12 METER MILLIMETER WAVE TELESCOPE
MEMO No. 247

National Radio Astronomy Observatory
Tucson, Arizona

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MEMORANDUM

To: 12 m Memo Series

From: P. R. Jewell and T. K. White

Subject: 12 m Structural Tilt Measurements

I. Introduction

We are currently experiencing two problems with the azimuth pointing of the 12 m. First, the azimuth offsets show a hysteresis loop depending on the azimuth drive direction from which the source is approached. Second, we see a significant ~sin(2•Az) residual in the azimuth pointing offsets. We have put terms in the pointing model to compensate for the sin(2•Az) effect, but they have proved only partially successful in removing the residuals.

In an effort to isolate the causes of these effects, and to better characterize the telescope mount in general, we have examined tilts and flexures of the telescope structure at a number of different positions. We have compared these results with a similar set of measurements taken in the summer of 1978 by Robert MacDowall and Bobby Ulich. The telescope was the "36-ft" at that time, of course. The current 12 m mount from the elevation axle down is substantially the same as for the 36 ft, although we added a larger and heavier elevation service platform in the summer of 1988. This platform is not counter-balanced about the azimuth axis.

All the tilt measurements, including the ones from 1978, were made with a Rank-Taylor-Hobson TALYVEL 2 tiltmeter. This tiltmeter can provide relative angular tilt measurements accurate to about 0.2" from point to point. The unit could be susceptible to long-term drifts, but most measurements take less than 30-40 minutes to complete. Repeatability of measurements indicate that the unit is stable to within ~2" over that time interval. The linear translation measurements were made with a Hewlett-Packard laser interferometer borrowed from NOAO.

II. Measurements

In the discussion and figures that follow, we compare the results recently obtained with those made by MacDowall and Ulich in 1978. MacDowall and Ulich made tilt-angle measurements at 15 different positions on the telescope structure. We have not repeated all of these positions, although we have done several of them and have also done measurements in a few positions not done in 1978. The original data from MacDowall and Ulich are in a notebook kept by PRJ. We describe the most notable results here:

1. Tilt angle measured just above the azimuth bearing as a function of azimuth rotation angle of the telescope is dominated by the azimuth bearing tilt. This produces a sinusoidal variation in tilt angle, but with some significant residuals around 270° (Figure 1: June 1991 measurements; Figure 2: July 1978 measurements).

2. Measurements below the azimuth bearing on the pedestal are dominated by a $\sin 2\theta$ curve as the telescope is rotated in azimuth angle. The 1991 data are well-fit with a sin(2•(Az - phase)) term (Figure 3). The data from 1978 seem to have higher order terms, e.g., $\sin 4\theta$ (Figure 4).

3. In May 1989, we made tilt measurements below the azimuth bearing at the four cardinal azimuth positions: 0°, 90°, 180°, and 270° as the telescope was rotated in azimuth (Figure 5).

4. Tilt measurements on the azimuth inductosyn housing as the telescope is rotated in azimuth show $\sin\theta$ and $\sin 2\theta$ components (Figure 6). This result may be a significant clue to some of the problems we are having now. There was no comparable measurement in 1978. In January 1990, R. Freund, J. Kingsley, and PRJ made lateral translation measurements of the inductosyn house using the NOAO laser interferometer. The result (Figure 7) shows a double-peaked curve as a function of telescope azimuth rotation angle similar to that shown by the tiltmeter.

5. Measurements on the concrete floor, inside the pedestal, about halfway between the inductosyn stand and the door, show a simple sine-wave (Figure 8). There was no comparable measurement in 1978.

6. Measurements on top of the east elevation yoke arm are different depending on whether the tiltmeter is oriented parallel or perpendicular to the elevation axis. Perpendicular to the axis, the tilt is largely sinusoidal as the telescope is rotated. Parallel to the axis, some significant residuals appear, particularly near ~250° azimuth. Results from May 1989 (Figure 9) agree well with those from 1978 (Figures 10 and 11).

7. MacDowall and Ulich also measured tilts in the structure as the telescope is tipped over in elevation, particularly at the mounting points of the old elevation Baldwin encoder. They found that the mounting flange tilted significantly with elevation tipping angle (Figure 12). The Baldwin encoder, which is still on the telescope, is mounted on a bracket that extends about 40 in from the east yoke arm. The encoder is turned by a spindle extending about 12 in from the east elevation torque motor. The elevation inductosyn, which is the angle resolver currently in use, is mounted flush to the west elevation torque motor.

   We made measurements as a function of elevation angle on top of the west torque motor (near the inductosyn) and below the torque motor on top of the west yoke arm. No deflections >1" were observed. When the telescope was driven in elevation angle, rather large deflections were observed on the tiltmeter, presumably because of the reaction force of the motors against the yoke. The tiltmeter takes a long time (1-2 min) to settle down after a large deflection. Because of this effect, we consider these measurements less reliable than most of these others. They should be repeated, perhaps with another tiltmeter or with an autocollimation device mounted on the dome floor.

