NATIONAL RADIO ASTRONOMY OBSERVATORY
GREEN BANK, WEST VIRGINIA

ENGINEERING DIVISION INTERNAL REPORT NO. 105
(TUCSON OPERATIONS INTERNAL REPORT NO. 1)

POINTING CHARACTERISTICS OF THE 36-FOOT TELESCOPE

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FEBRUARY 1976

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I. INTRODUCTION

A basic requirement for radio astronomical observations with high spatial resolution is precise pointing of the telescope beam. That is, the angular positioning control system should have a resolution and a repeatability that is a small fraction of the antenna half power beamwidth. For convenience and efficiency the pointing should be not only precise, but also accurate in an absolute sense. Most optical telescope mounts are very precise, but usually little effort is made to achieve accurate absolute pointing. Because of the fact that large area detectors are used in the focal plane, many sources in principle are visible simultaneously, and guiding corrections are easily applied. The only requirement is that the absolute pointing be sufficiently accurate to insure that the desired object is somewhere in the wide field of view. Radio telescopes in current use, however, have only point detectors in the focal plane and thus have a very restricted field of view (the diffraction beam). This limitation, coupled with the relatively small number of intense radio sources, prompts the need for a more accurate (although generally less precise) position control system than used for optical telescopes.

The NRAO 36-foot diameter reflector antenna on Kitt Peak is routinely used for radio astronomical observations at wavelengths between 1.3 cm and 1.3 mm. Because of random surface errors in the reflector, the telescope is not diffraction limited at all wavelengths, and the half power beamwidth is nearly constant at about 1 minute of arc for 1.3 mm < λ < 2.6 mm. A pointing error of 1/10 the half power beamwidth (6" for the 36-foot telescope at high frequencies) results in a 3 % gain reduction. This criterion is commonly used as a guideline for the maximum permissible pointing error for precise radiometry. To my knowledge no existing telescope of any type meets this specification: ± 6" peak absolute pointing error over the entire visible sky. The existing control system for pointing the 36-foot telescope is capable of about 6" RMS (∿ ± 15" peak), which is as good as any other telescope in the world, but still worse (by a factor of about 2.5) than the ideal criterion.

The purposes of this report are:

(1) to describe the general pointing characteristics of the 36-foot telescope,
(2) to analyze both the repeatable and nonrepeatable pointing errors, and
(3) to make recommendations for future study and for modifications and additions to the present control system.

A previous report by J. Schraml (1969) outlined a method of determining pointing parameters for the 36-foot telescope. This basic method is still in use with only minor modifications. In this report I will summarize the results of all pointing tests made from March, 1970 up to February, 1976. The data from 1970 - 1972 were taken by E. K. Conklin.

II. FACTORS AFFECTING POINTING

The second chapter of this report deals in detail with each of the factors which are known to significantly affect the absolute pointing accuracy of the 36-foot telescope.

A. COMPUTER CORRECTIONS

The error signals in the telescope azimuth and elevation servo control loops are generated in the on-line PDP-11/40 computer by comparing the actual encoder readings with the commanded coordinates. The commanded position is determined by adding the pointing corrections to the calculated source position. The pointing corrections are computed according to the following equations:

$$\begin{aligned}\Delta A &\equiv A(\text{indicated}) - A(\text{true})\\ &= A_{off} + \frac{c + c' \sin(h) + i_A \sin(h) \sin(A-e_A)}{\cos(h)}\\ &\quad + \frac{\text{Azimuth Thumbwheel Offset}}{\cos(h)} \qquad (1)\end{aligned}$$

$$\begin{aligned}\Delta h &\equiv h(\text{indicated}) - h(\text{true})\\ &= h_{off} + r \cot(h) + b \cos(h) + i_h \cos(A-e_h)\\ &\quad + \text{Elevation Thumbwheel Offset} \qquad (2)\end{aligned}$$

where ΔA = Azimuth pointing correction
Δh = Elevation pointing correction
A = True source azimuth
h = True source elevation
A_{off} = Azimuth encoder offset
h_{off} = Elevation encoder offset
c = Collimation error of electrical axis and telescope elevation axis
c' = Collimation error of telescope azimuth and elevation axes

r = Refraction constant
b = Telescope gravitational flexure constant
i_A, i_h = Inclination of the telescope azimuth axis from the true vertical
e_A, e_h = Azimuth toward which the telescope azimuth axis is inclined

These equations correct for telescope mount eccentricities and misalignments to first order; they are derived in Appendix I of Schraml's original report (Schraml 1969).

A large amount of pointing data has been taken at 3.5 mm wavelength since 1969. The basic procedure for determining the constants in the pointing correction equations is as follows:

(1) A set of pointing constants known to be reasonably good is entered into the on-line computer program to correct gross pointing errors.

(2) Many five-point observations of various radio sources are made over a wide range of azimuth and elevation angles. The sources must be relatively intense, be of angular size much smaller than the HPBW of the 36-foot telescope (78" at 85 GHz), and have a well determined absolute sky position. Most observations were of planets, although some quasars and HII regions were also observed to get more complete sky coverage.

(3) The telescope encoder readings and the residual pointing errors are recorded for each five point observation.

(4) Using an off-line computer (the CDC 6400 operated by Kitt Peak National Observatory in Tucson) the

pointing corrections used in making the five-point measurements are recalculated and added to the residual errors to determine the total corrections as a function of the source position.

(5) Using the off-line computer Equations 1 and 2 are fit to the total pointing corrections by the method of least squares, and the constants A_{off}, h_{off}, c, c', r, b, i_A, i_h, e_A, and e_h are determined.

(6) The newly determined pointing constants are entered into the on-line computer program for future observations.

Table I summarizes the 3.5 mm radiometric pointing data taken between March 1970 and November 1975. Values are given for the 10 pointing constants determined from each of the 18 data sets. Table II lists the RMS residual errors of each data set using both the previous and the newly determined pointing parameters.

Figure 1 is a histogram plot of the residual pointing errors after fitting the pointing parameters. These data were taken during four separate runs in 1975 with the cooled Cassegrain receiver at 3.5 mm wavelength. Both the azimuth and elevation error plots are roughly gaussian in shape, each with a standard deviation of about 4". The gaussian shaped plots indicate that systematic (non-random) pointing effects are small compared to random errors. This is graphically shown in the next series of scatter plots. Figures 2 and 3 show the remaining azimuth angle (horizontal) errors as functions of the source azimuth and elevation, respectively. Figures 4 and 5 display the elevation (vertical) pointing residuals as functions of source azimuth and elevation, respectively. Careful inspection of these plots also fails to uncover any significant systematic errors. From this result I conclude

TABLE I

3.5 MM POINTING DATA SUMMARY

DATA SET	DATE	NOTES	RECEIVER CODE NUMBER	NUMBER OF DATA POINTS	A_{off} (':")	h_{off} (':")	c (")	c' (")	c + c' (")	r (")	b (")	i_A (")	i_h (")	e_A (°)	e_h (°)
1	3/1970		12	117	-17:42	+10:41	+18	+11	+29	46	-53	29	36	288	284
2	9/1970		12	23	-17:34	+10:51	+10	+ 7	+17	49	-70	27	36	288	290
3	2/1971	1	12	337	-17:34	+11:00	+ 4	+14	+18	51	-86	23	23	305	290
4	9/1971	2	12	84	-19:01	+10:55	+62	+19	+81	45	-65	11	29	289	301
5	10/1971		12	39	-19:32	+10:58	+114	-22	+92	54	-79	14	26	304	310
6	11/1971		12	101	-19:36	+10:56	+129	-37	+92	47	-68	21	29	306	301
7	1/1972		12	73	-19:32	+11:00	+110	-18	+92	46	-74	12	26	297	303
8	2/1972		12	33	-19:25	+10:57	+ 99	- 2	+97	39	-55	28	27	263	305
9	9/1972	3,4	12	57	-14:56	+10:51	-158	+ 9	-149	56	-98	10	33	302	307
10	9/1973	4	12	90	-13:56	+ 6:48	+168	-22	+146	46	-88	24	39	310	302
11	4/1974		12	25	-14:07	+ 6:15	+168	-34	+104	47	-79	8	26	304	284
12	8/1974	4,5,6	12	155	-13:17	+ 1:15	+ 72	+ 3	+ 75	50	-88	20	12	54	3
13	9/1974	7,8	18	48	-12:59	+ 2:01	+102	+36	+138	44	-56	14	26	314	306
14	12/1974	8,9	18	105	-13:30	+ 1:22	+170	+18	+188	44	-62	18	25	323	308
15	3/1975	8	20	20	-14:41	- 0:44	- 22	-60	- 88	40	-35	16	25	332	302
16	5/1975	8	20	34	-13:32	- 1:05	-127	+42	- 85	26	-30	16	27	305	314
17	7/1975	8	20	57	-14:21	- 0:49	- 50	-28	- 78	48	-26	15	21	311	309
18	11/1975	3,5,6,8	20	77	+ 0:14	- 1:03	+384	+11	+395	43	-79	20	19	300	302

NOTES

1 Feed leg accident occurred 1/29/71
2 New azimuth feed legs installed
3 Azimuth encoder replaced or realigned
4 Elevation encoder replaced or realigned
5 Changed telescope coordinates
6 Aligned focus and polarization drive system
7 Unweighted Cassegrain receiver box
8 Subreflector position +2.00'
9 Weighted Cassegrain receiver box

RECEIVER CODE NUMBER	DESCRIPTION
12	85 GHz Prime focus radiometer
18	85 GHz Uncooled Cassegrain radiometer
20	85 GHz Cooled Cassegrain radiometer with offset feed

TABLE II

RESIDUAL POINTING ERRORS

DATA SET	RMS HORIZONTAL POINTING ERROR (")	RMS VERTICAL POINTING ERROR (")	RMS TOTAL POINTING ERROR (")	UNCORRECTED RMS TOTAL POINTING ERROR (")	LATITUDE ERROR ± 1σ (")	LONGITUDE ERROR ± 1σ (SECONDS)
1	4.4	5.9	7.4	7.8	-0.2 ± 0.7	+0.30 ± 0.05
2	2.3	4.0	4.6	7.4	+2.0 ± 0.9	+0.31 ± 0.05
3	7.5	9.0	11.7	12.7	-2.8 ± 0.6	+0.12 ± 0.04
4	6.8	6.2	9.2	21.7	+5.9 ± 0.9	+0.59 ± 0.11
5	6.8	4.4	8.1	13.1	+4.3 ± 1.2	+0.30 ± 0.28
6	6.9	6.1	9.2	23.2	+1.6 ± 1.7	+0.32 ± 0.12
7	7.6	7.3	10.5	14.9	+4.2 ± 1.2	+0.44 ± 0.07
8	8.2	4.4	9.3	14.7	+9.6 ± 1.5	-0.24 ± 0.15
9	2.8	6.6	7.2	32.5	+7.5 ± 0.9	+0.71 ± 0.07
10	4.9	6.6	8.2	18.0	+2.9 ± 0.9	+0.58 ± 0.05
11	3.4	8.2	8.9	14.6	+0.9 ± 3.0	+0.74 ± 0.20
12	7.3	8.2	11.0	27.8	-0.1 ± 0.8	+0.62 ± 0.05
13	3.8	4.0	5.5	14.6	+3.1 ± 0.7	+0.45 ± 0.05
14	3.4	5.4	6.4	14.0	+0.5 ± 0.5	+0.35 ± 0.03
15	4.4	4.5	6.3	8.4	-0.4 ± 1.5	+0.53 ± 0.11
16	3.3	7.7	8.4	10.8	+4.7 ± 1.6	+0.24 ± 0.12
17	5.1	5.8	7.7	9.2	+1.9 ± 1.2	+0.22 ± 0.09
18	3.9	3.4	5.2	18.9	+0.0 ± 0.5	-0.05 ± 0.03

