TDA Progress Report 42-95 July–September 1988

DSN 70-Meter Antenna X-Band Gain, Phase, and Pointing Performance, With Particular Application for Voyager 2 Neptune Encounter

S. D. Slobin and D. A. Bathker
Radio Frequency and Antenna Microwave Subsystems Section

The gain, phase, and pointing performance of the DSN 70-m antennas are investigated using theoretical antenna analysis computer programs that consider the gravity-induced deformation of the antenna surface and quadripod structure. The microwave effects are calculated for normal subreflector focusing motion and for special fixed-subreflector conditions that may be used during the Voyager 2 Neptune encounter. The frequency stability effects of stepwise lateral and axial subreflector motions are also described. Comparisons with recently measured antenna efficiency and subreflector motion tests are presented. A modification to the existing 70-m antenna pointing squint correction constant is proposed.

I. Introduction

With the approaching Voyager 2 Neptune encounter, scheduled for August 25, 1989, it is important to characterize the operation of the DSN 70-m antenna network in its newly upgraded configuration. It was predicted that the upgrade would improve antenna gain by 55 percent (1.9 dB) or more, relative to the gain in its 64-m configuration. This has been accomplished and verified for the three 70-m antennas by efficiency measurements using radio sources as reference standards. The gain/noise temperature ratio has been increased even more due to a decrease of system noise temperature at all elevation angles. A more complete description of these results will be reported in future TDA Progress Reports.

Normally, antenna subreflector (SR) focusing motion is made to optimize the gain at all elevation angles. This subreflector motion is necessary because the antenna changes shape and the quadripod moves (a total of three inches laterally and one-half inch axially) as a function of elevation angle. Because the best-fit focus of the deformed main reflector is generally not coincident with the subreflector focus (after quadripod movement), subreflector movement commanded by the subreflector controller (SRC) is necessary. Although the antenna gain is optimized by this method, pointing is not preserved. A "squint correction" to the predicted elevation angle for SR lateral motion along the antenna Y-axis (vertical for AZ-EL antennas pointing at the horizon) is made by offsetting the predicted elevation angle as a function of subreflector position only (not elevation angle). Somewhat more complete descriptions of these antenna and subreflector motions for the 64-m antennas are given in [1] and [2]. The study in [1] grew out of a problem that occurred during the Voyager 2 Uranus encounter wherein a mispositioned subreflector degraded the gain and pointing capabilities of the DSS-43 (Australia) 64-m antenna. A recent study [3] compares 70-m antenna performance predicted by both GTD (Geometrical Theory of Diffraction) calculations and traditional ray tracing methods.

For the purposes of frequency stability of the DSS-43 70-m antenna during the Voyager 2 Neptune closest approach (approximately 0700 to 0915 GMT, Earth-received time, over an elevation angle range of approximately 45 to 70 degrees), two modifications of subreflector positioning are being considered: (1) fix the subreflector in its axial (Z) motion at a position corresponding to an elevation angle of approximately 60 degrees, or (2) fix the subreflector in both its axial (Z) and vertical (Y) motions at a position corresponding to an elevation angle of 60 degrees. The subreflector X-axis position (horizontal) does not change, as there is no net gravity component in that direction, and hence no net change in the loading as a function of elevation angle. A previous study concerning the phase and frequency stability of Cassegrainian antennas (e.g., DSS-43 in its 64-m configuration and the present DSS-42 HA-DEC antenna) is presented in [4]. Typical maximum subreflector axial (Z) rates of motion are 0.050 in./sec, resulting in an RF path length change of 0.090 in./sec. (In the study reported in [4] it was found that the ratio of change in RF path length to change in subreflector axial position was 1.8. (An earlier study [5] determined this factor to be 1.76.) For X-band frequency (8420 MHz), this results in a frequency signature (for this example) of about 0.064 Hz. This low frequency signature confuses radio science data analysis, hence the proposal to fix subreflector motion. The purpose of the study presented here is to determine the gain and phase effects of this nonstandard antenna configuration. It should be noted that the DSN 70-m antennas have somewhat different subreflector velocities than those used for the 64-m antennas. The maximum z-rate is not typically used. Actual operational methods will be discussed in Section III.