8. MacDowall and Ulich also noted that the elevation encoder readout varied as the telescope was rotated in azimuth angle, perhaps because structural deformations were transmitted to the elevation encoder mounting bracket (Figure 13). We repeated these measurements with the elevation stow pin inserted (telescope at 90° elevation). A peak-to-peak deviation of 1.6" was observed (Figure 14). The terms compensating for this effect and the one discussed in Item 7 (the old ROTEL and ROTAZ terms) are no longer in the telescope pointing model. We should do some more investigation into the term involving azimuth angle.

   Of incidental interest, the elevation brakes were unable to hold the telescope firmly in position, even at zenith. We observed elevation creep of many arc seconds with the telescope nominally still. For this reason, we did not attempt a measurement at a lower elevation angle.

9. Figures 15 and 16 show the hysteresis effect in azimuth pointing offsets. These measurements were made with the optical pointing and data acquisition system, programmed by Tom Folkers. With Tom's help, we restricted the sources to be between 25° and 35° elevation. We then drove the telescope counter-clockwise (CCW) to the azimuth limit position, then took data CW, then CCW, CW again, and once more CCW. The curves taken in the same azimuth drive direction agree well, but are separated from the curves taken in the opposite direction by more than 10" (Figure 15). In case the hysteresis results from some binding in the cable wrap at the azimuth limit positions, we did a second run staying ~60° away from the wrap position. The results are shown in Figure 16 and are similar to those with 360° azimuth rotation.

10. While tracking a star and observing it with the optical telescope, we had the duty operator walk on the elevation service platform. Although we were expecting to see position deflections in the elevation direction, the largest deflections were, interestingly, in the azimuth direction (15-30"). This may be further evidence that unexpected and undesired torques are being transmitted through the azimuth shaft to the encoder.

III. Discussion

The hysteresis in the azimuth offsets is a serious problem that cannot be modeled easily. If the hysteresis were removed, we could probably successfully model the sin(2•Az) residual; however, this latter effect is a relatively new and undesirable feature that should be eliminated. Quite possibly, the two effects are related. Isolation and correction of these problems should assume high priority during the 1991 Summer Shutdown.

We can make some speculations about the problems, but they are strictly guesses. The hysteresis loop indicates that the azimuth encoder is not accurately measuring the true azimuth movement of the telescope. The are two likely candidates for this problem: (1) the flexible coupling between the azimuth shaft and the inductosyn, which was replaced about 2 years ago; or, (2) the connection between the azimuth shaft and the elevation yoke structure, which conceivably could have loosened over the years. The hysteresis loop seems to open up to its maximum separation nearly immediately upon reversal of drive direction; however, the normal servo overshoot is apparently not enough to unwind the hysteresis. This suggests that the azimuth drive must reach slew rate for the hysteresis effect to be seen.

The tilt measurements made on the azimuth inductosyn box indicate that the box is under undesirable stresses. If the box is tilting with respect to the telescope pier, the inductosyn is probably not reading the proper azimuth position of the telescope. The stresses could be introduced through the shaft coupling or through the shaft bearing collar and tachometer mount just above the inductosyn shaft. This should be investigated in more detail with mechanical instrumentation.

The measurements indicate that above the azimuth bearing the tilts are mainly 1θ sinusoidal, below the bearing on the pedestal they are mainly 2θ sinusoidal, and on the floor the tilts are again 1θ sinusoidal. This suggests the following qualitative mechanical model for the telescope.

The sinusoidal tilt above the bearing is a combination of the tilt of the azimuth axis with respect to the vertical and a pedestal tilt caused by the unbalanced service platform. The unbalanced platform produces a high load point on the azimuth bearing at the position of the service platform. This causes the bearing and pedestal to deform into an elliptical shape in which the two sides 90° away from the service platform are squeezed inward to form the minor axis of the ellipse. When the platform is rotated 180° in azimuth, the bearing has the same shape, thus producing the 2θ sine wave measured on the pedestal tiltmeter brackets. (To visualize this, take a paper cup, hold it firmly by the base, and press down on one point of the lip.) Because the concrete pier is nearly completely rigid, this 2θ deformation is transformed back to the 1θ tilt measured on the floor of the pedestal. Hence, the whole pier is moving as the result of the unbalanced service platform. The tilt of the inductosyn housing showed both 1θ and 2θ components; the 1θ component must be coming from the tilt of the floor and the 2θ component must be transferred from the azimuth torque tube. The $\sin 2\theta$ residual in azimuth pointing offsets could result from the motion of the inductosyn box, although a misalignment of the main azimuth and inductosyn shafts might also contribute to the problem. We reiterate that this is all conjecture at this time.

IV. Course of Action

Below, we suggest a step by step approach toward eliminating the hysteresis and $\sin(2\theta)$ problems. Hasty "remedies" could make the problems worse instead of better. If any one of the steps below indicates a problem, it may not be necessary to proceed further; in fact, consider most of these suggestions as "food for thought" for now. About 1 hour with the optical telescope is enough to see whether the problem has been fixed or not.