FIGURE 1

AZIMUTH AND ELEVATION POINTING ERROR DISTRIBUTIONS

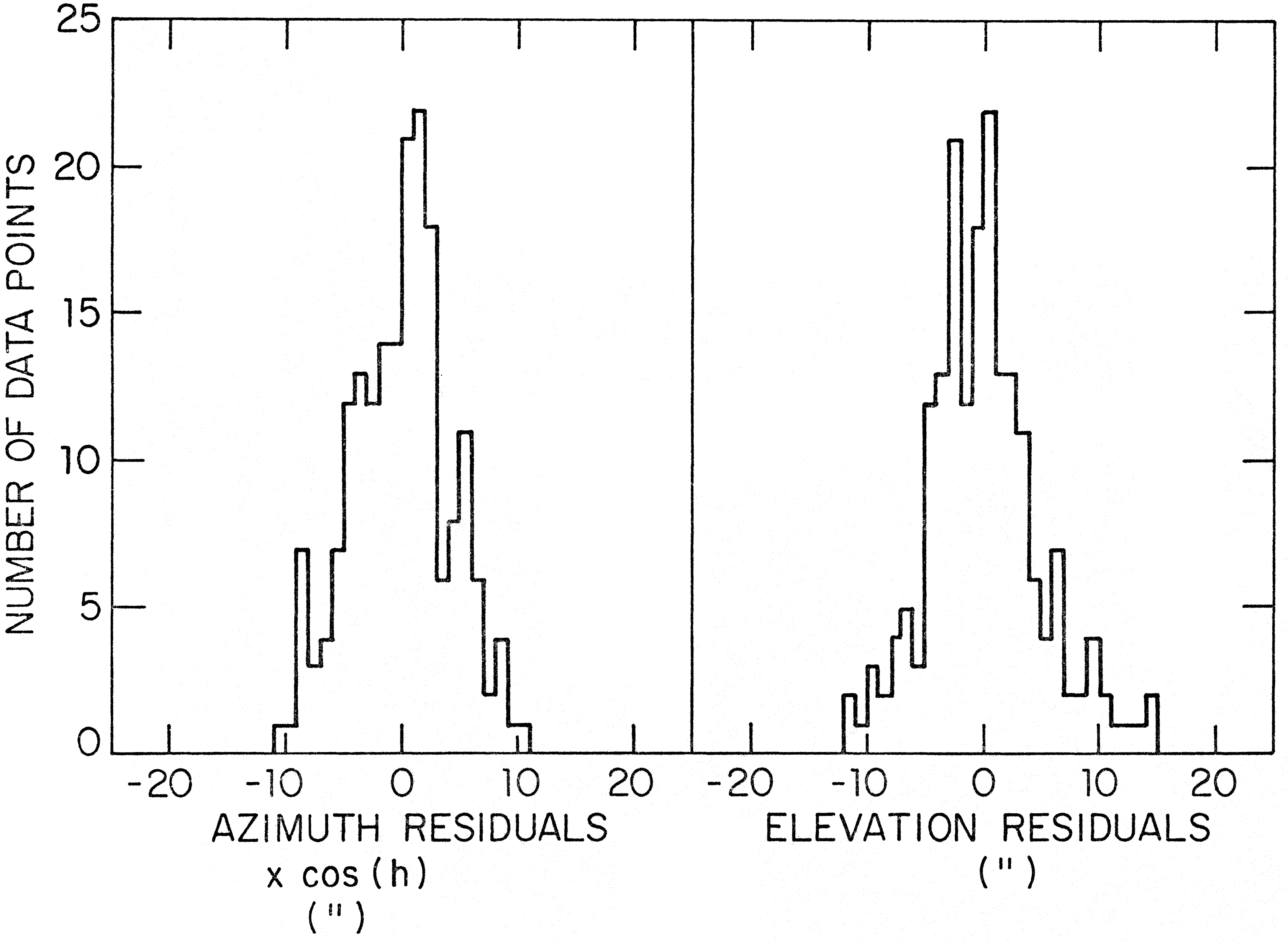


FIGURE 2

AZIMUTH POINTING RESIDUALS vs. TELESCOPE AZIMUTH

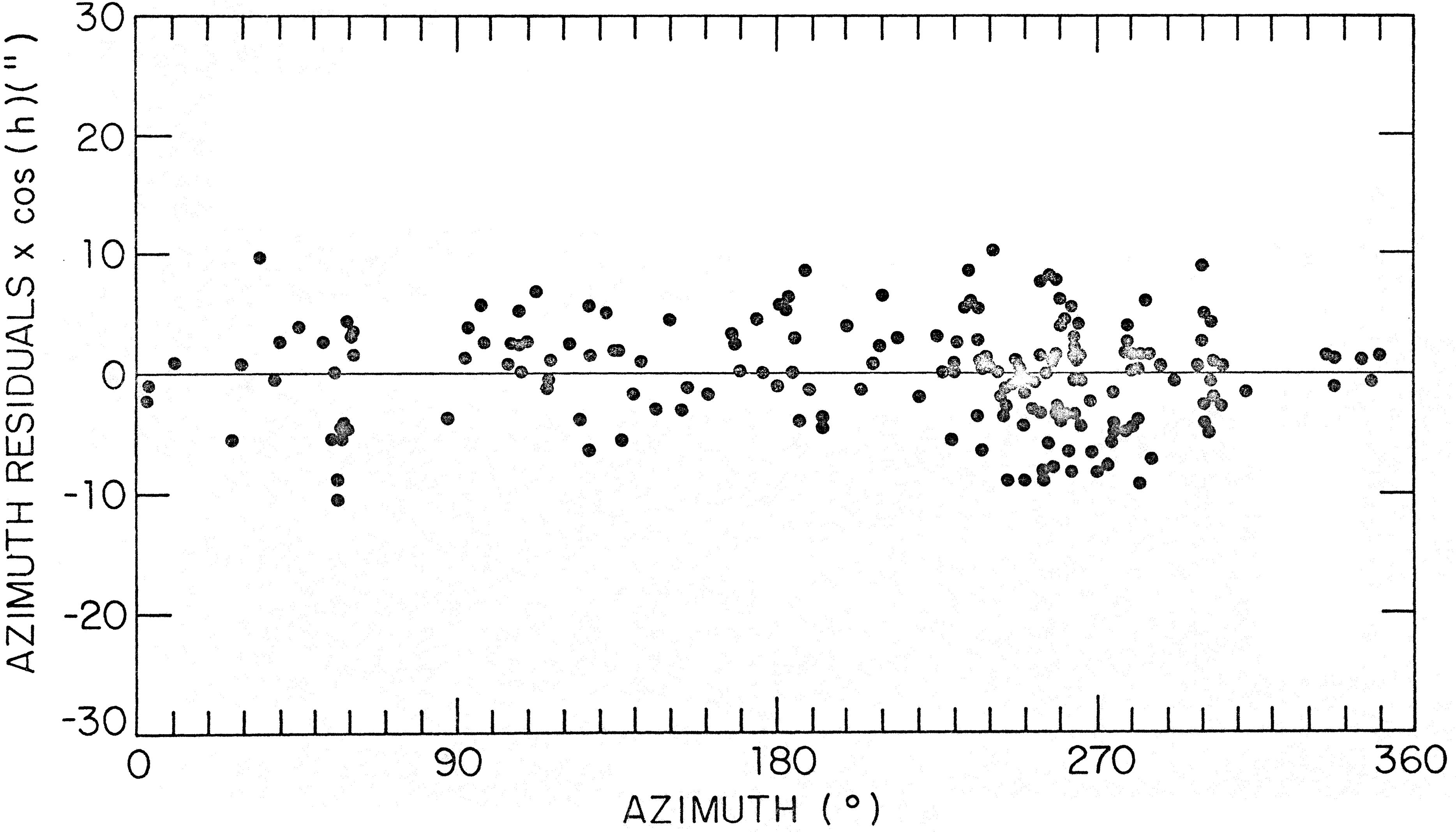


FIGURE 3

AZIMUTH POINTING RESIDUALS vs. TELESCOPE ELEVATION

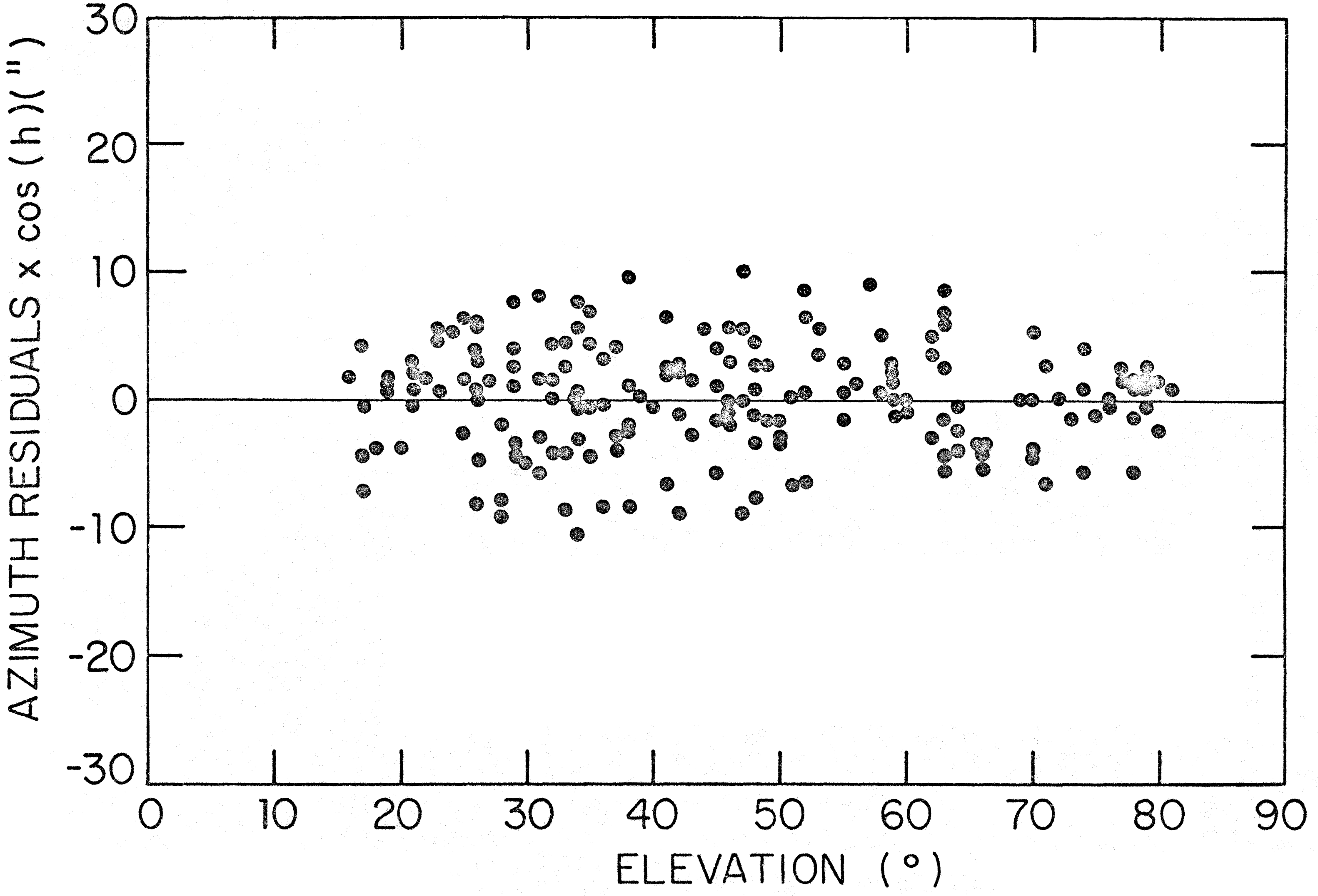


FIGURE 4

ELEVATION POINTING RESIDUALS vs. TELESCOPE AZIMUTH

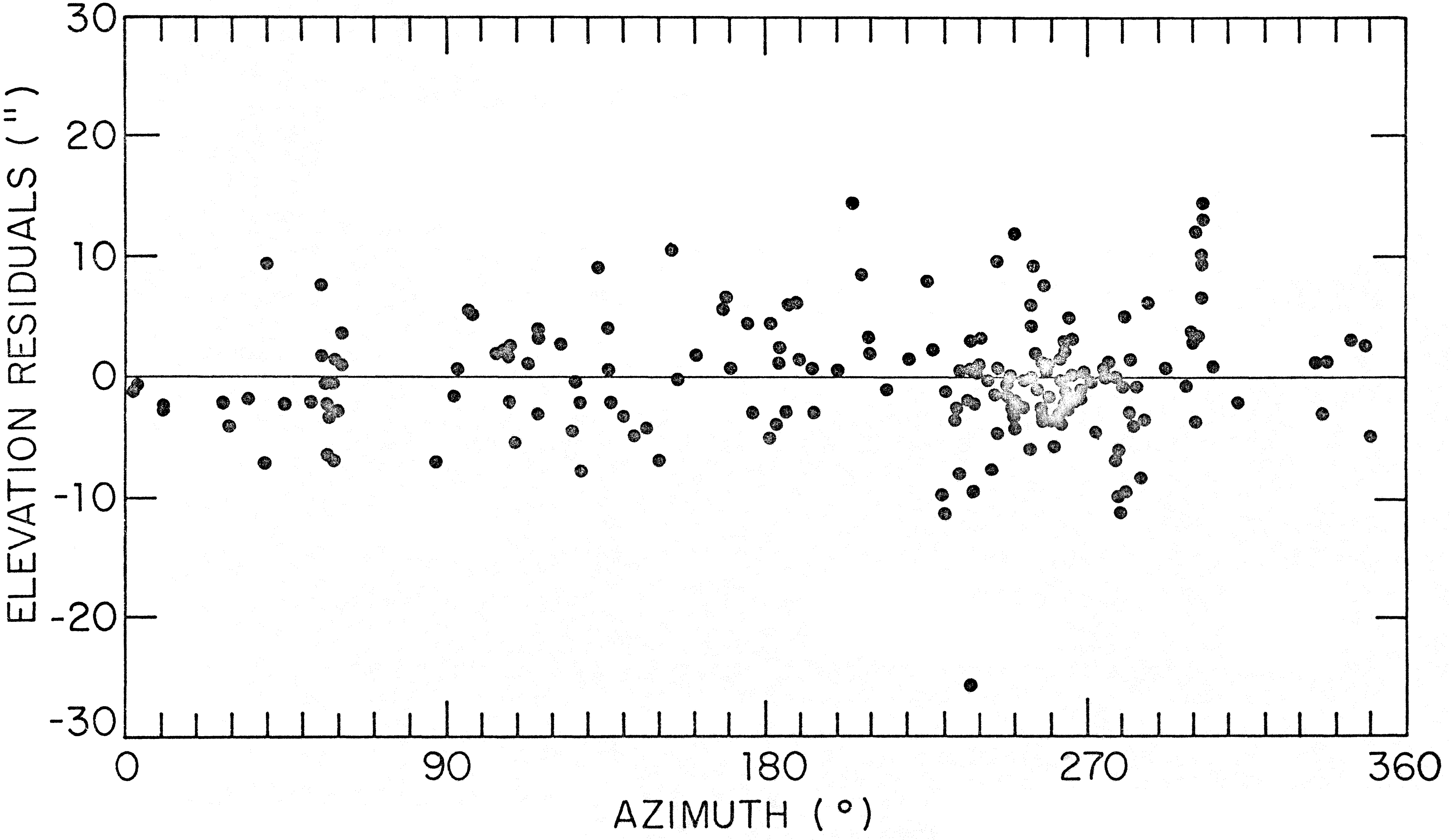
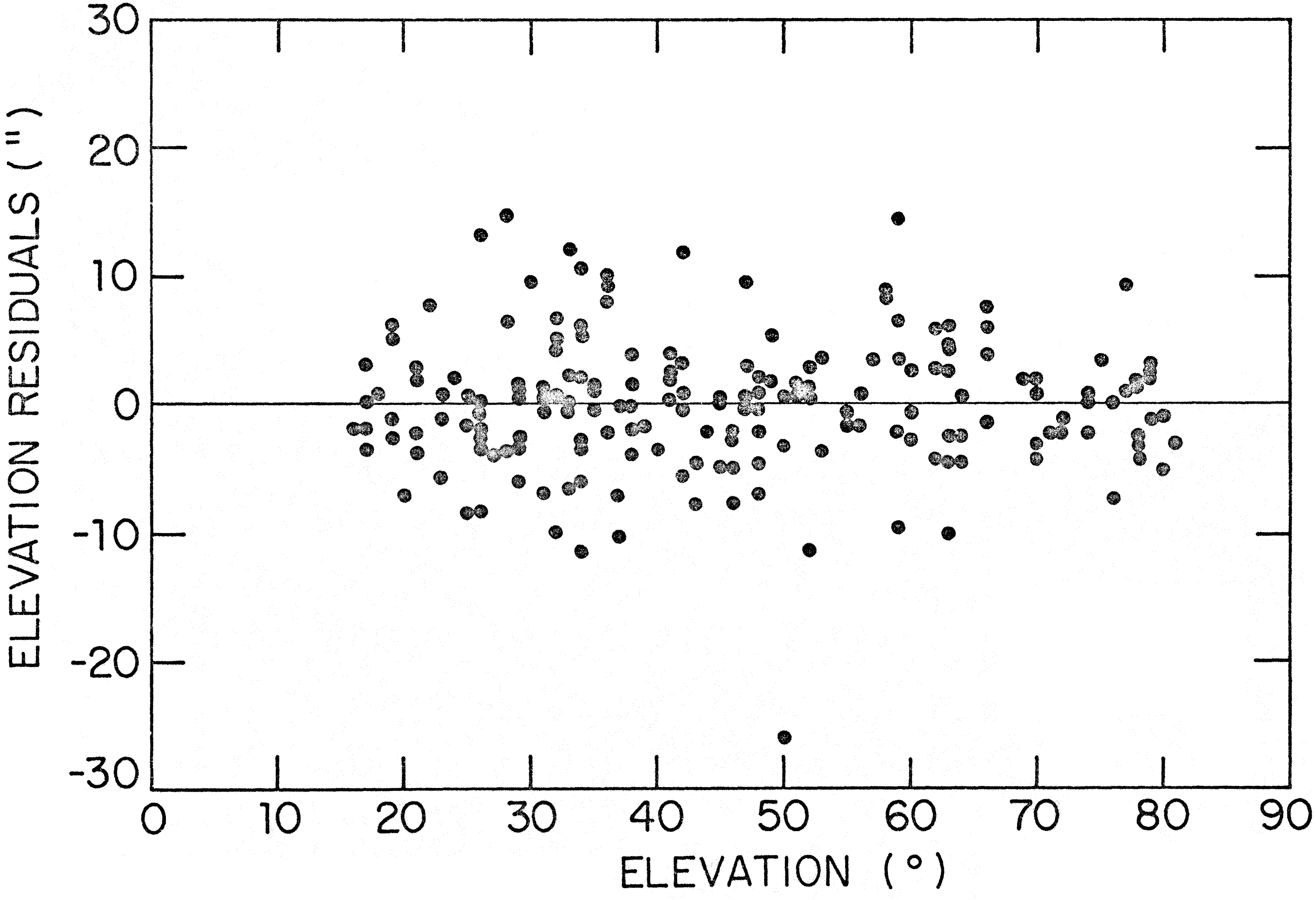


FIGURE 5

ELEVATION POINTING RESIDUALS vs. TELESCOPE ELEVATION



that the basic form of the on-line pointing corrections (i.e., Equations 1 and 2) is satisfactory and requires no revision. That is not to say, however, that systematic errors are never present. Table I indicates that some of the parameters appear to vary significantly during periods of several months. As shown in Table II the uncorrected RMS total pointing error is always significantly larger than the corrected RMS pointing error. This result indicates that some of the parameters (particularly r, b, i_A, i_h, e_A, and e_h) are functions of time (or temperature). When a new set of parameters is entered into the on-line computer, the RMS total pointing accuracy is about 6". After several months, however, the RMS increases to 10" and in some cases even to 20" as the result of variations in the pointing "constants".

I conclude that on a short time scale ($\sim$ 1 week) the residual pointing error of the 36-foot telescope is dominated by random effects. On a longer time scale ($\sim$ several months), however, changes occur which produce large errors. One goal of this pointing study is obviously to find means to <u>prevent</u> or to <u>predict</u> these variations. Several proposed methods of prevention and prediction are discussed in the following sections of this chapter.

B. TELESCOPE COORDINATES

In the pointing offset Equations 1 and 2 the tilt of the telescope azimuth axis may be determined independently by both the azimuth and elevation pointing measurements. This leads to two independent estimates of the inclination angle; i_h and i_A are independently determined by the elevation and azimuth pointing data, respectively. Similarly, the azimuth angle toward which the axis is inclined is estimated twice by e_h and e_A from the elevation and azimuth data, respectively. The reason the two equations are allowed to have different values of i and e is to search for possible systematic errors in the assumed telescope coordinates. The latitude correction which must be added to the assumed latitude in order to obtain the true geocentric telescope latitude is

$$\Delta \text{ Latitude} = \frac{i_h \cos(e_h) - i_A \cos(e_A)}{2} \qquad (3)$$

Similarly the longitude correction is given by

$$\Delta \text{ Longitude} = \frac{i_h \sin(e_h) - i_A \sin(e_A)}{2 \cos(\emptyset)} \qquad (4)$$

where $\emptyset$ is the true telescope geocentric latitude. These residual systematic telescope position errors are given in Table II for each set of radio pointing data.

The geodetically determined telescope coordinates used in the on-line pointing program prior to August 1974 are

Latitude:	N	31°	57'	11"
Longitude:	W	7^h	26^m	27.20^s

In 1969 Schraml deduced systematic errors of N 3.2" ± 0.7" in latitude and W $0.21^s \pm 0.08^s$ in longitude. The average position errors from the data in Table II from March 1970 until April 1974 are N 3.3" ± 1.1" in latitude and W 0.38^{s} ± 0.09^{s} in longitude, in reasonable agreement with the earlier results. In August 1974 an error was found in the geodetic calculations (Smith 1974) and the assumed telescope coordinates were changed to