Figure 1 shows the elevation angles of the three 70-m antennas on the day of Voyager 2 Neptune encounter. The proposed tracking plan at DSS-43 entails normal tracking using conscan and normal subreflector Y-Z focusing until an elevation angle of about 40-43 degrees is reached. The subreflector would then be moved abruptly in Z, fixed in its 60-degree position, and conscan would be turned off. (At the time of the writing of this report, the Voyager 2 radio science plan is to fix the subreflector motion in Z-axis only.) The spacecraft would be tracked in the fixed-subreflector mode up to about 70-degree elevation (covering the period between the two 71K-Ring Earth Occultation events). At an elevation of about 70 degrees, the subreflector would be returned to automatic mode and conscan turned on for the remainder of the pass except for a short interval during Triton occultation.

The structural model of the DSN 70-m antenna surface was developed by JPL's Ground Antenna and Facilities Engineering Section (R. Levy and M. S. Katow, private communication). For reference, the model is designated JRMFL-FX-03J/70M-MAR88, and at this time (August 1988) is the most recent model being used to describe antenna structural deformation as a function of gravity loading. The subreflector controller (SRC) model (P. Lipsius, private communication) used in the calculations here is given by equations describing subreflector motions along the Y (lateral) and Z (axial) directions:

$$Y = -0.0369\,A - 6.4516\,B + 0.0257$$

$$Z = -1.7270\,A - 0.0732\,B - 0.0982$$

where

$A = \sin(45^\circ) - \sin(\mathrm{EL})$

$B = \cos(45^\circ) - \cos(\mathrm{EL})$

EL = elevation angle

These equations are programmed in PROMs in the SRC. Additional SR position offsets are computed and applied in field operation by numerous measurements made to maximize efficiency at a particular elevation angle (D. Girdner and W. Wood, Goldstone Deep Space Communications Complex, private communication). Typically, both best antenna shape and maximum efficiency are obtained at 45-degree elevation, and bias terms (different from SR position offsets) arise from uncontrollable nonzero values occurring in installation of position readouts, etc. All 70-m antennas have identical PROMs in the SRC containing identical constant terms, however operator-applied inputs from the Local Monitor and Control (LMC) console could vary from antenna to antenna as a result of differing local conditions. Errors in panel setting, later structural modification, or special cases may result in changes from the 45-degree optimum position. For the calculations performed here, it is assumed that perfect shape and maximum gain are obtained at 45-degree elevation. For these GTD calculations only, the constants in the above equations describing subreflector position were made equal to zero.

It should be noted that in the GTD computer programs currently used to calculate dual-shaped reflector performance, the description of subreflector and feed relative positions requires special attention. It is important to note that the net subreflector movement in the main reflector coordinate system is a combination of both the quadripod movement and the subreflector movement relative to the quadripod. As the feedhorn is referenced to the subreflector coordinate system, yet remains fixed (to a good approximation) in the main reflector coordinate system, its position relative to the "moving" subreflector coordinate system must also be calculated.

II. Computed Gain Effects

Figure 2 shows the GTD-computed gains for the three subreflector modes of operation: (1) operating normally in automatic mode, (2) Z fixed in its 60-degree elevation position, and (3) Y and Z fixed in their 60-degree elevation positions. The computed gains include only the losses due to aperture illumination, feed and subreflector spillover, phase error, and cross-polarization. Effects that are not included are waveguide and dichroic plate loss, quadripod blockage, VSWR, surface roughness, and several other items. The predicted theoretical operational antenna gain is about 1 dB lower than the values shown in Fig. 2. Table 1 shows all the components going into the design expectation of operational gain (at the peak gain elevation angle of 45 degrees). Note that the design expectation of 74.39 dBi (71.94-percent efficiency) is 0.96 dB below the GTD-calculated value of 75.35 dBi (89.74-percent efficiency). The actual measured antenna efficiencies for the 70-m network are about 68 percent (peak, without atmosphere, at a 45-degree elevation angle), corresponding to an antenna gain of 74.15 dBi. The quarter-dB difference between design expectation and actual performance will be investigated to test the validity of the values presented in Table 1. For this study the absolute values of gain and efficiency are not critical to the phase-effect problem. It is the difference between the normal automatic mode of SR operation and the two fixed-SR modes that gives the effect import for radio science data.