1. Carefully inspect the azimuth shaft coupling to the yoke.

2. Using precision dial indicators, measure the run-out on the shaft just above the encoder coupling. Accuracies to a few microns will be required.

3. Unbolt the shaft collar bearing just above the inductosyn coupling and measure inductosyn box tilts as a function of azimuth rotation angle.

4. Consider isolating the azimuth inductosyn from azimuth axle torques through a redesign of the inductosyn mount and the shaft bearing mount.

5. Consider alternative shaft-inductosyn couplings (e.g., a constant-velocity joint).

6. Consider constructing a "two-pointer" jig with an LVDT sensor to be placed on either side of the inductosyn shaft coupling. Rotate the telescope and measure any possible twist-up in the coupling.

7. Consider reducing the weight of the service platform (e.g., replace the steel grates with aluminum grates) and counter-balancing the platform on the opposite side of the pedestal.

8. Consider stiffening the pedestal to eliminate the measured deformations.

Figure Captions

Figure 1: Tilt angles measured just above the azimuth bearing as the telescope was rotated in azimuth angle. The mounting flange for the tiltmeter was ~6 in above the bearing, directly below the elevation bull gear, on the side in which the dish tips in elevation. The sine curve was fitted by non-linear least-squares.

Figure 2: Tilt data from the same position, taken by MacDowall and Ulich in July 1978. The tiltmeter was oriented 180° different from our measurements, hence the phase difference in the curves.

Figure 3: Tilts measured on the pedestal below the azimuth bearing, as the telescope is rotated in azimuth angle. The mounting flange is on the slanted part of the pedestal, about 1 ft below the azimuth bearing, at a position facing directly south (180° Azimuth). The curve was fitted by non-linear least-squares.

Figure 4: Tilt data from the same position, taken by MacDowall and Ulich in July 1978. The residuals show more pronounced higher order terms than the more recent data. The fit was by eye.

Figure 5: Tilts measured on the pedestal, below the azimuth bearing, at the four cardinal points (0°, 90°, 180°, and 270°) as a function of telescope azimuth rotation angle.

Figure 6: Tilts measured with the tiltmeter on top of the azimuth inductosyn house (near right-hand side as you look through the pedestal door), as a function of telescope azimuth rotation angle. The curve shows a combination of $\sin\theta$ and $\sin 2\theta$ terms.

Figure 7: Linear translations in the azimuth inductosyn house as a function of telescope azimuth rotation, measured with the NOAO laser interferometer in January 1990. The laser was stationed just outside the west end of the control room. The retro-reflector was positioned on the inductosyn house on the near right-hand side as you look through the door (same place as the tiltmeter described in Fig. 6). The break at 70° azimuth results from the cable wrap limit; the break at ~280° azimuth occurred when the service platform ladder interrupted the laser beam.

Figure 8: Tilts measured on the floor of the pedestal as a function of azimuth rotation angle. The tiltmeter was placed about half-way between the door and the inductosyn mounting stand. The fitted sine curve was done by eye.

Figure 9: Tilts measured just atop the east elevation yoke arm as a function of azimuth rotation angle, in May 1989. The solid squares show the measurements with the tiltmeter aligned perpendicular to the elevation axis, and the pluses show the measurements with the

tiltmeter parallel to the elevation axis.

Figure 10: Same as Figure 9, but measured by MacDowall and Ulich in July 1978. The tiltmeter was oriented perpendicular to the elevation axis. Position "B" was 14 in below the elevation encoder (the old Baldwin), east end of the elevation axis, and corresponded to tipping south. Position "C" was below and to the north of the elevation axis, about 5" from the old air conditioner unit and corresponds to tipping south.

Figure 11: Same as Figure 10, but with the tiltmeter oriented parallel to the elevation axis.