Latitude: N 31^{o} 57' 12"
Longitude: W 7^{h} 26^{m} 27.41^{s}

Pointing data from August 1974 to July 1975 indicate additional residual systematic errors of N 1.6" ± 0.8" in latitude and W 0.40^{s} ± 0.07^{s} in longitude. The true telescope coordinates determined by the average of the 1969 data and the 1970-4 data are

Latitude: N 31^{o} 57' 14.2" ± 0.6"
Longitude: W 7^{h} 26^{m} 27.49^{s} ± 0.06^{s}

Using the 1974-5 data alone the true geocentric telescope coordinates are

Latitude: N 31^{o} 57' 13.6" ± 0.8"
Longitude: W 7^{h} 26^{m} 27.81^{s} ± 0.07^{s}

The averages of both sets of true geocentric telescope coordinates are

Latitude: N 31^{o} 57' 14.0" ± 0.5"
Longitude: W 7^{h} 26^{m} 27.63^{s} ± 0.05^{s}

and this position was adopted in November 1975 for data set number 18. As shown in Table II, the residual telescope coordinate errors are now essentially zero indicating that the assumed coordinates are now correct.

At the elevation of the 36-foot telescope on Kitt Peak (1920 m above sea level and 6374 km from the center of the earth), one arc second corresponds to a surface distance of 31 m. The total precision with which we have located the telescope using radio pointing data is about 1.2" RMS or 37 m. This is remarkable in view of the fact that the antenna HPBW for the 3.5 mm pointing data is about 78".

C. TIME

A systematic timekeeping error cannot be distinguished from an error in telescope longitude since they both affect the calculation of the source local hour angle. The master UTC (Coordinated Universal Time) clock used at the 36-foot telescope is slaved to a crystal standard which is adjusted to run within a few milliseconds per week with the shortwave time signals broadcast from WWV in Fort Collins, Colorado. The UTC clock is started about 4 ms prior to the reception of the appropriate "tick" from WWV to allow for propagation delay. The overall accuracy of the UTC clock is maintained to better than ± 10 ms. A correction is necessary before the sidereal time can be computed; UTC must first be converted to UT1, which is directly related to the rotation of the earth. This correction factor is DUT1 where

$$\mathrm{DUT1} \equiv \mathrm{UT1} - \mathrm{UTC} \qquad (5)$$

DUT1 varies between ± 0.7 seconds and is discontinuous when leap seconds are introduced into UTC. Precise values of extrapolated measurements by the U.S. Naval Observatory (1976) are available and are inserted into the on-line computer clock program approximately once per week. The accuracy of our DUT1 correction is about ± 20 ms. The overall UT1 clock error is thus less than ± 30 ms. The computer calculation of local apparent sidereal time from UT1 is accurate to about 50 ms. The total error in sidereal time is therefore less than ± 80 ms which corresponds to less than ± 1.2" on the celestial equator. In addition there are computer truncation errors of at most 2" in the source coordinate transformations. The total error in the computed true source azimuth and elevation (assuming the telescope coordinates are correct) is thus less than about 3". This is barely adequate for the 36-foot telescope at present, and more precise computer calculations will be a necessity in order to achieve the desired pointing accuracy for the proposed 25-meter telescope.

