\approx$ 5.5° less than the subreflector Xs axis, making the design slope for the support triangle $\approx$ 31.7°. Record these slopes in Data Sheet W5. Adjust the gooseneck interface to reduce the errors to within ± 0.2° in either direction.

(6) Secure the gooseneck to the tip as required by CRSI Drawing No. 121038.

(7) Rotate the antenna to its rigging angle and remeasure the subreflector targets using the total station. Record these positions in Data Sheet W5.

(8) Repeat Steps (3) – (7) until the required slopes and positions have been achieved.

## 9.2 Final Alignment of the Subreflector Positioner

The following steps are used to perform the final alignment of the subreflector positioner:

(1) Move the reflector to rigging angle (≈ 50.29°). Set up the total station in the center of the reflector and orient the coordinate system to the six targets R1-R6 distributed near the reflector periphery that were measured previously in 8.0.

**CAUTION:** The panels are designed to support the weight of a 250 lbs. person walking carefully anywhere on the surface. All personnel who may be working on the panel surface shall wear clean, light-colored sole shoes to prevent marring of the surface finish.

(2) Adjust the subreflector positioner to the location of Xs = 0.00, Ys = 1.91, and Zs = -2.59 inches which corresponds to the optimum offset position for the ≈ 50.29° rigging angle.

(3) Use the total station to measure the six targets T1-T6 on the subreflector. Compare these measurements to those listed in Data Sheet W2 to calculate the error relative to the best fit focal point.

(4) Rotate the antenna to the 77.67° access position. Adjust the gooseneck at its interface with the feed arm tip structure to reduce the errors determined in Data Sheet W9 to within ± 0.25 inches of theoretical.

(5) Use a digital level to determine the sideways and front-to-back slopes of the subreflector support triangle. Note that the front-back slope is ≈ 5.5° less than the subreflector Xs axis, making the design slope for the support triangle ≈ 31.7°. Record these slopes in Data Sheet W9. Adjust the gooseneck interface to reduce the errors to within ± 0.2° in either direction.

(6) Secure the gooseneck to the tip as required by CRSI Drawing No. 121038.

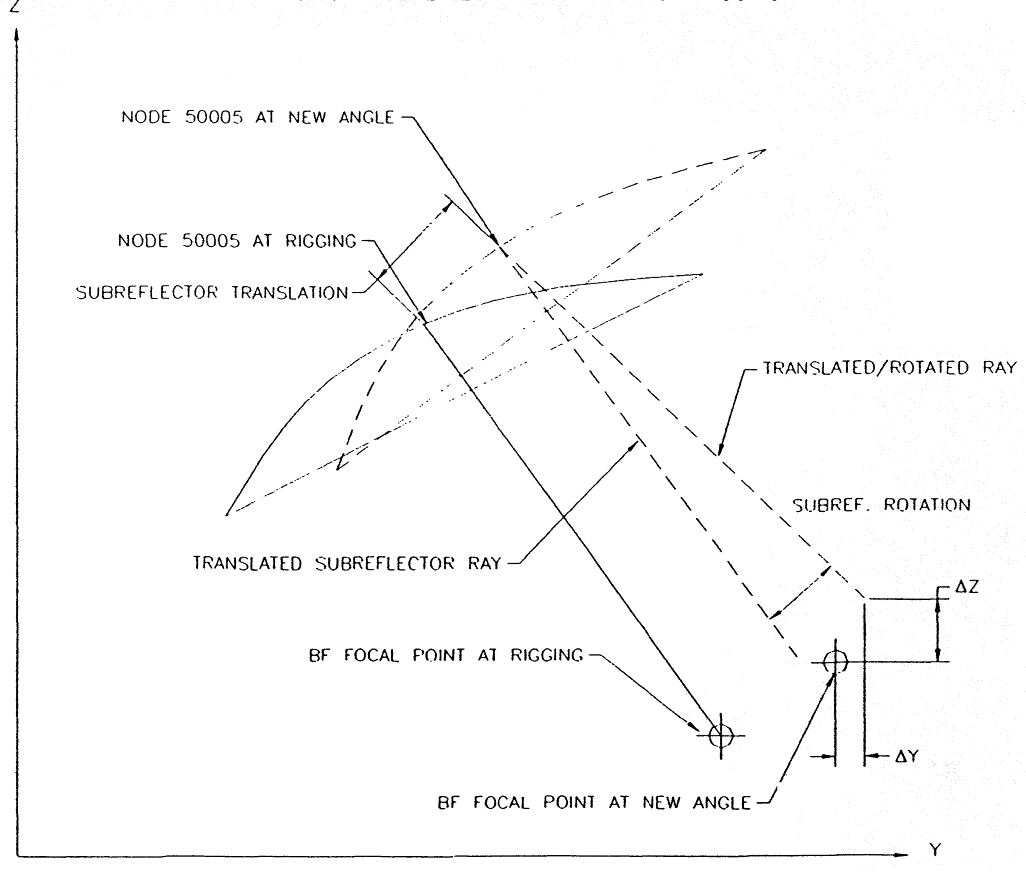
(7) Rotate the antenna to its rigging angle and remeasure the subreflector targets using the total station. Record these positions in Data Sheet W9.

(8) Repeat Steps (3) – (7) until the required slopes and positions have been achieved.