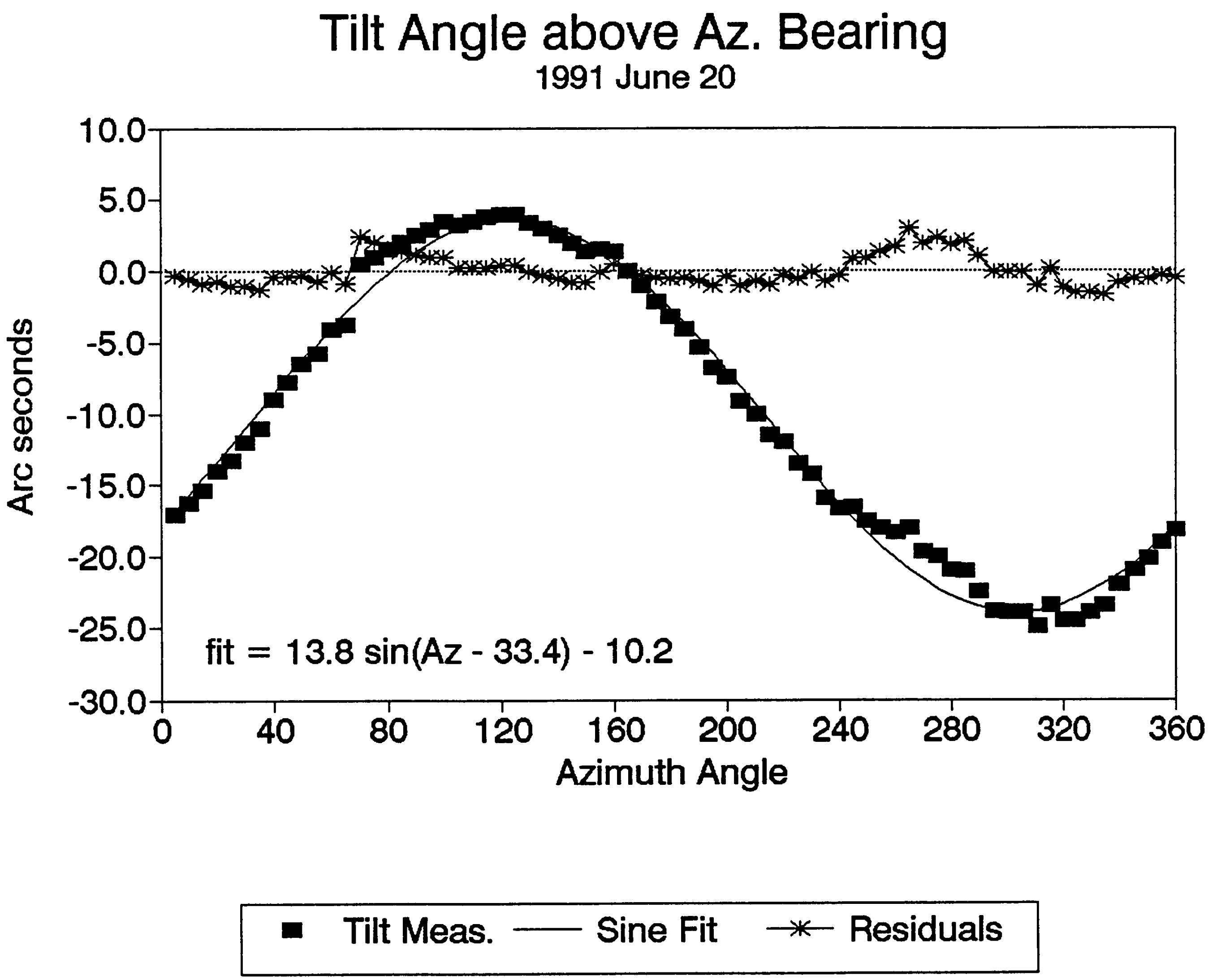
Figure 12: Tilts in the elevation structure as a function of telescope elevation angle as measured by MacDowall and Ulich in July 1978. Position "I" was at the top of the yoke, on the (Baldwin) encoder side. Position "K" was on the shelf directly below the elevation coupling. Positive deflections correspond to tipping south.

Figure 13: Changes in the elevation encoder reading, with the elevation brakes on, as the telescope is rotated in azimuth, as measured by Ulich in September 1978. The top curve was as at an elevation angle of 90°, the bottom at 30°.

Figure 14: Similar measurement to Figure 13, but done in June 1991. The measurement was done with the elevation stow-pin inserted.