D. REFRACTION

The optical refraction correction R to be added to the true source elevation h is given to first order by

$$R = A \cot(h) \tag{6}$$

where A is a constant. According to McNally (1974)

$$A = \frac{P/760}{1 + T/273}\ 60.4'' \tag{7}$$

where P is the surface atmospheric pressure in mm Hg and T is the surface temperature in °C. Typical values for Kitt Peak are 620 mm Hg and 10° C; the corresponding value of A is 47.5". The optical constant measured by Schraml (1969) with the 12-inch optical finder telescope on the 36-foot antenna is 47.9" ± 0.6", in excellent agreement with the calculated value. The weighted average of the 3.5 mm refraction constant r from Table I is 47.5"± 1.6". Thus at 85 GHz the average radio refraction is identical within the measurement errors to that observed optically. Davis and Cogdell (1970) have investigated the possible dependences of mm wavelength refraction on the presence of water vapor and on the frequency of observation. However, more data are needed before definite conclusions can be drawn. Some of the variations in the refraction constant r in Table I may be due to weather.

For $15° < h < 90°$ Equation 6 appears to correct for radio refraction within a few arc seconds. If more precision is required or for $h < 15°$ a higher order correction is given by McNally (1974) as

$$R = A \cot(h) + B \cot^3(h) \tag{8}$$

The second term corrects for the finite curvature of the Earth. The most precise (and most complex) optical theory has been developed by Garfinkel (1944, 1967) and should be used where maximum accuracy is desired. Work is in progress toward simplifying Garfinkel's corrections so they may be readily calculated on a minicomputer. In taking future radio pointing data at 3.5 mm with the 36-foot telescope, the refraction will be assumed known ($r = 48''$) and r will not be allowed to vary in the least squares fit. This will aid in decoupling the refraction and bending terms in Equation 2 and will allow a more exact study of gravitational flexure.

E. TELESCOPE GRAVITATIONAL FLEXURE

Gravitational forces distort the telescope structure and cause a shift in the electrical axis of the antenna. From the mechanical symmetry inherent in the design of the 36-foot telescope, one would expect the beam shift to affect only the elevation coordinate and to first order to be proportional to cos(h). This simple model adequately describes the effect of gravitational flexures of the 36-foot telescope, although the proportionality constant b in Equation 2 depends on the weight of the particular receiver or subreflector installed on the telescope. Table III lists the weighted average flexure constants from the radio pointing data in Table I.

TABLE III

GRAVITATIONAL FLEXURE CONSTANTS

RECEIVER CODE	DESCRIPTION	APEX WEIGHT (lb)	VERTEX WEIGHT (lb)	$b \pm 1\sigma$ (")
12	85 GHz Prime Focus	65	0	-78 ± 4
18	85 GHz Uncooled Cassegrain	100	350	-60 ± 4
20	85 GHz Cooled Cassegrain	100	650	-49 ± 5

The total flexure is apparently due to two effects. First the feed legs (which are attached directly to the main reflector) sag with respect to the reflector surface. This lowers the feed (or subreflector) and raises the radio beam ($b < o$). The second effect is the sag of the entire reflector structure with respect to the elevation axle, which lowers the radio beam ($b > o$). The radio pointing measurements reflect the algebraic sum of the two flexures. Increasing the weight at the apex makes b more negative while increasing the weight at the vertex makes b more positive. By properly designing the reflector support structure and feed legs one could in principle make the magnitudes of the deflections such that the two effects cancel; the beam direction would then be independent of gravity ($b = o$).

For the 36-foot telescope the gravitational flexures are large and the overall beam shift may be an order of magnitude larger than the RMS residual elevation pointing error. In addition the installation of a 650 lb vertex box will affect the pointing of prime focus receivers by as much as 30". Inspection of Table III reveals that for Cassegrain systems b appears to increase by about 1" for each additional 30 lb of vertex weight. At present it is impossible to measure b for each of the many possible receiver configurations because of the limited telescope time available for pointing measurements. Therefore it is imperative to keep the apex and vertex box weights as constant as practicable so that b will remain nearly constant. All Cassegrain boxes should be weighted internally so their total weights and the locations of their centers of gravity are identical. A properly weighted Cassegrain box should be installed at the vertex for all observations, including those made at prime focus. The existing prime focus receivers (except the 1 mm bolometer) weigh between 65 lb and 90 lb and probably do not require additional counterweights. The 1 mm bolometer and its associated retracting mount and vacuum system weigh approximately 150 lb. The measured value of b for this receiver is -130" ± 15", which is in the direction one would expect after adding more weight to the apex. However, most of the difference in b between the 1 mm bolometer and the 3.5 mm prime focus receiver may be due to flexures in the retracting dewar mount, so more data are needed to determine the exact relation between b and the apex load. An experiment conducted in November 1975 showed that b changes less than 10" for an additional 60 lb apex load.

A further complication is the fact that gravitational feed leg flexures shift the Cassegrain beam less than the prime focus beam. As will be discussed later in this report, lateral subreflector displacements move the beam through a smaller angle (about 6 % less) than equal lateral prime focus feed displacements. This small difference could be compensated for by making the subreflector assembly heavier than the prime focus receivers. Then the mechanical feed leg sag could be made 6 % larger and the resultant beam shift (and flexure constant b) would be the same as for a prime focus system.

Another method of compensating for flexure is to build a computer controlled measuring system to monitor deflections of the apex structure and to correct the telescope pointing in real time.

F. TRACKING ERRORS

The drive signals to the 36-foot telescope position servo loops are generated every 100 ms in the on-line computer, which simply subtracts the actual encoder readings from the commanded positions and outputs DC voltages through D/A converters. The duration of the computer tracking cycle limits the effective bandwidth of the servo loops and as a result both systematic and random tracking errors occur when following a celestial source across the sky. For a Type I servo loop with both position and velocity feedback, these errors are expected to have a non-zero mean and an RMS on the order of one or two bits in the shaft angle encoders. The 36-foot telescope uses identical 20 bit optical encoders on both the azimuth and elevation axes. The least significant bit corresponds to an angle of 1.24", so the expected RMS for a well-designed tracking loop is about 2". The principal effect of the random tracking error is to effectively broaden the antenna beam and to slightly reduce the peak gain. The systematic bias of the tracking loop may prove more bothersome, however, since it may be larger than the RMS of the random error. Table IV gives the results of a series of recent measurements of the tracking errors of the 36-foot telescope at the normal sidereal rate. The mean and the RMS of a large sample of errors were computed for each axis in each possible direction under calm and windy conditions.

The 36-foot telescope torque motors are directly coupled to the axes with no additional gearing. This, along with the fact that the original design specification made no allowance for wind loading, means that the torque motors may not be sufficiently powerful for precise tracking in moderate to strong winds. In fact, in the past gusts of about 30 mph directly into the reflector have blown the telescope

TABLE IV

36-FOOT TELESCOPE TRACKING ERRORS

AXIS	TRACKING DIRECTION	WIND (MPH)	MEAN ERROR ± 1σ (")	RMS ERROR (")
Elevation	Up	0	-3.95 ± 0.09	0.91
Elevation	Up	20	-3.89 ± 0.19	1.87
Elevation	Down	0	+2.10 ± 0.09	0.92
Elevation	Down	10	+2.37 ± 0.11	1.12
Azimuth	CW	0	+1.35 ± 0.31	3.05
Azimuth	CW	10	+1.55 ± 0.31	3.06
Azimuth	CCW	0	+1.01 ± 0.35	3.47
Azimuth	CCW	20	+0.96 ± 0.35	3.46

off the source and into the limit switches. For this reason, and to protect the dome and personnel, routine observing is limited to downwind sources from about 20 mph to 35 mph and is completely curtailed above 35 mph. Inspection of Table IV reveals that the RMS tracking errors are about 3" in azimuth and 1"-2" in elevation. The RMS in azimuth is somewhat high, but not because of the lack of available torque, since it does not seem to change with wind loading. I mechanically measured the breakaway torque in azimuth to be about 350 ft-lb. The present DC motor-generator amplifier will supply about 50 A current to the azimuth drive motor, resulting in a peak torque of about 3500 ft-lb. The azimuth RMS error could probably be reduced by adjusting the servo loop gains, although some trade-off must be made with the good step response necessary for efficient ON-OFF observations. The RMS elevation error is about as good as can be expected, although it does increase significantly under wind loading, presumably because of the limited available torque. Even in a 20 mph wind, however, the RMS elevation tracking error is still less than 2". In azimuth the mean error is about + 1" regardless of the direction or wind loading. The independence on direction is particularly puzzling, although the amplitude is too small to warrant further investigation at this time. The mean errors in elevation do depend on the direction of rotation as expected and are about -4" going up and about +2" coming down. The Type I servo loops used in the 36-foot telescope drive system will lag a constant velocity signal with a constant position error (bias). This is exactly what happens in elevation; the telescope lags below (-4") the rising source and lags above (+2") the setting source. The two amplitudes may differ because of the telescope being slightly unbalanced when these data were taken. These biases are not accounted for in the elevation pointing Equation 2 and are large enough to detrimentally affect the determination of the other parameters, in particular the azimuth axis tilt. An effort should be made to reduce the elevation biases to 1" or less either by adjusting the present Type I servo loop or by converting to a Type II servo, which will maintain a zero mean position error for a constant velocity source.

G. TELESCOPE INCLINATION

The "vertical" axis of the telescope mount (about which it rotates in azimuth) is inclined somewhat from the true zenith direction. Here the zenith is defined as the direction of a line from the center of the Earth through the center of the telescope mount. This direction may differ from that of local gravity due to the presence of large nearby land masses such as mountain ranges. In Equations 1 and 2, i_A and i_h are two independent estimates of the tilt of the telescope axis from the zenith direction and e_A and e_h are two independent estimates of the azimuth toward which the telescope axis is inclined. As discussed previously, the two equations are allowed to have different values of i and e in order to search for errors in the assumed telescope geocentric latitude and longitude. These assumed coordinates have now been sufficiently refined to eliminate systematic errors, and single values of i and e will now suffice to describe the axis tilt in both pointing equations.

Using only the latest four data sets taken with the cooled Cassegrain receiver, the weighted (by the total number of data points) average of i is 19" and the weighted average of e is 307°. There is some indication that the inclination has decreased and rotated slightly clockwise since 1970, but this is uncertain because of the noise in the data and the previous errors in the assumed telescope coordinates. There is no obvious correlation with ambient temperature. In any case the axis position has, within the measurement errors, remained constant during the past year. In principle it is a simple matter to mechanically measure the inclination of the telescope mount as a function of azimuth position and thus to directly determine i and e. Such a system could be operated continuously and interrogated by the online pointing computer to generate directly measured tilt corrections in real time. In practice, however, three difficulties arise. First, the local gravity vector may be displaced from the zenith direction by an angle of up to several arc seconds. A level which has its reference based on gravity will read the tilt of the telescope axis with respect to gravity, not with respect to the zenith direction. Thus level readings cannot be directly compared with the astrometric results unless an independent measurement has been made of the direction of the gravity vector with respect to the zenith direction. The second difficulty is the fact that the telescope mount is not perfectly rigid; it flexes as it rotates in azimuth, resulting in different level readings at different points on the physical structure. A comparison was made on the 36-foot telescope with a sensitive electronic level with a repeatability of about 0.2" and an absolute accuracy of about 1". Level readings on the upper surface of the azimuth bearing differed systematically from readings at the upper end of the yoke arm near the elevation encoder by angles between +2.5" and -1.9". Of course, the radio pointing data refer to the tilt of the radio beam which may be different from the tilt at either of the two test locations. It seems reasonable to also expect systematic differences of up to a few arc seconds between the radio beam tilt and the tilt at any given point on the telescope mount. The third difficulty is the fact that the elevation servo loop is biased. As shown in Table IV the offset from zero mean tracking error is about -4" for rising sources and about +2" for setting sources. The least squares fit of the pointing equations will compensate for these errors by tilting the telescope azimuth plane toward the west (azimuth = 270°) by about 8" if the pointing data are evenly distributed over the sky. Thus the elevation bias errors affect the computer fitting of the telescope azimuth axis inclination i and its azimuth direction e.