Subreflector Adjuster:

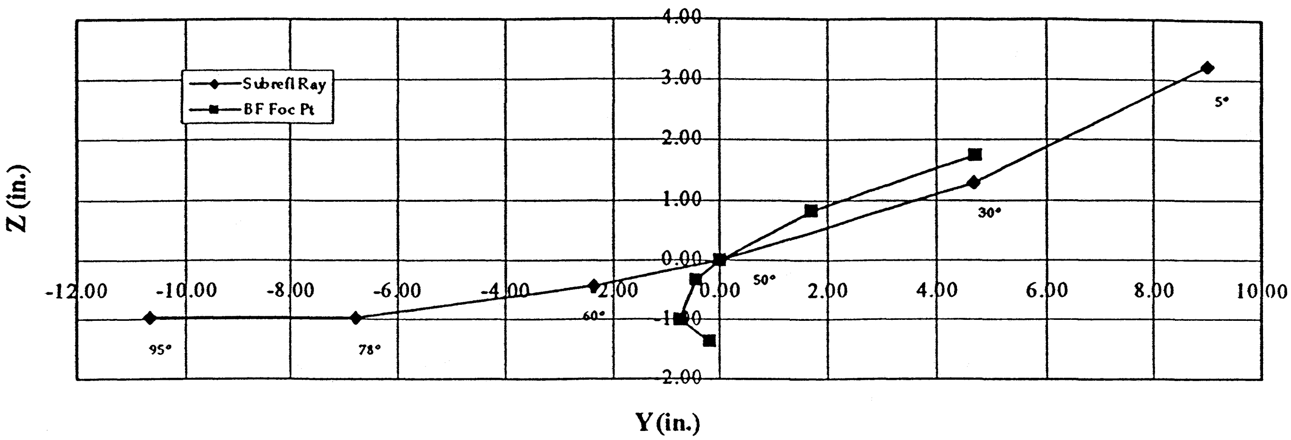
The situation with the subreflector is similar to that with the PFF with the exception that the rotation of the subreflector must be accounted for as well. This is shown in the diagram given in Figure 5. Here, it is shown how the BFP and the subreflector (Node 50005) translates with elevation movement. In addition, there is a rotation of Node 50005 that causes a displacement from the BFP. Both of the motions are considered in the centering of the subreflector adjuster at its mid-point.

FIG. 5 SUBREFLECTOR MOTION FROM RIGGING ANGLE



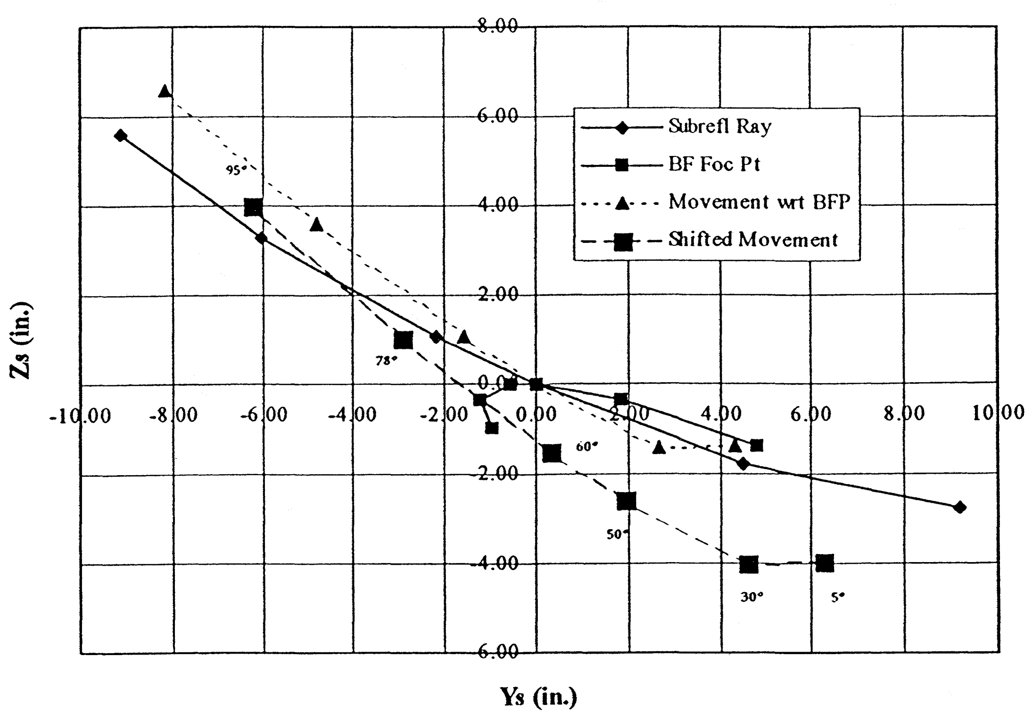

A similar approach is used for the subreflector whose movements in the global coordinate system are shown in Figure 6.

**Fig. 6 Subreflector**




These movements are then plotted in Figure 7 in the rotated (by 36.7°) coordinate system along with the movement and shifted movement.

**Fig. 7 Subreflector Adjuster**



Looking at the Shifted Movement line, it can be seen that the travel range is now equalized at ± 6.25 in. in Ys and ± 4.00 in. in Zs. The required offset to obtain equalization is –1.91 in. in Ys and 2.59 in. in Zs. This is accomplished by shimming the "gooseneck" at the connection to the feed arm by –3.08 in. in Y and 0.94 in. in Z. This means that the "gooseneck" be attached to the feed arm 3.08 in. "forward" and 0.94 in. "down" to center the adjuster.

As in the case of the PFF adjuster, these are theoretical shim sizes. In order to determine the actual sizes, it is necessary to drive the subreflector to the rigging offset position of Xs = 0.00, Ys = 1.91 and Zs = -2.59. In the reflector global coordinate system (i.e., one rotated by 36.7°), this corresponds to X = 0.00, Y = 3.08 and Z = -0.94 inches. The subreflector targets are then measured at rigging angle and the differences from the theoretical position determined. From these errors, actual shim requirements will be determined.

Summary:

This report describes how the optics devices are offset in order to minimize the errors from the best fit focus and the required travel range of the adjusters. This minimum travel range, combined with the specification required adjustments results in the movements dictated below:

| Item | PFF | Subreflector |
|---|---|---|
| Focus (in.): | | |
| Required | ±18+Yadj = ±(18+4.89)<br>= 45.78 | (+8 to –20)+Yadj = (+8+4.00) to –(20 + 4.00)<br>= 36.00 |
| Provided | 50 | 12.13 to –24.13 = 36.25 |
| X-translation (in.): | | |
| Required | ± Xadj = ± 5.58 | ± Xadj = ± 6.25 |
| Provided | ± 18.5 = 37 | ± 9.99 |
| Z-translation (in.) | | |
| Required | N/A | ± Zadj = ± 0.83 |
| Provided | N/A | ± 1.32 |

Thus, the provided adjustments meet those required.