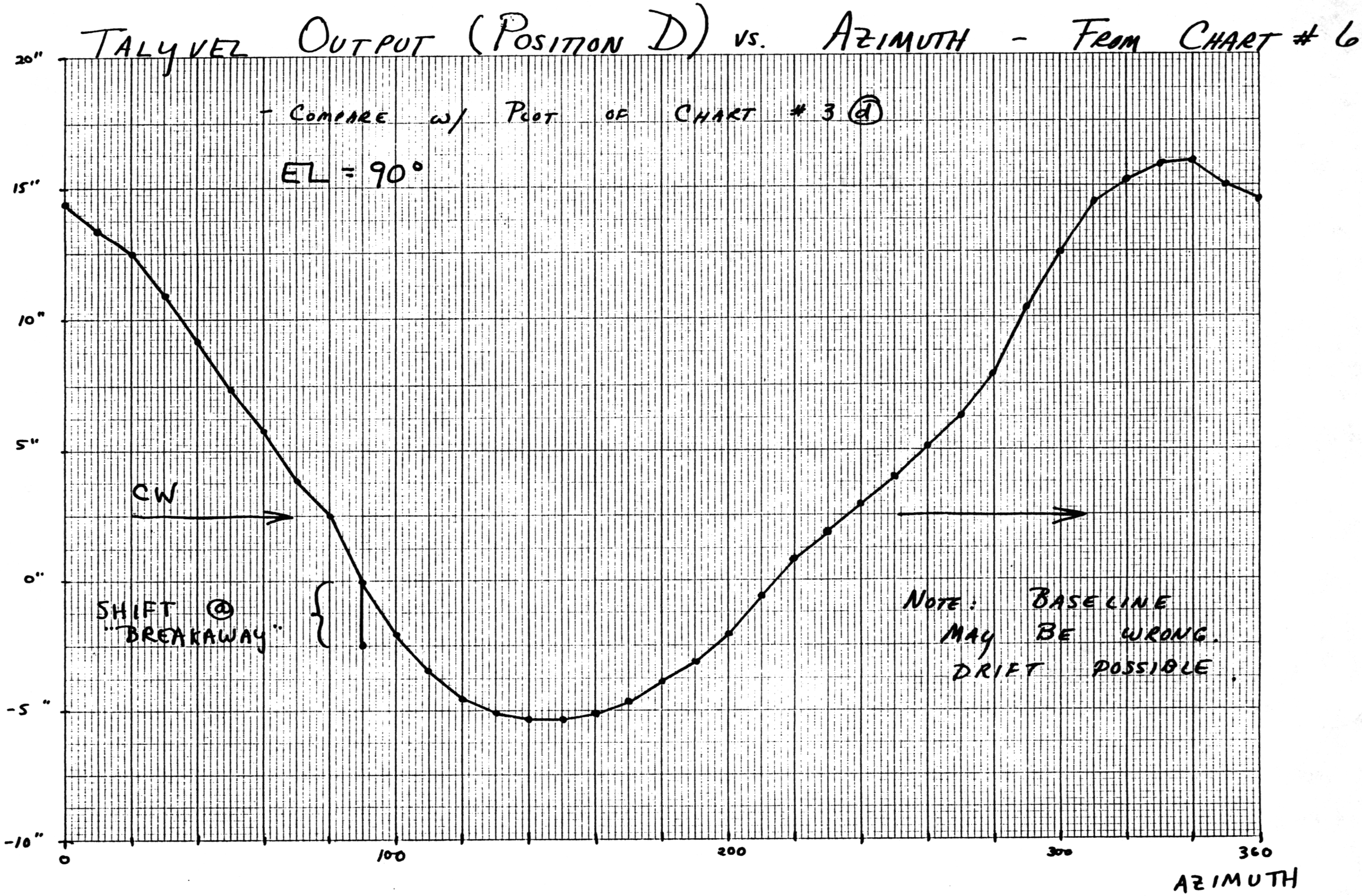
Figure 15: Display of hysteresis in the azimuth pointing offsets as a function of azimuth position. The observations were done with the optical pointing system. All stars were within an elevation band between 25° and 35°. The observations were made starting at 70° azimuth and rotating first clockwise (increasing azimuth), then counter-clockwise, back clockwise, and back again counter-clockwise.

Figure 16: Same as Figure 15, but in a restricted azimuth range, to investigate the possibility that the hysteresis is introduced in the azimuth cable wrap region.



Tilt Angle above Az. Bearing
1991 June 20
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
Arc seconds
0
40
80
120
160
200
240
280
320
360
Azimuth Angle
fit = 13.8 sin(Az - 33.4) - 10.2
Tilt Meas.
Sine Fit
Residuals