The line in Figure 6 is the inclination curve predicted by the average radio pointing data (i = 19" and e = 307°). The filled circles in Figure 6 are the averages of the electronic level readings at the two test points on the telescope mount. These data indicate that the telescope axis is inclined 15" toward an azimuth of 336° with respect to gravity. Figure 7 is a vector plot in polar coordinates of the true inclination of the telescope axis from the zenith (15" at 336°). The vector representing the additional effective axis tilt caused by the elevation servo bias errors (8" at 270°) is added to the directly measured tilt, and the resultant is 20" at an azimuth of 314°. As shown in Figure 7, this is very close to the radio data fit of 19" at 307°. This good agreement seems to indicate that the deviation of local gravity from the true zenith is small. Only if the elevation servo bias errors can be reduced to near zero will the radio data fit of the axis tilt agree with the electronic level data. In this case they will differ only because of telescope mount flexures and the deviation of gravity from the zenith. Because of these confusing effects, if does not seem worthwhile at the present to construct a computer-controlled on-line measuring system for correcting the axis tilt in real time or to mechanically adjust the telescope mount to reduce the tilt.

In the past additional systematic elevation errors as a function of telescope azimuth were present. Figure 8 shows the elevation residuals of the pointing data taken in September 1973. The histogram overlying this data is an empirical correction generated from all the 1970-1972 data. It appears that this error was stable with time and was most probably caused by roughness in the azimuth bearing of the telescope mount. This bearing was in fact damaged after initial installation because of lack of proper

FIGURE 6

TELESCOPE INCLINATION CURVES

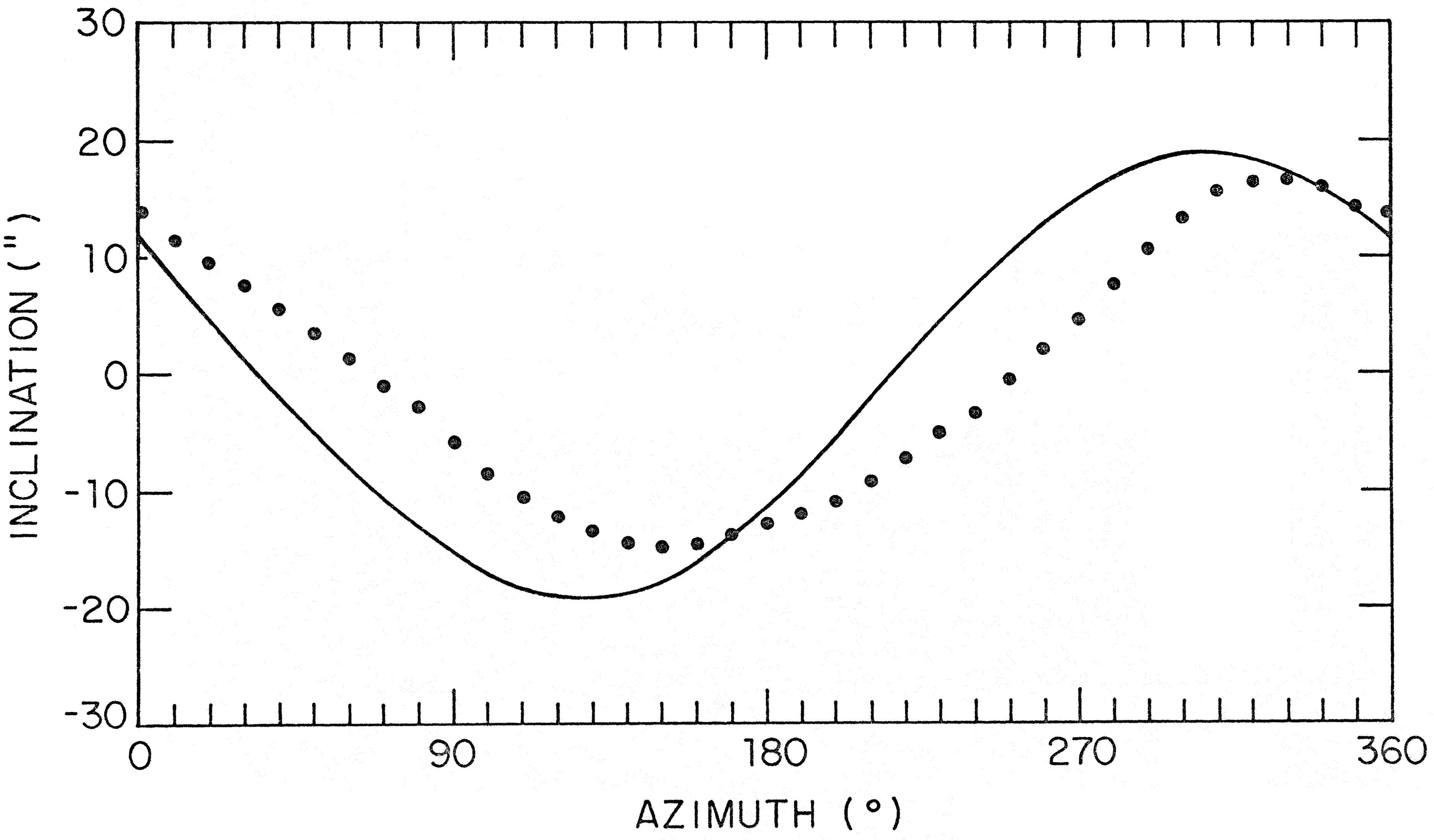


FIGURE 7
TELESCOPE INCLINATION VECTORS

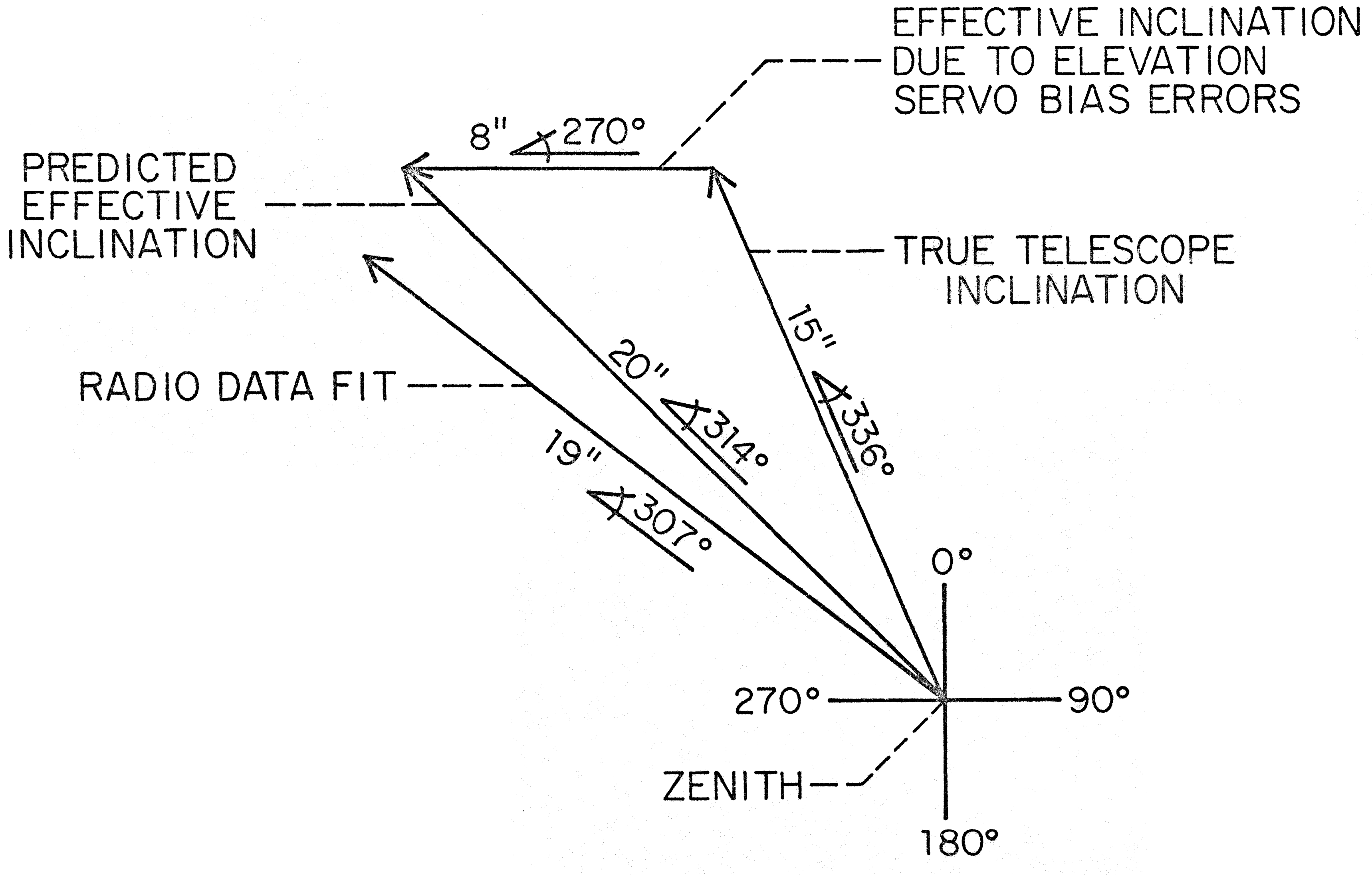
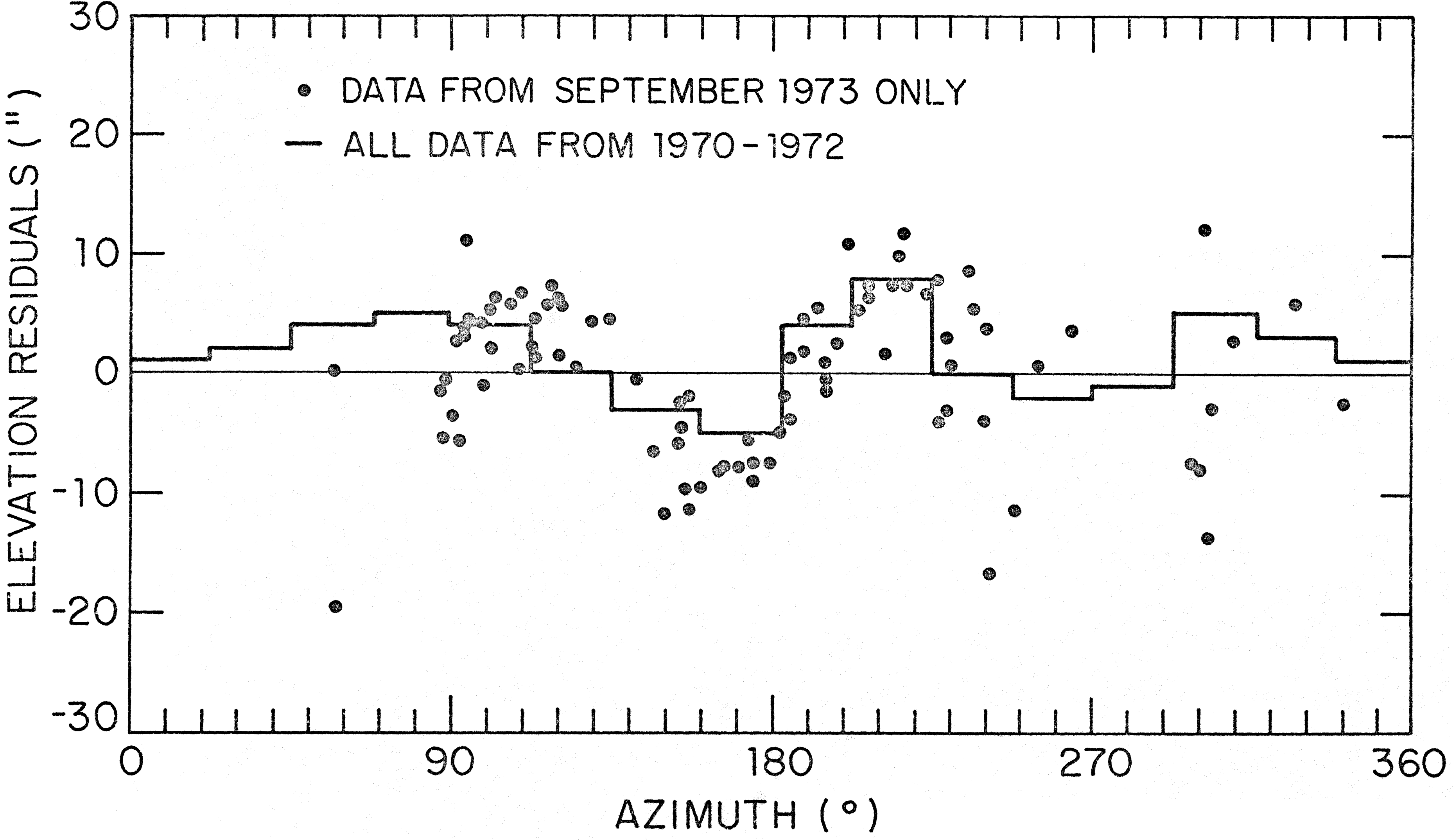