| | |
|---|---|
| Nominal Focal Length = | 2362 inch |
| PFF Coordinate System Rotation = | 45.50 deg |
| Subreflector Coordinate System Rotation = | 36.70 deg |

| | BEST-FIT FOCAL POINT | | | | | | FEED ROOM NODE 40700 | | | | | | PRIME FOCUS FEED NODE 50001 | | | | | | | | SUBREFL NODE 50005 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ELEV ANGL (degs) | GLOBAL BF FOCUS | | PFF System BF FOCUS | | Sub System BF FOCUS | | GLOBAL FEED ROOM | | FEED ROOM wrt FOCUS | | OFFSET FEED ROOM TRAVEL | | GLOBAL PFF ADJ | | PFF System PFF ADJ | | PFF ADJ wrt FOCUS | | OFFSET PFF ADJ TRAVEL | | GLOBAL SUB REFL | | Sub System SUB REFL | | SUB REFL wrt FOCUS | | OFFSET SUBREFL TRAVEL | |
| | Y | Z | Ya | Za | Ys | Zs | Y | Z | Y | Z | Y | Z | Y | Z | Ya | Za | Ya | Za | Ya | Za | Y | Z | Ys | Zs | Ys | Zs | Ys | Zs |
| 5.00 | 4.70 | 1.76 | 4.55 | -2.12 | 4.82 | -1.40 | 7.25 | 3.25 | 2.55 | 1.49 | 5.45 | 0.83 | 8.98 | 3.15 | 8.54 | -4.19 | 3.99 | -2.08 | 5.58 | -4.89 | 9.00 | 3.25 | 9.16 | -2.77 | 4.34 | -1.38 | 6.25 | -3.96 |
| 30.00 | 1.69 | 0.83 | 1.78 | -0.62 | 1.85 | -0.34 | 3.75 | 1.34 | 2.06 | 0.51 | 4.96 | -0.15 | 4.67 | 1.27 | 4.18 | -2.44 | 2.40 | -1.81 | 4.00 | -4.62 | 4.67 | 1.29 | 4.52 | -1.76 | 2.67 | -1.42 | 4.57 | -4.00 |
| 50.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.89 | -0.66 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.59 | -2.81 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.91 | -2.59 |
| 60.00 | -0.46 | -0.36 | -0.57 | 0.08 | -0.58 | -0.01 | -1.90 | -0.49 | -1.45 | -0.13 | 1.45 | -0.79 | -2.38 | -0.44 | -1.98 | 1.39 | -1.41 | 1.31 | 0.18 | -1.50 | -2.38 | -0.43 | -2.16 | 1.07 | -1.59 | 1.09 | 0.32 | -1.50 |
| 77.67 | -0.77 | -1.00 | -1.25 | -0.15 | -1.21 | -0.34 | -5.43 | -1.16 | -4.66 | -0.16 | -1.77 | -0.83 | -6.81 | -1.03 | -5.51 | 4.13 | -4.26 | 4.29 | -2.67 | 1.48 | -6.79 | -0.97 | -6.03 | 3.28 | -4.82 | 3.62 | -2.91 | 1.03 |
| 95.00 | -0.19 | -1.38 | -1.11 | -0.83 | -0.97 | -0.99 | -8.53 | -1.32 | -8.34 | 0.06 | -5.45 | -0.61 | -10.70 | -1.10 | -8.29 | 6.87 | -7.17 | 7.70 | -5.58 | 4.89 | -10.67 | -0.96 | -9.13 | 5.60 | -8.15 | 6.59 | -6.25 | 4.00 |
| MID-POINT | | | | | | | | | | | | | -0.86 | 1.03 | 0.13 | 1.34 | | | | | -0.83 | 1.14 | | | | | | |
| TRAVEL RANGE | | | | | | | | | | | 10.89 | 1.66 | | | | | | | 11.16 | 9.77 | | | | | | | 12.50 | 8.01 |
| ROOM OFFSET (Global System) | | | | | | | | | -2.89 | 0.66 | | | | | | | | | | | | | | | | | | |
| PFF ADJ OFFSET (Pff System) | | | | | | | | | | | | | | | | | -1.59 | 2.81 | | | | | | | | | | |
| PFF ADJ OFFSET (Global System) | | | | | | | | | | | | | | | | | -3.12 | 0.83 | | | | | | | | | | |
| SUB REFL OFFSET (Sub System) | | | | | | | | | | | | | | | | | | | | | | | | | -1.91 | 2.59 | | |
| SUB REFL OFFSET (Global System) | | | | | | | | | | | | | | | | | | | | | | | | | -3.08 | 0.94 | | |

| BEST-FIT PARABOLOID RESULTS | | | | | | | | | NODE 40700 | | NODE 50001 | | NODE 50005 | | | NODE 50000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| El angle | New FL | Del FL | elev | azim | Yvtx | Zvtx | Yfp | Zfp | Y | Z | Y | Z | Y | Z | ROT | Y | Z |
| 5.00 | 2361.38 | -0.83 | -0.12 | 0.00 | -7.34 | 0.77 | -2.47 | 1.60 | 9.96 | 0.43 | 12.61 | 0.11 | 13.43 | 0.82 | -0.0060 | 12.53 | 0.01 |
| 30.00 | 2361.41 | -0.79 | -0.15 | 0.00 | -11.69 | -0.13 | -5.48 | 0.67 | 6.46 | -1.49 | 8.30 | -1.76 | 8.89 | -1.38 | -0.0046 | 8.24 | -1.84 |
| 50.00 | 2361.55 | -0.65 | -0.16 | 0.00 | -13.63 | -0.82 | -7.17 | -0.16 | 2.71 | -2.83 | 3.64 | -3.04 | 3.94 | -2.97 | -0.0028 | 3.60 | -3.08 |
| 60.00 | 2361.64 | -0.56 | -0.15 | 0.00 | -13.97 | -1.08 | -7.62 | -0.51 | 0.81 | -3.31 | 1.26 | -3.48 | 1.42 | -3.57 | -0.0019 | 1.23 | -3.51 |
| 77.67 | 2361.85 | -0.36 | -0.14 | 0.00 | -13.56 | -1.52 | -7.93 | -1.15 | -2.72 | -3.99 | -3.17 | -4.07 | -3.28 | -4.43 | 0.0000 | -3.17 | -4.06 |
| 95.00 | 2362.08 | -0.13 | -0.11 | 0.00 | -11.92 | -1.67 | -7.35 | -1.53 | -5.82 | -4.15 | -7.07 | -4.14 | -7.43 | -4.72 | 0.0018 | -7.04 | -4.10 |