It is seen in Fig. 2 that the Z-fixed SR condition shows less than 0.1-dB loss of gain over the elevation range of 45 to 70 degrees. The actual Z-mispositioning of the subreflector remains small over that elevation angle range, compared to the mispositioning resulting from fixing Y also. For example, at 45-degree elevation, the subreflector is mispositioned 0.259 inches in Z and 1.330 inches in Y, relative to their positions at a 60-degree elevation angle. From previous studies,[1] the loss arising from the Z-mispositioning is predicted to be

$$\Delta G = 2.18(0.259)^2 \text{ dB}$$

$$= 0.146 \text{ dB}$$

This loss is somewhat larger than the 0.1 dB shown in Fig. 2.

For the case of Y and Z fixed, there also exists a mispositioning of the subreflector in Y (at elevation angles differing from 60 degrees), and this mispositioning results in about 1.5 beamwidths of scan at 45-degree elevation. Pointing effects will be discussed later. From the previously quoted study by R. Levy, the gain loss at 45 degrees associated with the 1.330-in. mispositioning of the subreflector in Y is given by

$$\Delta G = 0.28(1.330)^2 \text{ dB}$$

$$= 0.495 \text{ dB}$$

This is almost exactly the difference between the Z-fixed and Y/Z-fixed curves in Fig. 2. It appears then that the R. Levy model may overestimate the effect of the Z-mispositioning of the subreflector. A further comparison of the R. Levy model and the GTD-calculated gain losses should be made.

For preservation of gain, it is seen that fixing the subreflector Z-movement at its 60-degree position has minimal effect over the 45- to 70-degree elevation Neptune encounter period.

III. Computed Phase Effects

Figure 3 shows the far-field phase effect associated with normal SR movement. There is a total of more than 650 degrees of phase change over the elevation range of 5 to 90 degrees. This phase change is due almost entirely to the Z-movement of the subreflector.

A model for the particular curve shown in Fig. 3 is

$$\text{phase} = 814 - 718 \sin(\text{EL})$$

where EL = elevation angle, degrees.

Note that the constant term in the above equation is arbitrary, and could be set to zero. What is important is the phase variation with elevation angle.

The net Z subreflector movement over this range is 1.048 in. (1.504 in. commanded by the SRC and −0.456 in. from quadripod movement) relative to the main reflector vertex, and includes both the effect of the SR movement and the deformation of the quadripod structure. Tests carried out at Goldstone[2] and subsequent GTD calculations (described later in this report) indicate that the effect of Z subreflector

[1] R. Levy, "Gain Losses for Non-Optimal Antenna Subreflector Offsets," JPL IOM 3325-88-009 (internal document), February 5, 1988.

[2] R. Riggs, "Preliminary Report of the Results of the Radio Science Tests Conducted at DSS-14," JPL IOM RLR-88-10 (internal document), May 10, 1988.

movement for a 70-m antenna (K-band feed in the XKR cone) is to change the path length by about 1.76 times the amount of movement. For Y subreflector movement using the same feedhorn, the path length factor was determined to be 0.093. A 1.048-in. net subreflector Z-movement thus gives 1.844 inches of path length change, or about 474 degrees of phase at 8420 MHz. The additional phase change is due to the deformation of the main reflector itself. The frequency signature of this phase change if the SR movement were absolutely smooth and continuous is probably of little consequence for radio science investigations. For an elevation change from 45 to 50 degrees over a time interval of 0.410 hours, the phase change is 42.4 degrees, resulting in a frequency signature of about 0.08 mHz. The actual Y and Z SR movements are made in abrupt steps, resulting in a much higher frequency signature.

Figure 4 shows a comparison among the normal, fixed-Z, and fixed-Y/Z subreflector conditions. Note that it is the fixing of the SR Z-movement that predominantly gives rise to the much reduced phase change. The residual change of phase results from both the quadripod movement and main reflector deformation. These deformations work in opposite directions as far as path length changes are concerned, and hence the net phase change effect is small.