FIGURE 8
EMPIRICAL ELEVATION CORRECTIONS



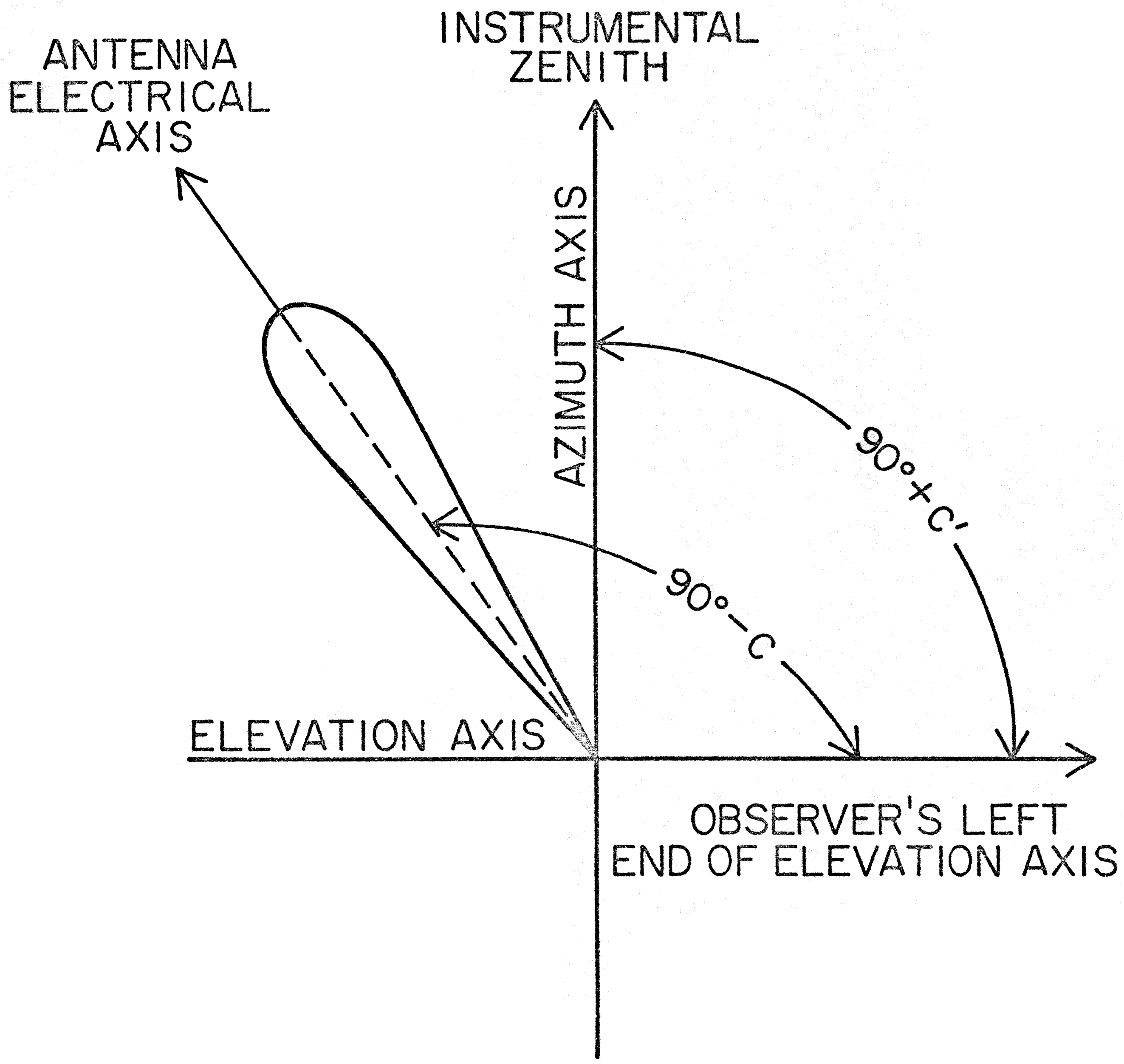
lubrication and the extra friction caused by thermal heating by the azimuth torque motor, which is directly attached to the inner race of the bearing. The installation of a bearing heater solved the thermal problem but the roughness persisted. The empirical elevation pointing corrections in Figure 8 were inserted in the on-line computer program in April 1974 and automatically applied to the commanded elevation position. In September 1974 the bearing was flushed and relubricated according to the manufacturer's specifications in an effort to reduce the "rocking" of the telescope. This succeeded in reducing the magnitude of the rocking motion to an almost undetectable level; this is evident in comparing the old data in Figure 8 with the latest results previously shown in Figure 4. Consequently, the empirical elevation corrections are no longer necessary and were removed from the on-line pointing program in October 1974.

H. TELESCOPE COLLIMATION

The azimuth and elevation axes of the telescope mount are not exactly perpendicular. This nonorthogonality is the collimation error c' in the pointing Equation 1. The angle between the instrumental zenith (azimuth axis) and the observer's left end of the horizontal (elevation) axis is 90° + c', as shown schematically in Figure 9. This mount misalignment is expected to be small and to remain constant with time. However, the experimentally determined values in Table I show a large scatter. This is because both the telescope mount collimation error c' and the telescope electrical axis collimation error c have similar functional forms in Equation 1. The angle between the telescope electrical axis and the observer's left end of the horizontal (elevation) axis is 90° - c (see Figure 9). The least square fitting procedure used on the radio data more accurately determines the sum c + c' than either of the individual errors; c + c' is simply the total collimation error when the telescope is pointed at the instrumental zenith. This is shown quantitatively in Table I where c + c' is tabulated for each pointing data set. Of course, any horizontal feed or subreflector displacement will affect c and thus c + c'. This is why c + c' in Table I changes when different receivers are used and when the focus and polarization mount at the apex is adjusted horizontally.

Determining the mount error c' accurately would reduce the number of unknown parameters to be fitted by one and thus should improve the overall pointing accuracy of the 36-foot telescope. The existing data are not sufficient to accurately determine c'; one limitation is the 15° elevation angle limit of the telescope pedestal. One way to precisely separate the two collimation errors is to take large amounts of data at very low and at very high elevations, particularly near

FIGURE 9
TELESCOPE COLLIMATION ERRORS



the azimuth angles e and e + 180°. One can improve the individual determinations of c and c' by making radio observations in selected regions of the sky where other terms in the pointing equations become negligible and thus less confusing.

I. FOCUS

The focal length of the 36-foot telescope is a function of temperature and increases by 0.4 mm per $^{\circ}$C ambient temperature rise. Thermistors mounted on the back of the reflector surface are automatically monitored by the computer. At the beginning of each scan a new focal length is calculated according to an empirical equation and the focus drive is commanded to the newly determined position. However, if the axis of the focus drive system is not parallel to the electrical axis of the antenna, then changing the focus introduces a lateral shift of the feed horn (or the subreflector in the Cassegrain configuration) which also shifts the antenna beam. Thus the telescope pointing may depend on the focus setting. In March 1971 Conklin found that the axis of the focus mount was inclined $4.4^{\circ} \pm 0.8^{\circ}$ with respect to the telescope axis at a position angle of $58^{\circ} \pm 14^{\circ}$. A focal length change of 10 mm resulted in a beam shift of 17".
On 15 August 1974 I realigned the Sterling mount in an effort to reduce the pointing shift. After mechanical adjustments the focus axis was found to be inclined about $0.9^{\circ} \pm 0.3^{\circ}$ at a position angle of $270^{\circ} \pm 30^{\circ}$. Now a 10 mm focus change shifts the beam by only 3" and the overall effect on the telescope pointing accuracy is considerably reduced. However, in the future additional mechanical adjustments will be made in an effort to reduce the beam shift even further.

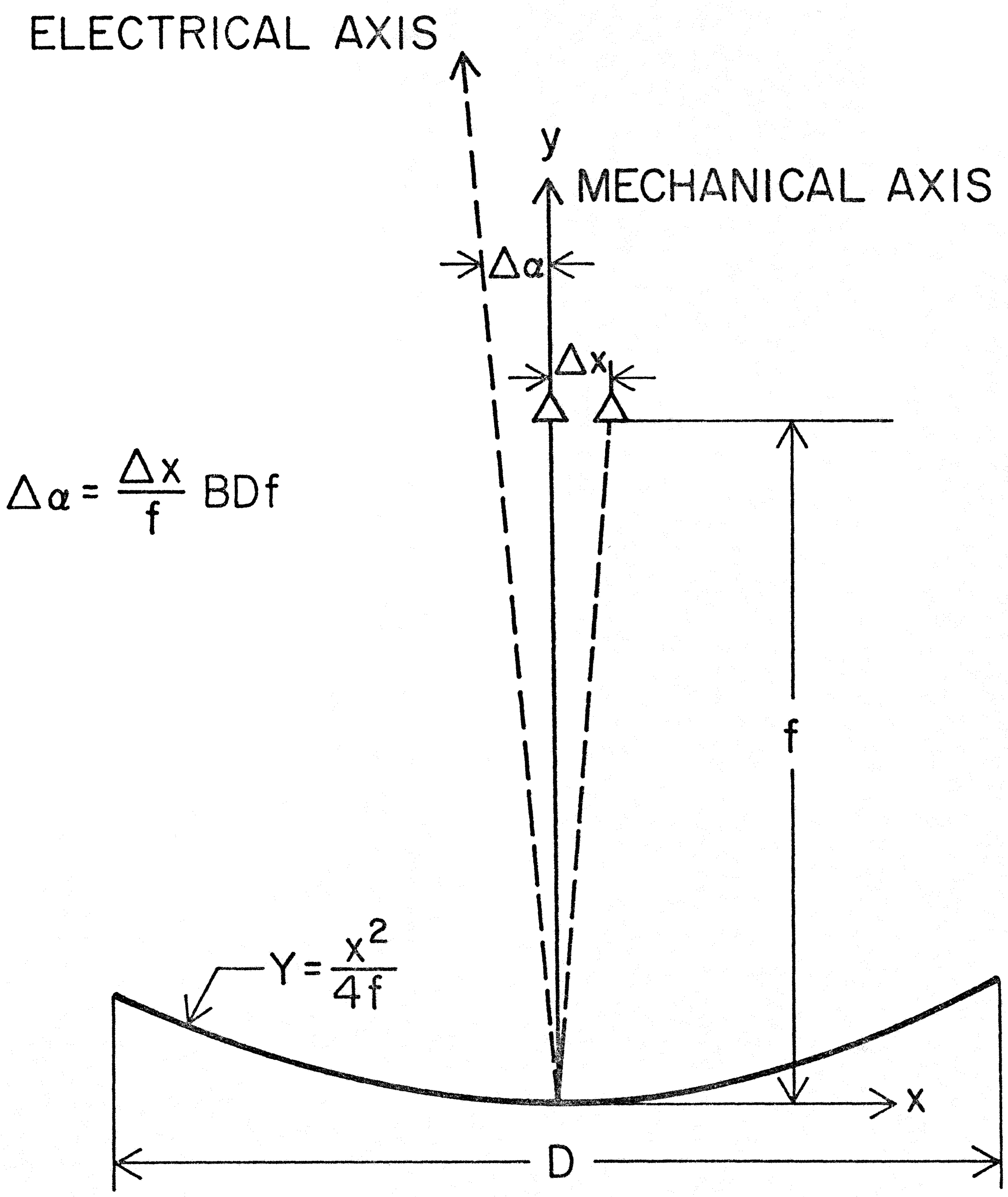
J. FEED AND SUBREFLECTOR DISPLACEMENTS

Each of the radiometer boxes used on the 36-foot telescope contains one or more feed horns, none of which are exactly aligned with the mechanical axis of the main reflector. In addition, the Cassegrain subreflector can be nutated in a plane; this type of beamswitching has become the standard mode of continuum observing. It is of interest, therefore, to investigate the effects of both linear and angular displacements of the prime focus feed, the Cassegrain feed, and the Cassegrain subreflector. Any shift of the telescope electrical axis in the vertical (elevation) plane will normally be compensated for in the elevation thumbwheel offset (see Equation 2), although there is no way to distinguish between the thumbwheel offset and the elevation encoder offset h_{off}. In the horizontal (azimuth) plane any beam shift shows up in the azimuth thumbwheel offset or in the electrical axis collimation error c (see Equation 1 and Figure 9).