| | | | | | Adjusted for rigging angle (50 degs) | | | | | | | | | | | Del S/R w/ROT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.00 | -0.18 | | 0.04 | 0.00067 | 6.29 | 1.59 | 4.70 | 1.76 | 7.25 | 3.25 | 8.98 | 3.15 | 9.48 | 3.79 | -0.0032 | 9.00 | 3.25 |
| 30.00 | -0.14 | | 0.01 | 0.00011 | 1.95 | 0.70 | 1.69 | 0.83 | 3.75 | 1.34 | 4.67 | 1.27 | 4.94 | 1.59 | -0.0018 | 4.67 | 1.29 |
| 50.00 | 0.00 | | 0.00 | 0.00000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0000 | 0.00 | 0.00 |
| 60.00 | 0.09 | | 0.00 | 0.00005 | -0.33 | -0.26 | -0.46 | -0.36 | -1.90 | -0.49 | -2.38 | -0.44 | -2.52 | -0.60 | 0.0010 | -2.38 | -0.43 |
| 77.67 | 0.30 | | 0.02 | 0.00036 | 0.07 | -0.69 | -0.77 | -1.00 | -5.43 | -1.16 | -6.81 | -1.03 | -7.23 | -1.46 | 0.0029 | -6.79 | -0.97 |
| 95.00 | 0.53 | | 0.05 | 0.00081 | 1.71 | -0.85 | -0.19 | -1.38 | -8.53 | -1.32 | -10.70 | -1.10 | -11.37 | -1.75 | 0.0047 | -10.67 | -0.96 |