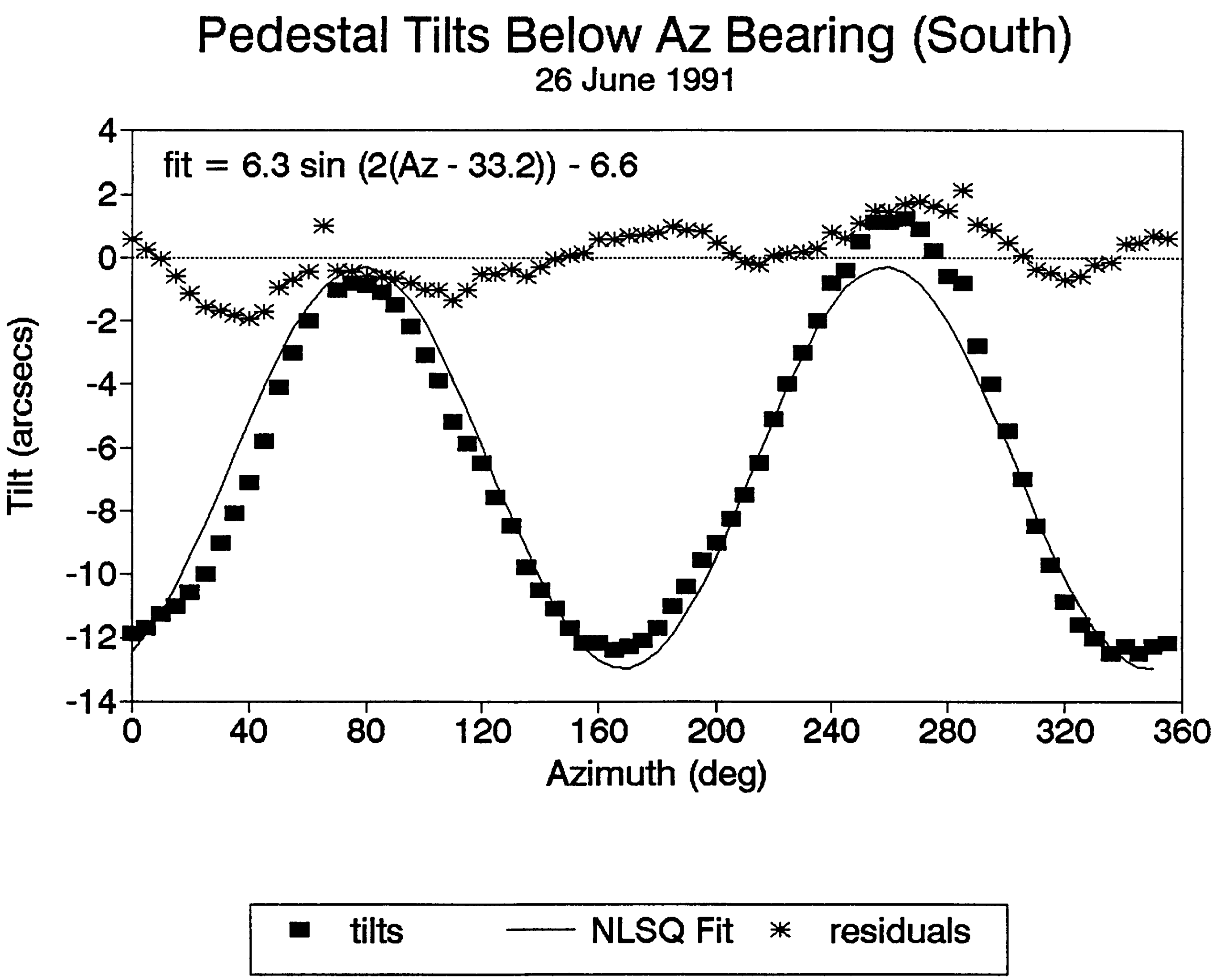
FIG. 1



TALYVEL OUTPUT (POSITION D) vs. AZIMUTH - FROM CHART # 6
- COMPARE w/ PLOT OF CHART # 3 (d)
EL = 90°
20"
15"
10"
5"
0"
-5 "
-10"
0
100
200
300
360
AZIMUTH
CW
SHIFT @ "BREAKAWAY"
NOTE: BASE LINE MAY BE WRONG. DRIFT POSSIBLE.