In contrast to the smoothly changing phase effects experienced when both Y and Z subreflector positions are fixed, the actual operational phase changes occur "abruptly" when the subreflector position is changed in small steps. For the 70-m antenna, the subreflector position is updated when an error of more than 0.009 in. is detected in either the Y or Z positions. The subreflector is commanded to move until the position error becomes less than 0.007 in. With overshoot due to motor and gear system inertia, the total movement is thought to be 0.005 to 0.006 in. (K. Nikbakht, private communication). The maximum sustained rate that the subreflector is capable of moving is 1 in./min (0.017 in./sec) in the Y direction, and 3.14 in./min (0.052 in./sec) in the Z direction. The subreflector is not generally operated in this mode, however, as the mechanical stresses are quite large. In actuality, gradual motor acceleration and reduced maximum speed result in the subreflector movements over the 0.005–0.006 in. range occurring in approximately 2 sec. The average rate resulting is thus about 0.003 in./sec, substantially lower than the Y and Z maximum rates. It will be shown in Section V that for the XRO cone on all 70-m antennas, the GTD-computed path length change for Y-movement is 0.0444 times the subreflector movement and for Z-movement is 1.671 times the subreflector movement. (The XRO cone is located at the upper left cone position when looking into the face of the main reflector.) Thus, the average pathlength rates for Y and Z, respectively, are about 0.00013 in./sec and 0.0050 in./sec. For a frequency of 8420 MHz, this results in Y and Z doppler frequency signatures of about 0.093 MHz and 3.6 MHz, respectively, with a probable uncertainty of at least 30 percent.

IV. Computed Pointing Effects

Figure 5 shows the actual antenna beam pointing resulting from the three different subreflector positioning schemes. In the case of the normal automatic SR movement, it is seen that the beam moves upward somewhat faster than the increasing elevation angle. Indeed, from a 45- to 80-degree elevation angle, the beam has moved up an additional 142 millidegrees as a result of the attempt to maintain optimum gain by proper positioning of the subreflector. In order to maintain proper pointing, the applied squint correction is the negative of this beam movement.

It can be seen from Fig. 5 that over the elevation range of 45 to 70 degrees, the Z-fixed subreflector condition results in negligible additional pointing error, to within the resolution of these calculations (1 millidegree). A simple analysis [6], [7] shows that even with the asymmetric off-axis tri-cone structure of the 70-m antennas, the 0.259-in. mispositioning of Z (for the Z-fixed subreflector condition) at 45-degree elevation results in a pointing error of less than 0.5 millidegrees. The reason for this is that Z-errors are just in-out position changes of the subreflector along the main reflector Z-axis. Fixing Y results in a deviation from normal pointing. The squint correction operates according to the Y-position of the subreflector relative to the quadripod structure, not from the net subreflector position, which includes quadripod movement also. It will be shown in Section V that the current (August 1988) squint correction as implemented in the Antenna Controller Subsystem (ACS) does not accurately follow the curve shown in Fig. 5. It has been necessary to employ a systematic error correction table to correct for such discrepancies. For the subreflector to be both Y- and Z-position fixed, the squint correction will be maintained constant over the 45- to 70-degree elevation range, and substantial pointing errors will result. For radio science purposes, it appears that fixing only Z introduces no effect that will seriously compromise the pointing capabilities of the antenna. The systematic pointing error correction developed with the SR in normal automatic mode should then be correct for SR Z-fixed operations.

V. Effects of Lateral and Axial Subreflector Motion at a 45-degree Elevation Angle and Modifications to Existing Squint Correction

A series of GTD calculations was made at 8420 MHz to assess the effects of lateral and axial subreflector motions on gain, phase, and pointing for both the X-band (XRO) and

K-band cones on the 70-m antennas. Looking into the antenna face with the antenna pointing at the horizon (elevation angle equal to 0 degrees), the K-band cone is at the bottom (6-o'clock, 0-degree clock angle) and the X-band cone is at the upper left (10-o'clock, 120-degree clock angle). Table 2 presents the results of these calculations for the X-band cone with the antenna positioned at a 45-degree elevation angle (and hence with a perfect surface). It is seen that for the movements shown, substantial (tenths of a dB) gain changes result. For Y-subreflector movements, small phase changes result, whereas for Z-movements, substantial phase changes occur. From these calculations, dimensionless "K-factors" can be derived linking phase change to subreflector movement (inches of path length change/inches of subreflector movement). Thus phase change (degrees) at any frequency can be determined. For the X-band (XRO) cone at a clock angle of 120 degrees, the values of K determined were:

$$K_y = +0.0444$$

$$K_z = -1.671$$

These are consistent with the propagation sign convention, $\exp(-jkr)$, in the GTD program where increasing path length results in more negative (or decreasing) phase.