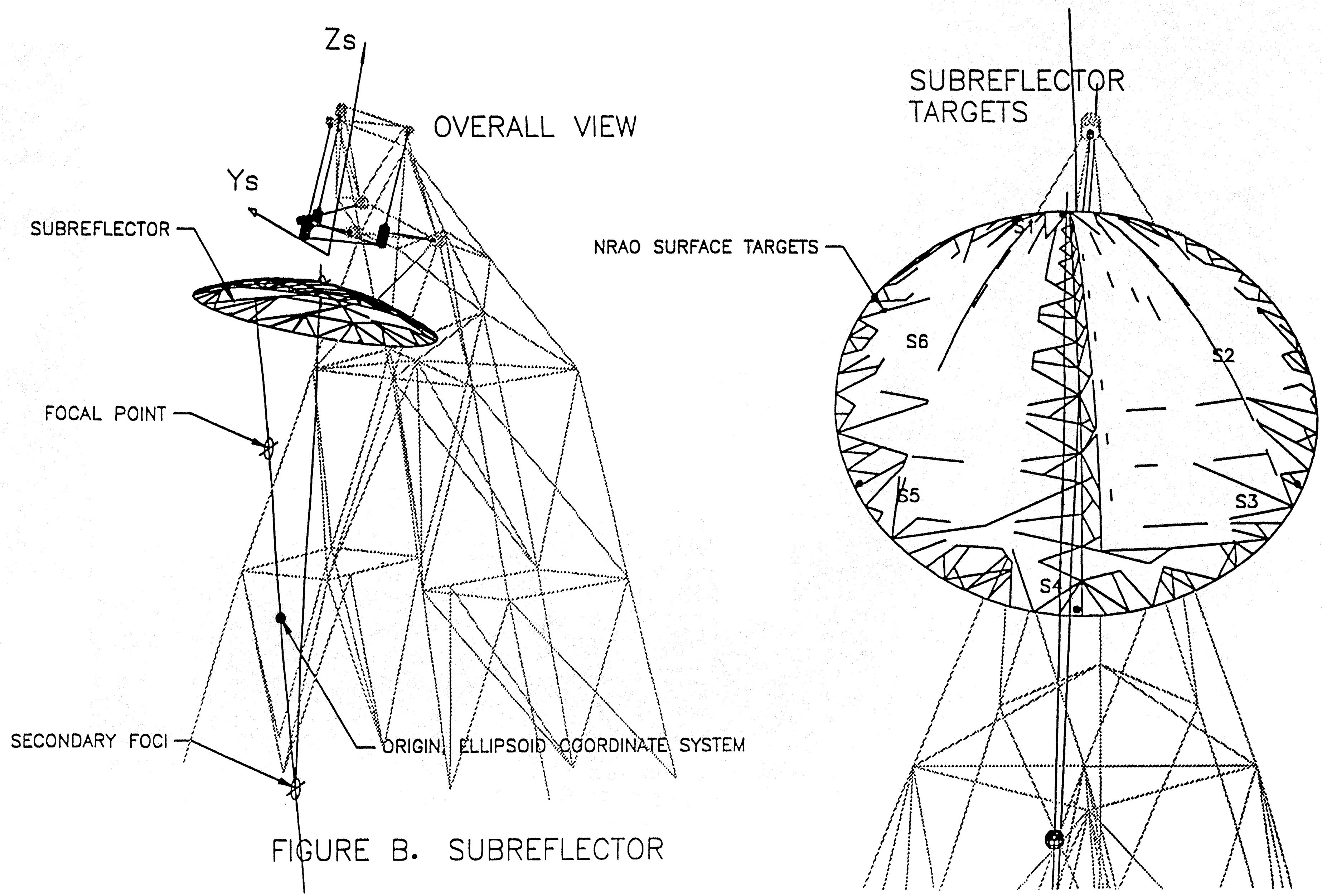



FIGURE B. SUBREFLECTOR

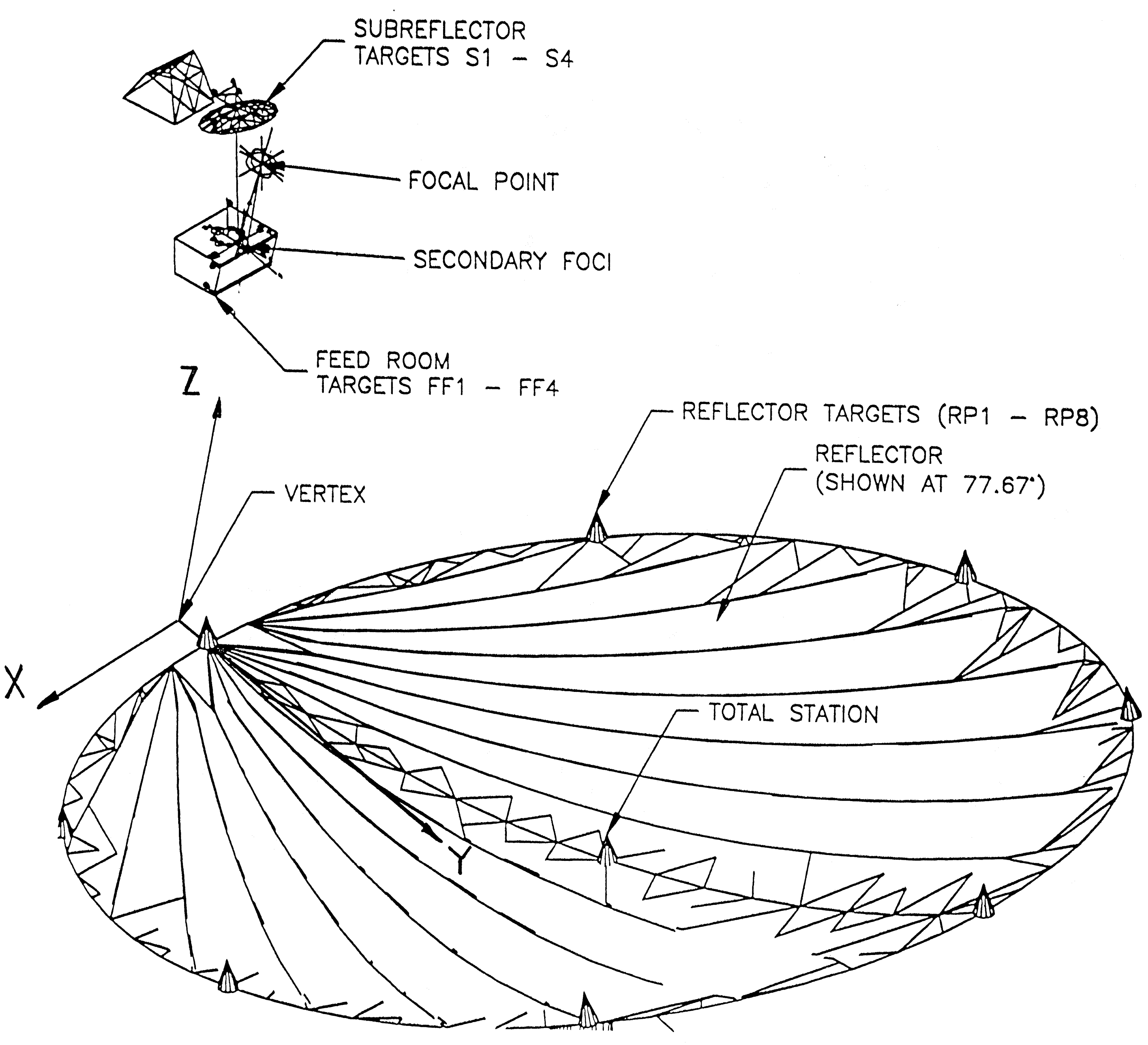



FIGURE E FINAL ALIGNMENTS

# DATA SHEET W2
## SUBREFLECTOR TARGET MEASUREMENT

| | | X | Y | Z |
|---|---|---|---|---|
| 1. | Photogrammetry targets (NRAO measurements) | X | Y | Z |
| | S1 | 4.045 | -17.078 | 2556.137 |
| | S2 (Target not visible and not used for orientation) | -116.335 | -87.393 | 2522.126 |
| | S3 | -135.582 | -199.384 | 2453.713 |
| | S4 | 3.300 | -283.459 | 2406.660 |
| | S5 | 135.737 | -199.203 | 2453.779 |
| | S6 | 116.413 | -87.578 | 2522.037 |
| 2. | Measured total station targets | X | Y | Z |
| | T1 | -12.285 | -16.120 | 2555.956 |
| | T2 | -135.502 | -98.207 | 2509.736 |
| | T3 | -128.871 | -214.761 | 2444.457 |
| | T4 | -19.124 | -283.152 | 2406.219 |
| | T5 | 125.640 | -219.029 | 2442.346 |
| | T6 | 137.079 | -102.763 | 2507.562 |
| 3. | Rigging angle offsets | 0.00 | 3.08 | -0.94 |
| 4. | Offset total station targets (2 + 3) | X | Y | Z |
| | T1 | -12.285 | -13.040 | 2555.016 |
| | T2 | -135.502 | -95.127 | 2508.796 |
| | T3 | -128.871 | -211.681 | 2443.517 |
| | T4 | -19.124 | -280.072 | 2405.279 |
| | T5 | 125.640 | -215.949 | 2441.406 |
| | T6 | 137.079 | -99.683 | 2506.622 |
| Acceptance Criteria | | Yes | No | |
| 1. | 2. Total station targets measured | X | | |
| 2. | 4. Total station targets offset | X | | |