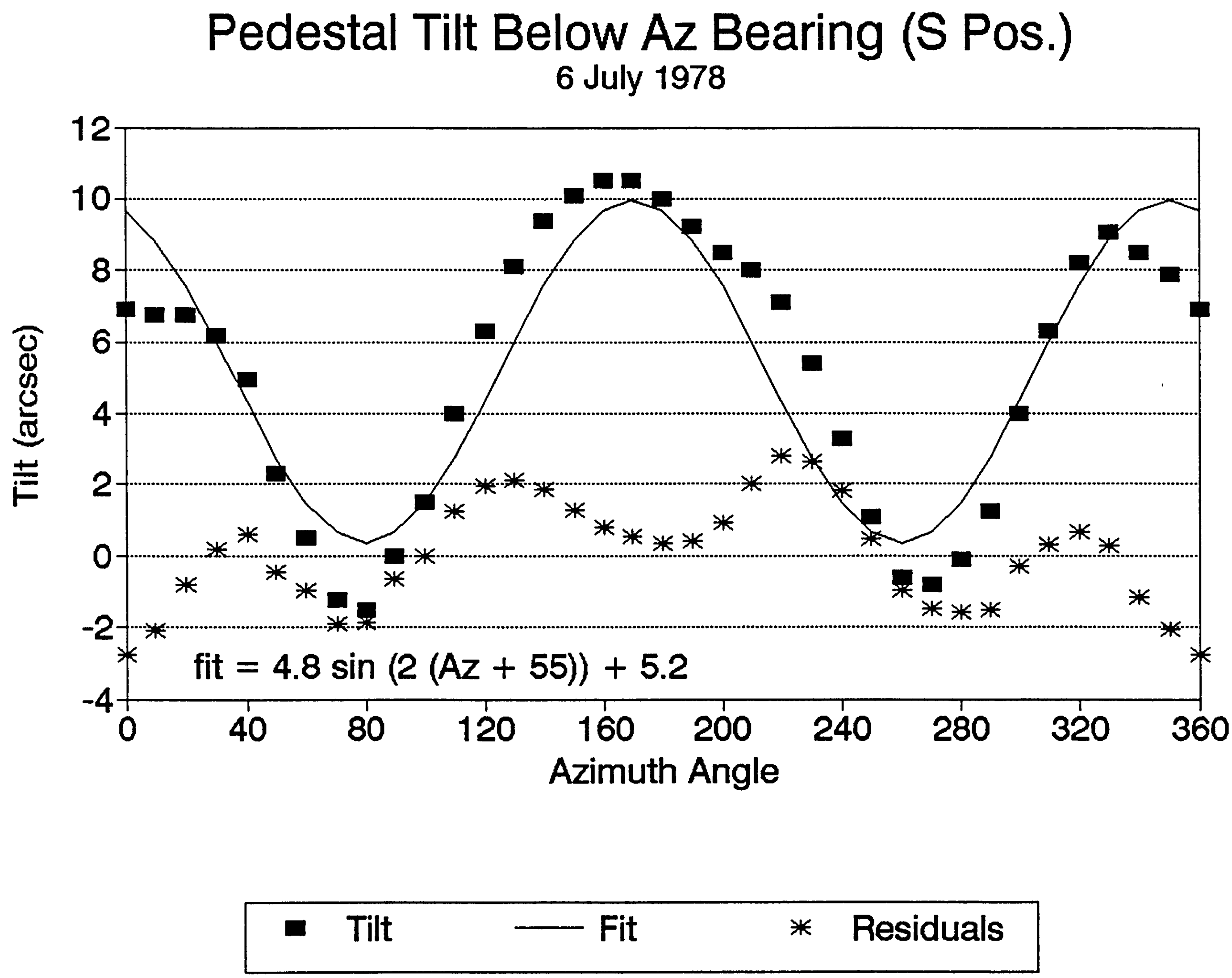
FIG. 2

RM 7/7/78



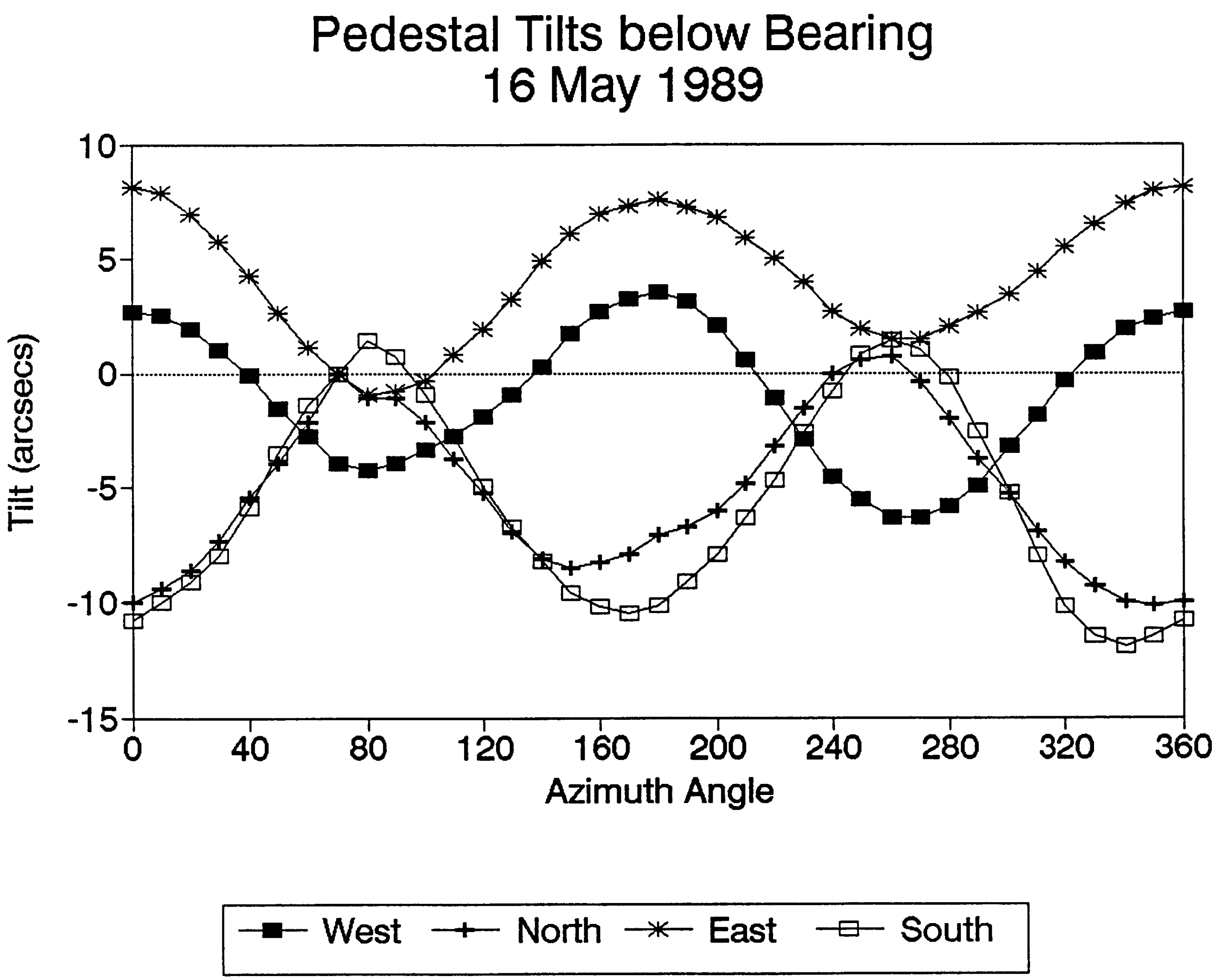
Pedestal Tilts Below Az Bearing (South)
26 June 1991
fit = 6.3 sin (2(Az - 33.2)) - 6.6
Tilt (arcsecs)
4
2
0
-2
-4
-6
-8
-10
-12
-14
0
40
80
120
160
200
240
280
320
360
Azimuth (deg)
tilts
NLSQ Fit
residuals