For the K-band cone, where Y-movements of the subreflector are directly "toward" or "away" from the cone, a surprising result occurs. Although the subreflector movement is "lateral" in both cases, the value for the K-band cone turns out to be

$$K_y = -0.0878$$

This value is almost exactly double the value (but of opposite sign) for the X-band cone. The K-band K_y and K_z compare well with the experimentally measured values of -0.093 and -1.76, respectively.

For subreflector movements purely lateral (at 90 degrees) to the cone direction, it is found that

$$K_y = 0.00078$$

which is deemed (for the purposes of this report) to be zero. (The nonzero result is undoubtedly due to roundoff error in the calculations.)

It is postulated that the value of K (lateral) is proportional to both the distance of the feed from the main reflector axis and to the component of subreflector movement directly "toward" or "away" from the feed in question. Thus, for a feed located directly at the center of the main reflector, very small subreflector movements would result in negligible phase changes. Figure 6 shows the lateral K-factor as a function of clock angle for cones located on three subreflector focus circles of varying diameter. The diameters increase in size from R_1 to R_3 ($R_1 = 0.25R_2$, $R_2 = 0.5R_3$). The curve with maximum amplitude (R_3) is the K-factor curve for cones located along the 70-m antenna subreflector focus circle (radius equal to 108.03 cm). Phase effects determined from these curves may assist in future positioning of outrigger horns or additional cones on the existing 70-m antennas.

The existing 70-meter squint correction, as implemented in the Antenna Controller Subsystem (ACS), uses the subreflector Y-position multiplied by a constant (0.0342 degrees/inch of SR Y-axis position) to calculate the amount of correction to the elevation angle needed to maintain the beam on target during a track. The existing constant as determined in [3] was verified in this study using similar computational methods. However, this constant predicts the amount of beam movement due to subreflector motion only; it does not account for additional beam movement arising from quadripod motion and main reflector deformation as the elevation angle changes. It is found from this study that another constant more appropriately predicts beam movement, using the SR Y-position as an *indicator* of total antenna "condition," rather than as the entire cause of beam mispointing.

Figure 7 shows the actual GTD-calculated beam-peak offset as a function of normal SR Y-position. It is seen that at a 90-degree elevation angle, more than 30 millidegrees of pointing error exist. This is larger than the 70-m 3-dB beamwidth! From this curve a new squint correction constant may be found:

$$K_{squint} = 0.04145 \text{ degrees/inch}$$

where the SRC Y-position (inches) is used as the indicator of squint correction needed. This new constant could be installed in the ACS as a replacement for the existing constant. (If this is implemented, new systematic pointing-error correction tables would have to be developed.)

It should be noted that the use of this new constant during normal subreflector focusing tests will now result in mispointing of the beam, as the original squint constant (0.0342) was really the correct one to use for conditions of subreflector movement only—it was not appropriate for normal tracking operations.

A new squint correction may be generated from the current squint correction plus a correction as a function of elevation angle (Fig. 8). The new squint correction as a function of SR Y-position (Y_{sr}) and elevation angle (EL) is given by

$$\text{SQUINT}(Y_{sr}, \text{EL}) = 0.0342\,(Y_{sr}) - 0.0329 + 0.0468\cos(\text{EL})$$

If this new squint correction is implemented, the result will be a "hybrid" squint correction model using both the old constant as a function of SR position and an additional pointing correction as a function of elevation angle. The additional pointing correction will also be generated in the ACS.

VI. Conclusion

The extensive series of calculations described here indicate several methods by which the Voyager Radio Science team might avoid the confusing effects of rapidly changing phase in the August 1989 Neptune encounter data. It appears that fixing the subreflector Z-motion over the elevation range of 45 to 70 degrees adequately solves this problem without significant gain degradation. A useful result of the gain, phase, and pointing determinations is a possible modification to the existing squint correction used on the 70-m antennas. This modification substantially changes the value of the "squint constant" in the ACS and appears to more accurately model existing antenna pointing as a function of subreflector position during normal tracking operations.

Acknowledgment

The authors wish to acknowledge the assistance of R. L. Riggs of the TDA Engineering Office. His technical guidance has aided in making this study of immediate value to the Deep Space Network and the Voyager Project.