COMSAT John W. [signature] DATE 10/10/00

NRAO ______________________ DATE ____________

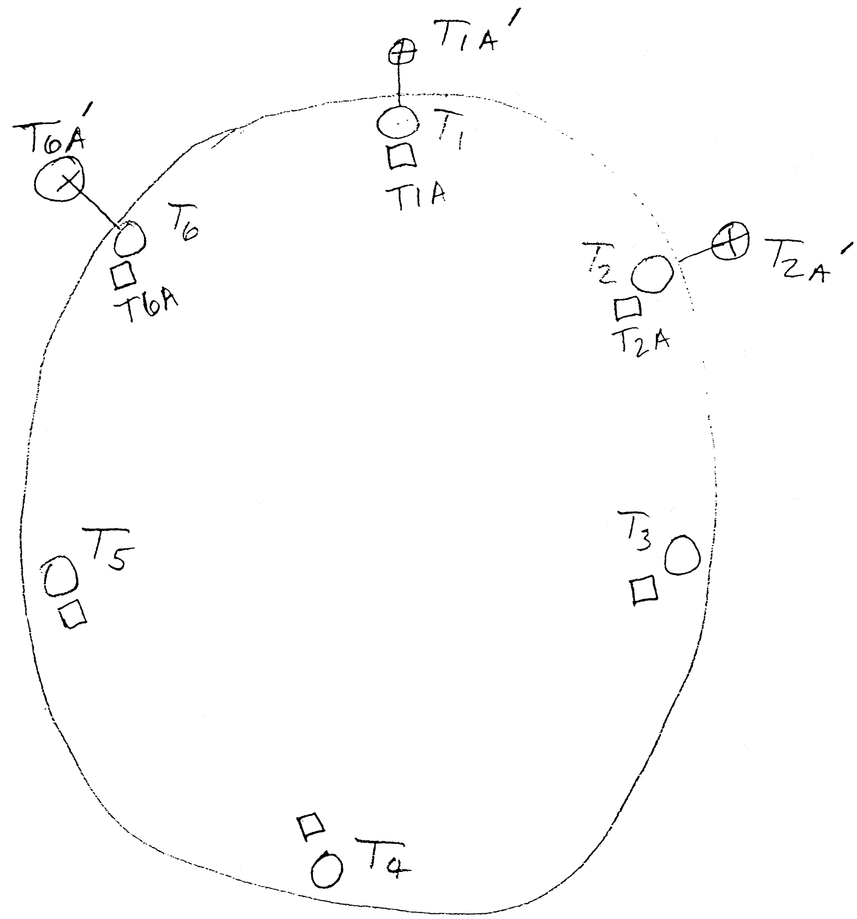
Subreflector Targets

Measurements at photogrametry target points.

| | | | | | |
|---|---|---|---|---|---|
| Photo-grammetry | T1 | 4.065 | -17.042 | 2556.151 | 0.000 |
| | T3 | -135.602 | -199.403 | 2453.711 | 0.000 |
| | T4 | 3.284 | -283.498 | 2406.626 | 0.000 |
| | T5 | 135.752 | -199.208 | 2453.784 | 0.000 |
| | T6 | 116.413 | -87.551 | 2522.054 | 0.000 |

Measurements of total station targets next to photogrametry targets.

| | | | | | |
|---|---|---|---|---|---|
| TS Tape | T1A | -12.285 | -16.120 | 2555.956 | 0.000 |
| | T2A | -135.502 | -98.207 | 2509.736 | 0.000 |
| | T3A | -128.871 | -214.761 | 2444.457 | 0.000 |
| | T4A | -19.124 | -283.152 | 2406.219 | 0.000 |
| | T5A | 125.640 | -219.029 | 2442.346 | 0.000 |
| | T6A | 137.079 | -102.763 | 2507.562 | 0.000 |



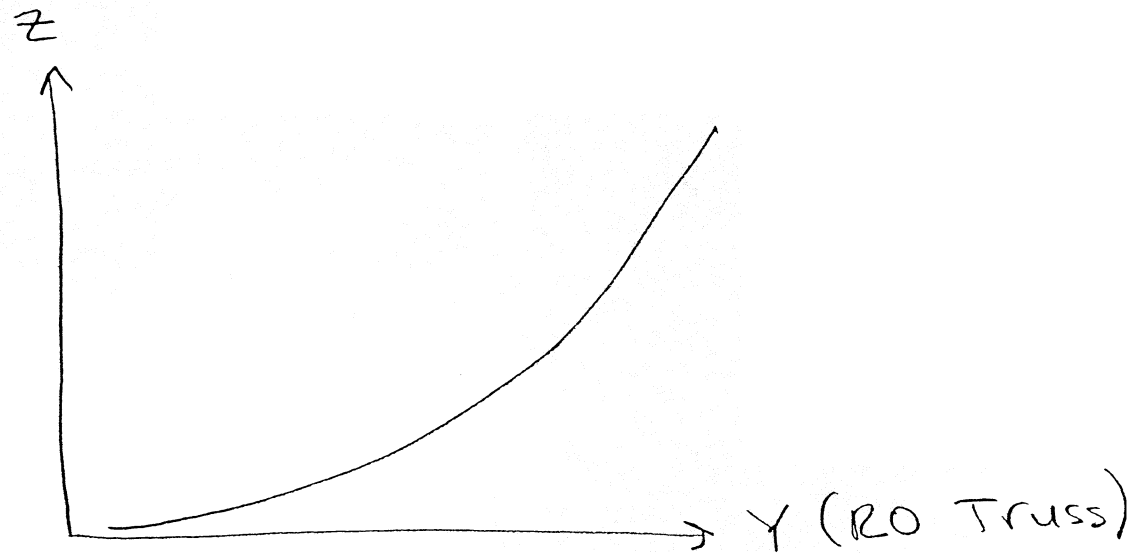
Subreflector Targets

Measurements at photogrametry target points.

| | X | Y | Z | |
|---|---|---|---|---|
| T1 | 4.065 | -17.042 | 2556.151 | 0.000 |
| T3 | -135.602 | -199.403 | 2453.711 | 0.000 |
| T4 | 3.284 | -283.498 | 2406.626 | 0.000 |
| T5 | 135.752 | -199.208 | 2453.784 | 0.000 |
| T6 | 116.413 | -87.551 | 2522.054 | 0.000 |

Measurements of total station targets next to photogrametry targets.

| | | | | |
|---|---|---|---|---|
| T1A | -12.285 | -16.120 | 2555.956 | 0.000 |
| T2A | -135.502 | -98.207 | 2509.736 | 0.000 |
| T3A | -128.871 | -214.761 | 2444.457 | 0.000 |
| T4A | -19.124 | -283.152 | 2406.219 | 0.000 |
| T5A | 125.640 | -219.029 | 2442.346 | 0.000 |
| T6A | 137.079 | -102.763 | 2507.562 | 0.000 |



GBT Subreflector Target Calculations 12/7/99

The origin of the following coordinates is located at the center of the design ellipsoid. The following 6 coordinates were given by Fred Schwab on 2/25/99.