The 36-foot telescope (with diameter D = 10.973 m) was originally designed as an f/D = 0.800 prime focus paraboloid with a focal length f = 8.778 m. Figure 10 is a schematic representation of the prime focus configuration. A lateral movement of the feed horn ΔX produces a beam shift $\Delta\alpha$. The theoretical relationships between various feed and subreflector displacements have been derived by Ruze (1969) and are given in Table V. In general rotating a feed horn about an axis through its phase center has no effect on the pointing since the feed is effectively a point source. The primary effect is asymmetrical aperture illumination and increased spillover. The parameter BDf in Table V is the prime focus beam deviation factor, which is a function of the telescope f/D. It is simply the ratio of the angular beam displacement to the angular feed displacement; the two differ because of the finite curvature

FIGURE 10

PRIME FOCUS SCHEMATIC DIAGRAM
(LATERAL FEED DISPLACEMENTS)



NRAO 36-FOOT TELESCOPE

D = 10.973 m	BDf = 0.95
f = 8.778 m	$\frac{\Delta\alpha}{\Delta x}$ = 22.3 "/mm
f/D = 0.800	

TABLE V

THEORETICAL BEAM SHIFTS

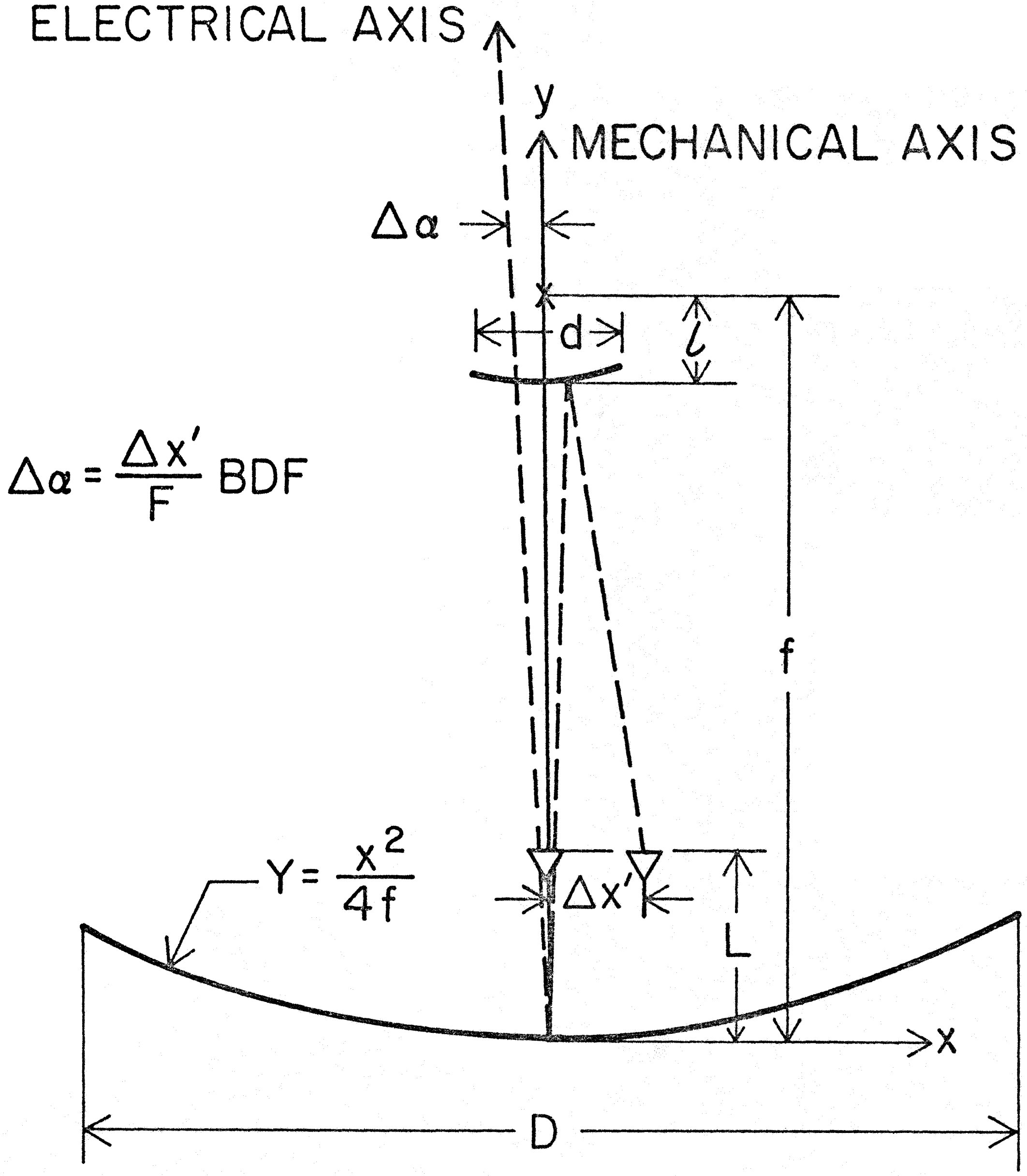
DISPLACEMENT	THEORETICAL BEAM SHIFT $\Delta\alpha$ (radians)	EQUATION FOR 36-FOOT TELESCOPE
Prime focus feed lateral displacement ΔX	$\frac{\Delta X}{f} BDf$	$\Delta\alpha\ ('') = 22.3\ \Delta X$ (mm)
Cassegrain feed lateral displacement $\Delta X'$	$\frac{\Delta X'}{F} BDF$	$\Delta\alpha\ ('') = 1.36\ \Delta X'$ (mm)
Subreflector lateral displacement $\Delta X''$	$\Delta X''\left(\frac{BDf}{f} - \frac{BDF}{F}\right)$	$\Delta\alpha\ ('') = 21.0\ \Delta X''$ (mm)
Subreflector rotation through angle $\Delta\beta$ radians	$-\frac{\Delta\beta \ell}{f}(BDf + BDF)$	$\Delta\alpha\ ('') = -0.0809\ \Delta\beta\ ('')$

of the primary mirror. For the 36-foot telescope with f/D = 0.8, BDf = 0.95 (Ruze 1965). Thus from Table V the expected plate scale in the primary focal plane is 22.3"/mm. Several independent measurements of the primary plate scale have been made by first measuring the physical separation of two identical feed horns mounted in a prime focus radiometer box and then by observing the angle between the two radio beams. Typical measured scale factors are 21.9 ± 0.5"/mm and 22.0 ± 0.5"/mm, both of which agree within the errors with the theoretical value.

In 1973 a Cassegrain subreflector and nutating mechanism were constructed by J. Payne for use on the 36-foot telescope. The hyperboloidal secondary mirror has a diameter d = 457 mm, a magnification factor m = 17.28, and an eccentricity e = 1.1229. The Cassegrain system has an effective focal length F = mf = 151.7 m and a focal ratio F/D = 13.82; it is schematically shown in Figure 11. With such a long focal length the Cassegrain beam deviation factor BDF = 1.00 (Ruze 1965). The vertex of the subreflector is at an axial distance ℓ = 364 mm from the primary focus toward the vertex of the main reflector. Similarly, the Cassegrain feed horn is at an axial distance L = 2.123 m above the vertex of the primary. The full angle subtended by the secondary mirror is 4.14°. From Table V the Cassegrain plate scale is 1.36"/mm. This scale factor has been measured by comparing the pointing offsets for the two 3.5 mm Cassegrain receivers. The uncooled receiver has its feed horn centered in the radiometer box; the cooled receiver's feed is located 121 mm ± 2 mm off axis. The measured pointing offsets differed by 160" ± 10", and the Cassegrain plate scale is thus 1.32"/mm ± 0.08"/mm, which is in good agreement with the theoretical value of 1.36"/mm.

FIGURE 11

CASSEGRAIN SCHEMATIC DIAGRAM (LATERAL FEED DISPLACEMENT)



NRAO 36-FOOT TELESCOPE

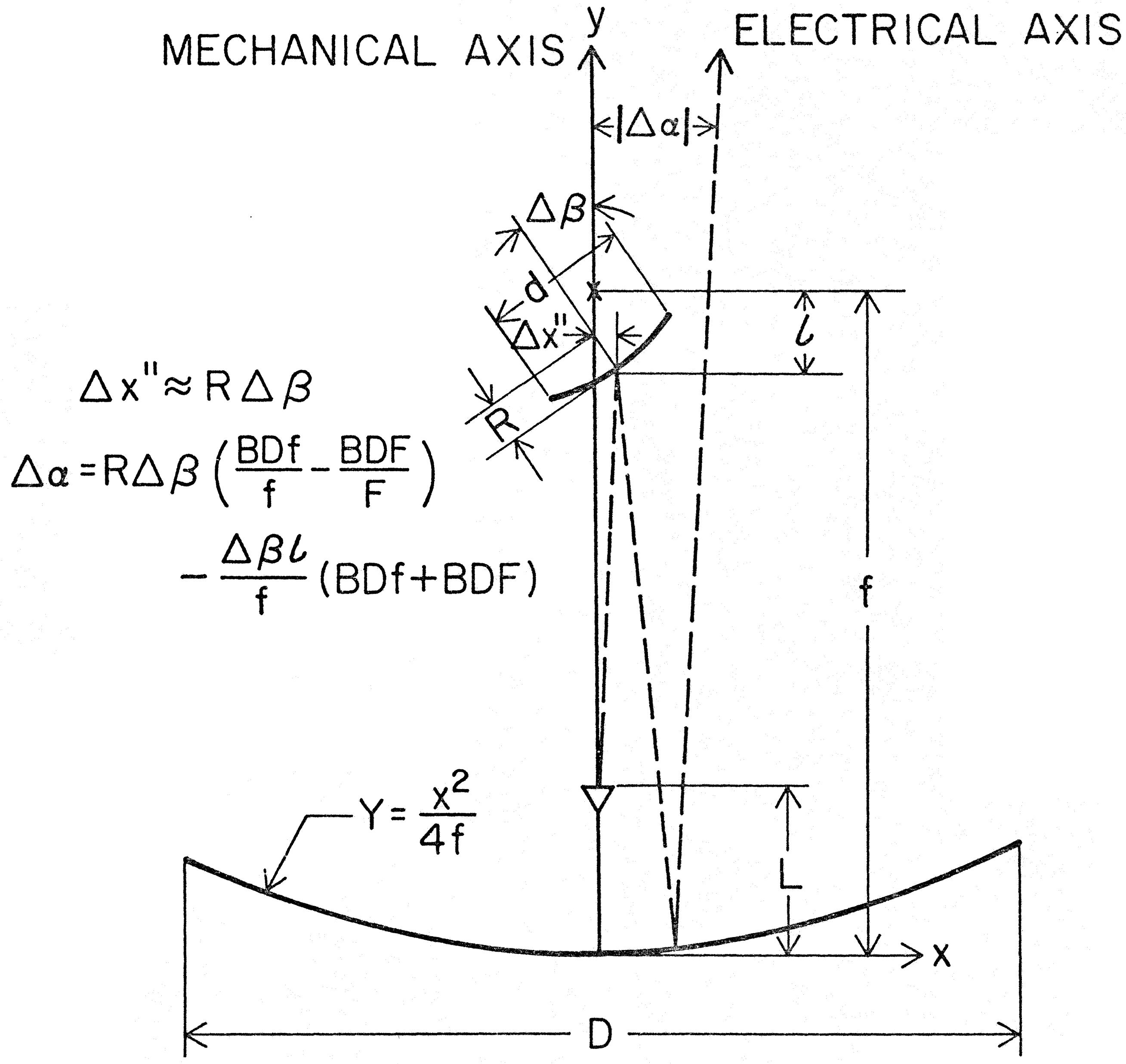
$D = 10.973$ m
$f = 8.778$ m
$f/D = 0.800$
$L = 2.123$ m