References

[1] S. D. Slobin and W. A. Imbriale, "DSS-43 Antenna Gain Analysis for Voyager Uranus Encounter: 8.45-GHz Radio Science Data Correction," *TDA Progress Report 42-90*, vol. April–June 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 127–135, August 15, 1987.

[2] C. N. Guiar and L. W. Duff, "64-M Antenna Automatic Subreflector Focusing Controller," *TDA Progress Report 42-78*, vol. April–June 1984, Jet Propulsion Laboratory, Pasadena, California, pp. 73–78, August 15, 1984.

[3] J. M. Schredder, "Seventy-Meter Antenna Performance Predictions: GTD Analysis Compared With Traditional Ray-Tracing Methods," *TDA Progress Report 42-92*, vol. October–December 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 166–174, February 15, 1988.

[4] A. G. Cha, "Phase and Frequency Stability of Cassegrainian Antennas," *Radio Science*, vol. 22, no. 1, pp. 156–166, January–February 1987.

[5] T. Y. Otoshi and W. V. T. Rusch, "Multipath Effects on the Time Delay of Microwave Cassegrain Antennas," *DSN Progress Report 42-50*, Jet Propulsion Laboratory, Pasadena, California, pp. 52–55, January–February 1979.

[6] A. M. Isber, "Obtaining Beam-Pointing Accuracy with Cassegrain Antennas," *Microwaves*, vol. 6, pp. 40–44, August 1967.

[7] Y. T. Lo, "On the Beam Deviation Factor of a Parabolic Reflector," *IRE Trans. Antennas and Propagat.*, vol. AP-8, pp. 347-349, May 1960.

Table 1. Design expectations for 70-m antenna with stovepipe feedhorn at 8420 MHz and 45-degree elevation angle

Item	Loss, dB	Net gain, dBi
100% area efficiency		75.82
GTD-included losses illumination amplitude illumination phase forward and rear spillover subreflector blockage $m \neq 1$ modes cross-polarization	−0.47	75.35
Waveguide loss	−0.07	
Dichroic plate loss	−0.035	
VSWR	−0.039	
Quadripod blockage	−0.454	
Antenna surfaces (0.7-mm rms) main reflector panel mfg. main reflector panel setting subreflector surface	−0.192	
Stovepipe feed compromise	−0.11	
Imperfect focus alignment	−0.05	
Panel gaps	−0.01	74.39
	(= 71.94% efficiency)	

Table 2. Effects of lateral and axial subreflector movement for X-band cone (clock angle = 120 degrees)

Displacements		GTD-computed gain, dBi at 8420 MHz	GTD-computed phase, deg at 8420 MHz
Y, inches	Z, inches		
+1.0	0	75.07	119.6
+0.5	0	75.28	114.2
0.0	0	75.35	108.5
−0.5	0	75.28	102.7
−1.0	0	75.07	97.0
0	+0.30	75.24	−20
0	+0.15	75.35	44
0	0.00	75.35	108.5
0	−0.15	75.26	173
0	−0.30	75.06	237

Results:

$K_y = +0.0444$

$K_z = -1.671$

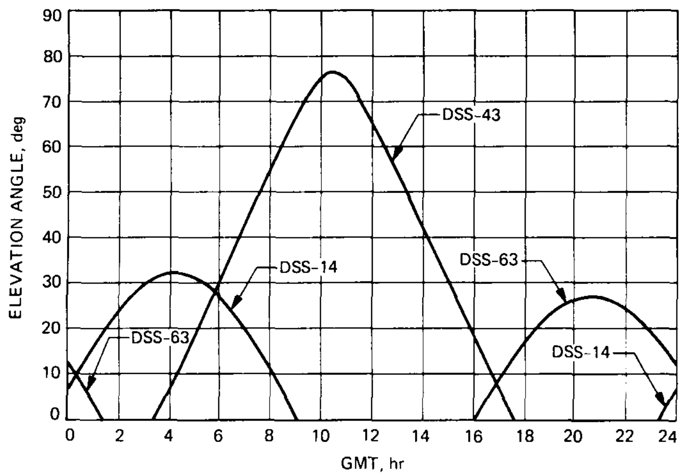

Fig. 1. Antenna elevation angles at Neptune Encounter, August 25, 1989, Earth-receive time.