THEO DEF
# 1 SHOULD Ref. Sys 0
X 407.8930
Y 35.8260
Z 4.0450

Rotated 5.57165504°

THEO DEF
# 2 SHOULD Ref. Sys 0
X 367.2150
Y 102.5070
Z -116.3350

THEO DEF
# 3 SHOULD Ref. Sys 0
X 288.2520
Y 207.3260
Z -135.5820

THEO DEF
# 4 SHOULD Ref. Sys 0
X 233.2590
Y 286.4360
Z 3.3000

THEO DEF
# 5 SHOULD Ref. Sys 0
X 288.3360
Y 207.1530
Z 135.7370

THEO DEF
# 6 SHOULD Ref. Sys 0
X 367.1090
Y 102.6820
Z 116.4130

THEO DEF (Focus)
# 10 SHOULD Ref. Sys 0
X 0.0000
Y 0.0000
Z 0.0000

(?)

THEO DEF (Center of Ellipsoid)
# 11 SHOULD Ref. Sys 0
X 216.5350
Y 0.0000
Z 0.0000

THEO DEF (M1 Focus)
# 12 SHOULD Ref. Sys 0
X -216.5350
Y 0.0000
Z 0.0000

---

Coordinates transformed to the parabolic system using WTUTOR.

THEO DEF
# 1 SHOULD Ref. Sys 1
X 4.0450
Y -17.0777
Z 2556.1373

THEO DEF
# 2 SHOULD Ref. Sys 1
X -116.3350
Y -87.3931
Z 2522.1256

THEO DEF
# 3 SHOULD Ref. Sys 1
X -135.5820
Y -199.3835
Z 2453.7126

THEO DEF
# 4 SHOULD Ref. Sys 1
X 3.3000
Y -283.4590
Z 2406.6602

THEO DEF
# 5 SHOULD Ref. Sys 1
X 135.7370
Y -199.2031
Z 2453.7794

THEO DEF
# 6 SHOULD Ref. Sys 1
X 116.4130
Y -87.5776
Z 2522.0371

THEO DEF (Focus)
# 10 SHOULD Ref. Sys 1 (?)
X -0.0000
Y -21.0235
Z 2146.6930

THEO DEF (Center of Ellipsoid)
# 11 SHOULD Ref. Sys 1
X -0.0000
Y -0.0000
Z 2362.2050

THEO DEF (M1 Focus)
# 12 SHOULD Ref. Sys 1
X -0.0000
Y -42.0470
Z 1931.1810

# DATA SHEET W9
## FINAL ALIGNMENT SUBREFLECTOR

| | | | |
|---|---|---|---|
| 1. Subreflector targets | | | |
| a. Theoretical at rigging (from W2, 4) | X | Y | Z |
| T1A | -11.754 | -7.105 | 2569.413 |
| T2A | -142.704 | -96.199 | 2513.744 |
| T3 | -128.871 | -211.681 | 2443.517 |
| T4 | -19.124 | -280.072 | 2405.279 |
| T5 | 125.640 | -215.949 | 2441.406 |
| T6A | 144.863 | -98.957 | 2512.000 |
| b. Measured | X | Y | Z |
| T1A | -11.146 | -7.166 | 2570.420 |
| T2A | -142.384 | -96.146 | 2515.086 |
| T3 | -128.798 | -211.387 | 2444.362 |
| T4 | -19.364 | -279.750 | 2405.551 |
| T5 | 125.724 | -215.821 | 2441.243 |
| T6A | 145.199 | -98.919 | 2512.026 |
| c. Errors (1b - 1a) | X | Y | Z |
| T1A | .608 | -.061 | 1.007 |
| T2A | .320 | .053 | 1.342 |
| T3 | .073 | .294 | .845 |
| T4 | -.240 | .322 | .272 |
| T5 | .084 | .128 | -.163 |
| T6A | .336 | .038 | 1.342 |
| Average errors | .197 | .129 | .555 |
| 2. Subreflector slopes | Frt-Back | Sideways | |
| a. Theoretical | 18.9° | 0° | |
| b. Measured | 18.7° | 0.3° | |
| c. Differences | 0.2° | 0.3° | |
| Acceptance Criteria | Yes | No | |
| 1. 2c Errors ≤ 0.2° | | No* | |
| 2. 3b Errors ≤ ± 0.25 inch | | No* | |

COMSAT [signature] DATE 10/10/00

NRAO DATE

* Jack Gurney has calculated that the remaining adjustment required to meet the specification is available in the actuator strokes.

Sub9_8.dat Data File 9/12/00

| | X | Y | Z | — On-site coords. |
|---|---|---|---|---|
| P1 | -2723.452 | -707.334 | 930.684 | Control point |
| P2 | -2215.747 | 611.416 | 564.71 | Control point |
| P3 | -316.051 | 1422.287 | 36.541 | Control point |
| P4 | 1432.489 | -274.407 | 35.243 | Control point |
| P6 | -623.401 | -2745.513 | -929.696 | Control point |
| T3 | -211.387 | 128.798 | 2444.362 | Data Point |
| T4 | -279.75 | 19.364 | 2405.551 | Data Point |
| T5 | -215.821 | -125.724 | 2441.243 | Data Point |
| T1A | -7.166 | 11.146 | 2570.42 | Data Point |
| T2A | -96.146 | 142.384 | 2515.086 | Data Point |
| T6A | -98.919 | -145.199 | 2512.026 | Data Point |

| | | | |
|---|---|---|---|
| T1 | -13.04 | 12.285 | 2555.016 |
| T2 | -95.127 | 135.502 | 2508.796 |
| T3 | -211.681 | 128.871 | 2443.517 |
| T4 | -280.072 | 19.124 | 2405.279 |
| T5 | -215.949 | -125.64 | 2441.406 |
| T6 | -99.683 | -137.079 | 2506.622 |
| RR1 | 23.716 | -152.515 | 1787.315 |
| RR2 | 11.575 | -152.693 | 1931.365 |
| RR3 | 23.305 | 152.432 | 1787.492 |
| RR4 | 11.334 | 152.213 | 1931.232 |
| PFF | 0 | 0 | 2362.205 |
| FT1 | -3.391 | -0.391 | 1941.522 |
| FT2 | -190.824 | -0.03 | 1900.565 |
| FT3 | -42.472 | -95.903 | 1932.997 |
| FT4 | -42.339 | 95.968 | 1932.726 |
| T1A | -7.105 | 11.754 | 2569.413 |
| T2A | -96.199 | 142.704 | 2513.744 |
| T6A | -98.957 | -144.863 | 2512 |