$d = 457$ mm
$F = 151.7$ m
$F/D = 13.82$
$\ell = 364$ mm

$\mathrm{BDF} = 1.00$
$\frac{\Delta\alpha}{\Delta x'} = 1.36$ "/mm

FIGURE 12

CASSEGRAIN SCHEMATIC DIAGRAM (SUBREFLECTOR DISPLACEMENT)



$$\Delta x'' \approx R\,\Delta\beta$$

$$\Delta\alpha = R\Delta\beta\left(\frac{BDf}{f} - \frac{BDF}{F}\right) - \frac{\Delta\beta\, l}{f}(BDf + BDF)$$

NRAO 36-FOOT TELESCOPE

$D = 10.973$ m
$f = 8.778$ m
$f/D = 0.800$
$L = 2.123$ m

$d = 457$ mm
$F = 151.7$ m
$F/D = 13.82$
$l = 364$ mm

$BDf = 0.95$
$BDF = 1.00$
$R = 80$ mm
$\frac{\Delta\alpha}{\Delta\beta} = -0.0728$

K. DOME

The 36-foot telescope is mounted inside a 95-foot diameter astrodome with a slit 40 feet wide. Because of thermal instabilities caused by direct sunlight on the reflector or feed legs, it is often necessary to observe sources near the sun through the semi-transparent dome. The side of the dome is preferred over the rigid door sections because a smaller area is blocked by metal framework and thus the microwave transmission is greater. The dome is a sandwich fabric about 1 mm thick with an effective dielectric constant of about 2.8. Thus the fabric is a thin curved lens which may perturb an incoming plane wave front and introduce up to second order phase errors across the telescope aperture.

I have investigated the effects of the dome on the pointing and antenna beam pattern at 3.3 mm wavelength. The results are given in Table VI. From the azimuthal symmetry of the astrodome, one would expect no pointing change in this direction, since no net linear phase error is introduced across the telescope aperture. However, the dome is mechanically asymmetric in the elevation plane and one would expect any detectable beam shift to be in this direction. At 50° elevation the measured pointing shift was $\Delta AZ = 0'' \pm 2''$ in azimuth and $\Delta EL = -14'' \pm 2''$ in elevation. The beam was shifted downward so that the source appeared higher in the sky through the dome than through the open slit. Partly shading the dish with the dome can produce an even larger pointing error, since the large constant phase retardation term now applies to only part of the telescope aperture; the result is a larger net linear phase error and thus a larger beam deflection. With half the aperture of the 36-foot telescope obscured at 3.3 mm the beam is deflected $\sim 40''$ toward the shaded region.

TABLE VI

90 GHz DOME EFFECTS

DOME	OPEN	CLOSED
POWER TRANSMISSION COEFFICIENT	1.00	0.51 ± 0.02
ΔAZ (")	0	0 ± 2
ΔEL (")	0	-14 ± 2
FOCUS CONSTANT (MM)	70.0 ± 0.5	66.6 ± 0.5
ΘAZ (")	85 ± 2	93 ± 2
ΘEL (")	72 ± 2	66 ± 2
$(\Theta_{AZ}\ \Theta_{EL})^{\frac{1}{2}}$ (")	78 ± 4	78 ± 4

The curvature of the dome introduces second order phase errors which defocus the telescope (curvature of field) and produce astigmatism. As shown in Table VI the measured focal length of the 36-foot telescope is 3.4 mm ± 0.7 mm shorter through the dome than through the open slit. The curvature of field is not serious since one can correct it by simply refocusing the telescope. However, there is no corresponding simple cure for astigmatism. As shown in Table VI the shape of the main lobe of the antenna power pattern is affected by the dome. The half power beamwidths change from 85" x 72" to 93" x 66" in azimuth and elevation, respectively, when observing through the dome. The antenna beam already has an elliptical cross section because of astigmatism in the primary reflector. The dome appears to actually increase the ellipticity of the main beam. Thus parabolic phase errors introduced in the wavefront by the dome fabric unfortunately have the same sense as the mechanical deformations in the 36-foot telescope. This increases the total astigmatism and decreases the antenna power gain. The power transmission coefficient in Table VI is actually due to two effects: (1) the loss in signal strength due to reflections and absorption in the dome fabric, and (2) the decrease in antenna gain due to the astigmatism caused by the non-uniform phase errors over the telescope aperture. It appears that simply measuring the power transmission coefficient of a small flat sample of dielectric material may not be sufficient to accurately predict the effects of a large curved sheet placed in front of a telescope. This effect may be important in selecting radome geometries and materials for future telescopes.

L. WIND AND TEMPERATURE EFFECTS

The RMS residual pointing errors of the 36-foot telescope are about 4" for each axis and are larger than one would expect based on the short-term (time scale of minutes) pointing repeatability of about 1"-2". Possible sources of random pointing errors are wind loading and thermal deformations of the reflector and the feed support structure. Since gravitational distortions of the antenna are known to be small, the reflector surface is relatively stiff and the boresight shift due to wind loading of the primary mirror is probably negligible. Wind loading of the apex structure appears to be a more serious problem. In the vertical plane the projected area near the focal point is about 20 ft^2 and in the horizontal plane it is about 10 ft^2. A wind of 12 mph (the mean nighttime wind speed on Kitt Peak) could exert forces up to about 9 lb horizontally and 4 lb vertically on the apex mount. The measured lateral force needed to deflect the structure 1 mm at the focal point is about 40 lb. Thus a 12 mph wind could move the subreflector up to 0.2 mm horizontally and 0.1 mm vertically and shift the Cassegrain radio beam up to 4" in azimuth and 2" in elevation. A 20 mph wind could cause beam shifts of up to 13" in azimuth and 6" in elevation. It seems likely that wind loading of the apex mount contributes significantly to the measured random pointing errors.

Thermal gradients across the primary reflector and backup structure may also shift the electrical axis. However, the feed support legs are attached directly to the reflector surface, and their corresponding movement is in the direction which tends to cancel the shift of the axis of the best-fit paraboloid. The net beam shift is difficult to predict but is probably small compared to the shift due to differential changes in the lengths of the aluminum feed support legs. For instance, an average temperature difference of 1° C between opposite feed legs will move the subreflector laterally about 0.26 mm and shift the radio beam by 5". Thermistors mounted near the midpoints of the upper and lower feed legs indicate typical temperature differentials of up to 0.8° C. No temperature information is available for the horizontal feed legs, but their thermal mass is much smaller and they probably develop even larger differentials. Thus temperature gradients in the focal point support structure will also contribute significantly to the random pointing errors.

Both wind loading and thermal distortions could be corrected for in real time with a system which precisely measures lateral shifts of the apex mount with respect to the elevation axis of the telescope. These lateral movements are easily converted to predicted beam shifts which can then be corrected for in the on-line computer pointing program. One possible system involves directing a narrow beam of light from a laser (securely attached to the elevation axle) through a small hole cut through the reflector to a quadrant detector near the focal point. The quadrant detector would generate two voltages corresponding to the azimuth and elevation deflections, which would then be fed into the pointing computer through A/D converters.

Another method of reducing random pointing errors is to prevent rather than to predict wind and temperature effects. This could be done by simply covering the slit of the astrodome with a thin lightweight material. This covering would reduce the wind loading to near zero and also reduce the ambient temperature variations around the telescope. Adding several large fans inside the dome to slowly circulate air would also help stabilize the telescope and keep it in thermal equilibrium. In order for this scheme to be practical the "window" must not attenuate the desired radio frequency signal significantly. If, in addition, the window material is chosen to be almost opaque at infrared wavelengths, then observations could also be made in the vicinity of the Sun. Presently it is very difficult to make precise measurements within about 45° of the Sun because direct sunlight through the slit onto the reflector causes a rapid decrease in antenna gain. The existing radome is used only as a last resort because of its large attenuation, boresight shift, and phase distortions. The proposed sun and windscreen could be made of a material similar to Griffolyn, which is a sandwich of two layers of polyethylene and a coarse mesh of nylon. I have conducted several tests with 0.15 mm thick Griffolyn which show that the black polyethylene is a good infrared filter but yet almost completely transparent (3 % loss) at 3 mm wavelength. The measured transmission of a small sample is identical with the loss measured through a 40 ft x 80 ft piece covering the entire slit of the 95-foot astrodome. It seems that detrimental wavefront distortions will be negligibly small (at least at 3 mm and most probably even at much shorter wavelengths). Any window material chosen must be a compromise between the low microwave loss necessary for efficient observations and the high mechanical strength needed to withstand moderate ($\sim$ 20 mph) winds when stretched across a 40 ft aperture with little or no extra mechanical support. If the mechanical problems of conveniently installing, supporting, and removing a highly transparent radio window can be solved, then such an addition to the astrodome of the 36-foot telescope should prove very worthwhile in improving the pointing accuracy, increasing the telescope stability, and enlarging the sky coverage.

III. CONCLUSIONS AND RECOMMENDATIONS

After a thorough analysis of the pointing characteristics of the NRAO 36-foot telescope, I have reached the following conclusions:

(1) The basic form of the pointing correction equations and the methods currently used to collect radio pointing data are completely adequate.

(2) On a time scale of one week the residual pointing errors are dominated by random effects and are 6" RMS.

(3) On a time scale of months the pointing accuracy degrades by a factor of 2 or 3 because of systematic but currently unpredictable effects.

(4) The assumed geocentric telescope coordinates were in error but have now been corrected.

(5) The accuracy of the present clock system is adequate.

(6) Computer truncation errors in coordinate conversions cause pointing errors which are not serious now but may be in the future if the pointing accuracy is substantially improved.

(7) The average radio refraction is well understood but temporal variations may not be negligible.

(8) The varying weights of radiometer boxes and subreflector mechanisms used on the 36-foot telescope cause large changes in the gravitational flexure of the antenna and result in large systematic pointing errors when new systems are installed on the telescope.

(9) The RMS elevation tracking error is as small as can be expected, but the non-zero bias is too large and affects the determinations of other parameters.

(10) The RMS azimuth tracking error is too large and should be reduced. The azimuth bias is negligibly small.

(11) The determination by radio observations of the inclination of the vertical axis of the telescope mount has been confused by other effects.

(12) The "rocking" of the telescope caused by roughness in the azimuth bearing has been effectively eliminated.

(13) The collimation error of the telescope mount axes is not well known and may change when large static loads (such as 400 lb cryogenic compressors) are installed on the telescope mount.

(14) The focus and polarization mount at the apex has been adjusted so that its mechanical axis is now nearly parallel to the antenna electrical axis. Focusing the antenna now shifts the radio beam only very slightly.

(15) The measured beam shifts due to feed and subreflector displacements are in excellent agreement with theoretical calculations.

(16) Observations through the existing radome material indicate large boresight shifts, a change in effective telescope focal length, and increased astigmatism.

(17) Wind loading of the apex structure and differential thermal expansion of the feed support legs contribute significantly to the large RMS residual pointing errors.

In an effort to improve the absolute pointing accuracy of the 36-foot telescope I make the following recommendations:

(1) The elevation servo control loop should be modified to Type II in order to eliminate the detrimental bias.

(2) The azimuth servo control loop should be adjusted to reduce the RMS tracking error.

(3) The focus and polarization drive should be carefully aligned parallel to the antenna electrical axis.

(4) Radio pointing data should be taken to accurately determine the azimuth axis inclination and the collimation error between the azimuth and elevation axes.

(5) All Cassegrain radiometer boxes should be adjusted to a standard weight ($\sim$ 700 lb) and one should be installed on the telescope at all times (even for prime focus observations).

(6) The total equipment weight at the apex should be kept constant ($\sim$ 115 lb). When lighter prime focus radiometers are installed compensating weights should be added to the apex structure.

(7) A sunscreen/windscreen should be constructed for the slit of the existing astrodome to prevent pointing errors due to wind and thermal effects. In addition, several large fans should be installed inside the radome to slowly circulate air. These additions will improve the pointing, reduce antenna gain variations, and allow observations of sources near the Sun.

(8) Radio pointing data should be taken about every three months to observe the effects of system modifications and to provide more information on the time and temperature variations of the pointing parameters.

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