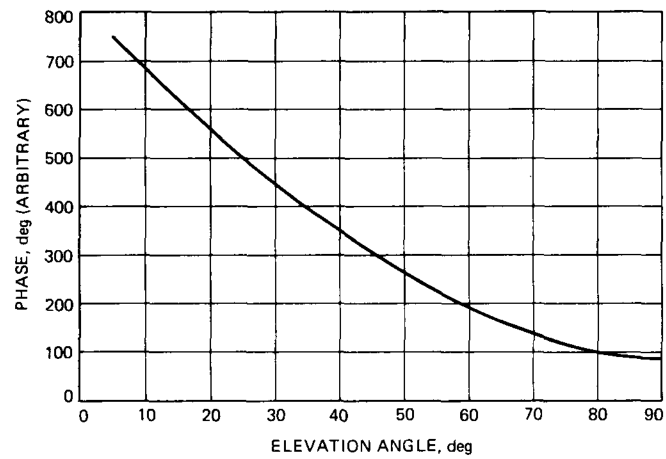

Fig. 3. 70-m antenna GTD-computed phase versus elevation angle, 8420 MHz, SR normal operation, arbitrary phase values.

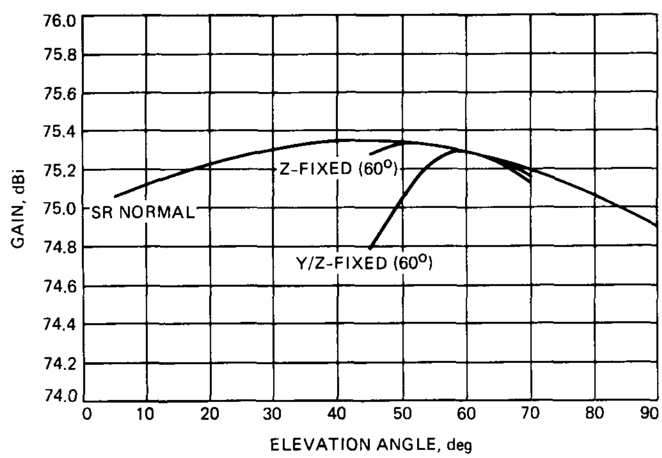

Fig. 2. 70-m antenna GTD-computed gain versus elevation angle, 8420 MHz, with three different subreflector configurations.

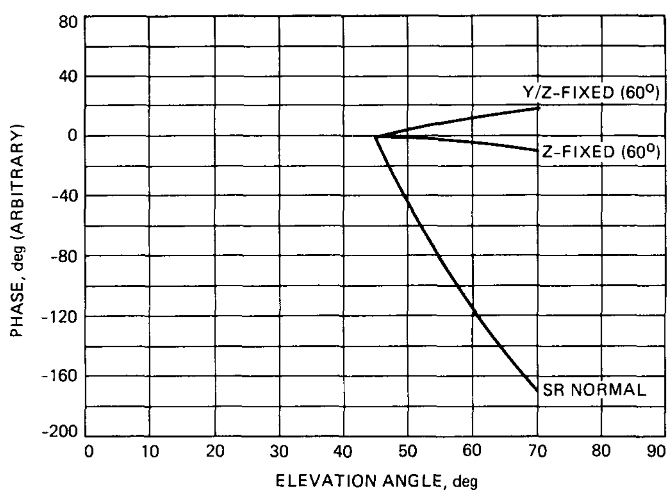

Fig. 4. 70-m antenna GTD-computed phase versus elevation angle, 8420 MHz, for three different subreflector configurations.

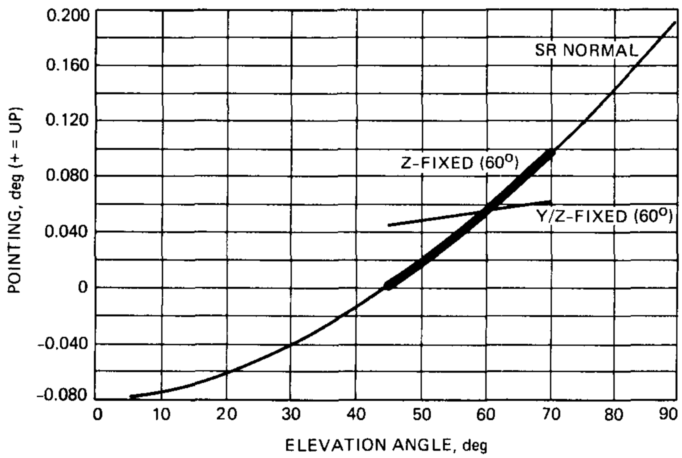

Fig. 5. 70-m antenna GTD-computed pointing versus elevation angle, 8420 MHz, for three different subreflector configurations.