Subreflector Measurements

The subreflector was measured at a reflector orientation of 95 degrees so that auxiliary points could be added to get a total of six points on the periphery of the subreflector. These auxiliary points were transformed to the global coordinate system using AutoCAD. The auxiliary points used in future work used the coordinates as determined from the AutoCAD sketch.

Sub measured at 95 Deg.

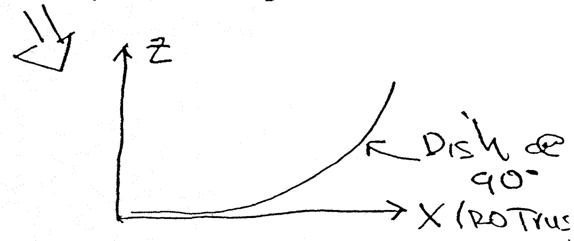
| | X | Y | Z |
|---|---|---|---|
| T1 | -2017.525 | -139.104 | 1989.502 |
| T2 | -2103.825 | -21.665 | 1936.1 |
| T3 | -2212.464 | -35.872 | 1859.429 |
| T4 | -2268.401 | -149.916 | 1814.213 |
| T5 | -2197.609 | -290.014 | 1855.738 |
| T6 | -2087.741 | -293.795 | 1932.062 |
| T1A | -2013.033 | -139.284 | 2004.624 |
| T2A | -2105.75 | -14.497 | 1941.079 |
| T6A | -2086.899 | -301.543 | 1937.498 |

Y -X Z → Equivalent 121960 Coords.

Nominals

X Y Z —On Site Coords

| | X | Y | Z |
|---|---|---|---|
| T1A | -7.105 | 11.754 | 2569.413 |
| T2A | -96.199 | 142.704 | 2513.744 |
| T6A | -98.957 | -144.863 | 2512 |
| T3 | -211.681 | 128.871 | 2443.517 |
| T4 | -280.072 | 19.124 | 2405.279 |
| T5 | -215.949 | -125.64 | 2441.406 |




First Measurement / Deltas(Meas-nom)

| | X | Y | Z | X | Y | Z |
|---|---|---|---|---|---|---|
| T1A | -7.828 | 10.532 | 2568.577 | -0.723 | -1.222 | -0.836 |
| T2A | -96.814 | 141.718 | 2513.174 | -0.615 | -0.986 | -0.57 |
| T6A | -99.666 | -145.741 | 2510.156 | -0.709 | -0.878 | -1.844 |
| T3 | -212.094 | 128.287 | 2442.465 | -0.413 | -0.584 | -1.052 |
| T4 | -280.5 | 18.753 | 2403.645 | -0.428 | -0.371 | -1.634 |
| T5 | -216.54 | -126.307 | 2439.374 | -0.591 | -0.667 | -2.032 |
| | | | Averages | -0.579833 | -0.784667 | -1.328 |
| | | | Std Dev | 0.1337377 | 0.3052014 | 0.5913226 |

After the first measurement, the S/R moved up .75" and left .50" at the gooseneck. A second measurement was taken.

Harry's 8-30 Data
After first shift

| | X | Y | Z | | X | Y | Z |
|---|---|---|---|---|---|---|---|
| T1A | -8.074 | 10.885 | 2569.245 | T1A | -0.969 | -0.869 | -0.168 |
| T2A | -97.057 | 142.187 | 2514.033 | T2A | -0.858 | -0.517 | 0.289 |
| T6A | -99.84 | -145.366 | 2510.88 | T6A | -0.883 | -0.503 | -1.12 |
| T3 | -212.351 | 128.571 | 2443.311 | T3 | -0.67 | -0.3 | -0.206 |
| T4 | -280.756 | 19.161 | 2404.457 | T4 | -0.684 | 0.037 | -0.822 |
| T5 | -216.801 | -125.832 | 2440.104 | T5 | -0.852 | -0.192 | -1.302 |
| | | | | Global Averages | -0.819333 | -0.390667 | -0.554833 |
| | | | | S/R coord. Averages | -0.988504 | -0.390667 | 0.0448024 |
| | | | | Std Dev | 0.1180096 | 0.3124002 | 0.6216798 |

The S/R was moved at the gooseneck out 1", up .5" and left by .38". Another measurement was taken.

Harry's 9-8 Data
After second shift

| | X | Y | Z | | X | Y | Z |
|---|---|---|---|---|---|---|---|
| T1A | -7.166 | 11.146 | 2570.42 | T1A | -0.061 | -0.608 | 1.007 |
| T2A | -96.146 | 142.384 | 2515.086 | T2A | 0.053 | -0.32 | 1.342 |
| T6A | -98.919 | -145.199 | 2512.026 | T6A | 0.038 | -0.336 | 0.026 |
| T3 | -211.387 | 128.798 | 2444.362 | T3 | 0.294 | -0.073 | 0.845 |
| T4 | -279.75 | 19.364 | 2405.551 | T4 | 0.322 | 0.24 | 0.272 |
| T5 | -215.821 | -125.724 | 2441.243 | T5 | 0.128 | -0.084 | -0.163 |
| | | | | Global Averages | 0.129 | -0.196833 | 0.5548333 |
| | | | | S/R coord. Averages | 0.4350114 | -0.196833 | 0.3677582 |
| | | | | Std Dev | 0.1514147 | 0.2906836 | 0.5971979 |

These are the present errors and are checked for S/R actuator adequacy.

Site coords converted to 121960 coords in Data Sheet W9.