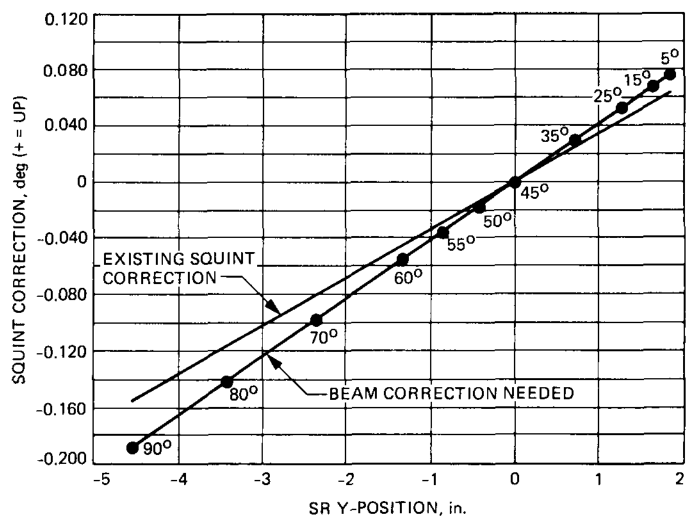

Fig. 7. 70-m antenna squint correction versus SR Y-position, existing squint correction and needed beam correction, elevation angle indicated.

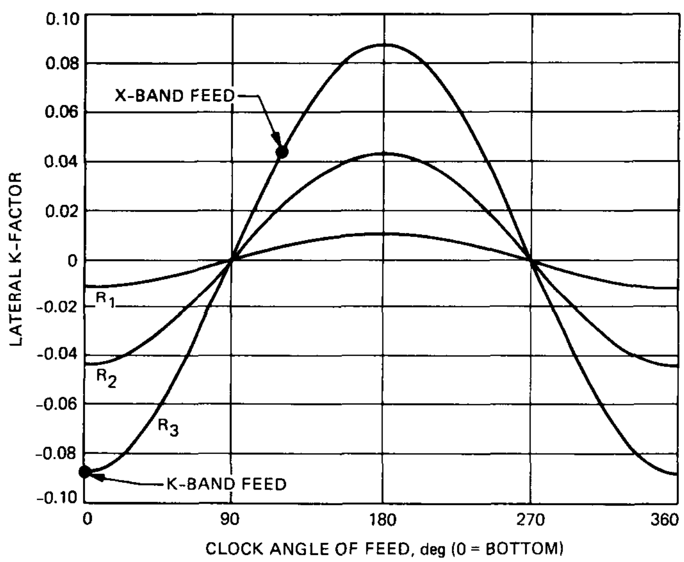

Fig. 6. Subreflector lateral movement K-factor as a function of feed clock-angle and radial distance from 70-m antenna main reflector axis.

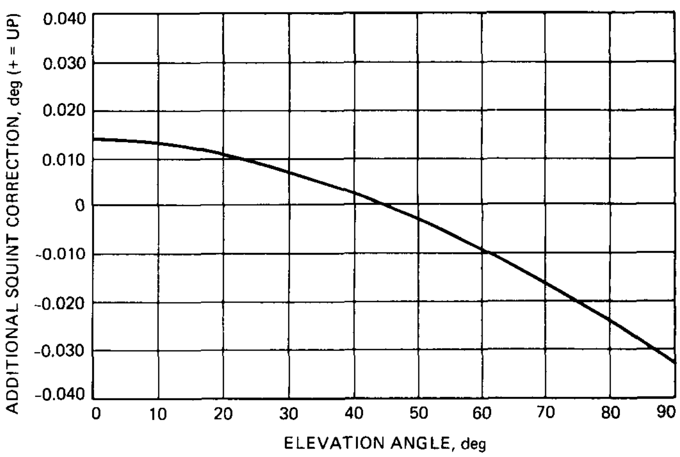

Fig. 8. 70-m antenna additional squint correction needed versus elevation angle.