FIG. 3



Pedestal Tilt Below Az Bearing (S Pos.)
6 July 1978
Tilt (arcsec)
12
10
8
6
4
2
0
-2
-4
fit = 4.8 sin (2 (Az + 55)) + 5.2
0
40
80
120
160
200
240
280
320
360
Azimuth Angle
Tilt
Fit
Residuals

FIG. 4



Pedestal Tilts below Bearing
16 May 1989
Tilt (arcsecs)
10
5
0
-5
-10
-15
0
40
80
120
160
200
240
280
320
360
Azimuth Angle
West
North
East
South

FIG. 5

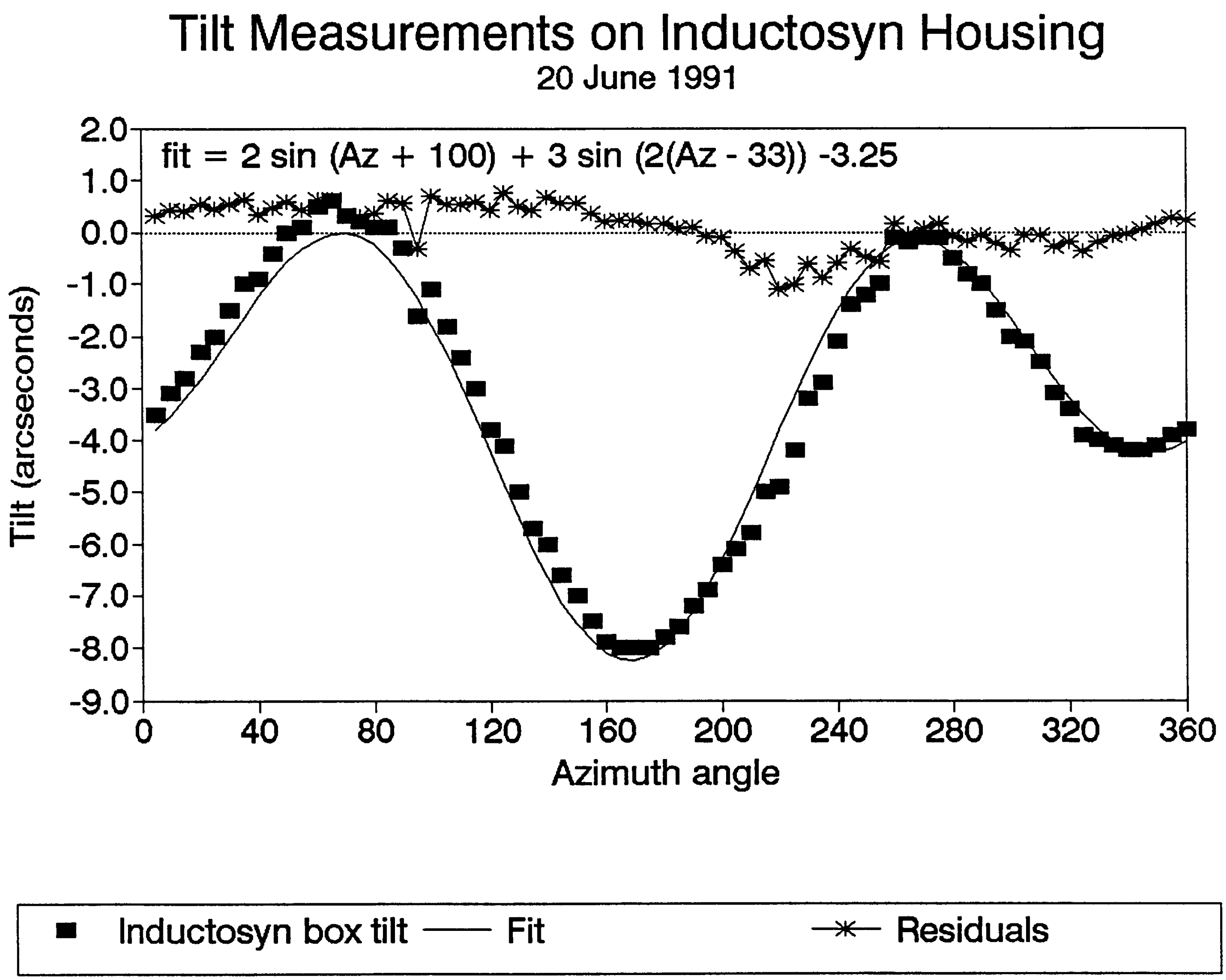
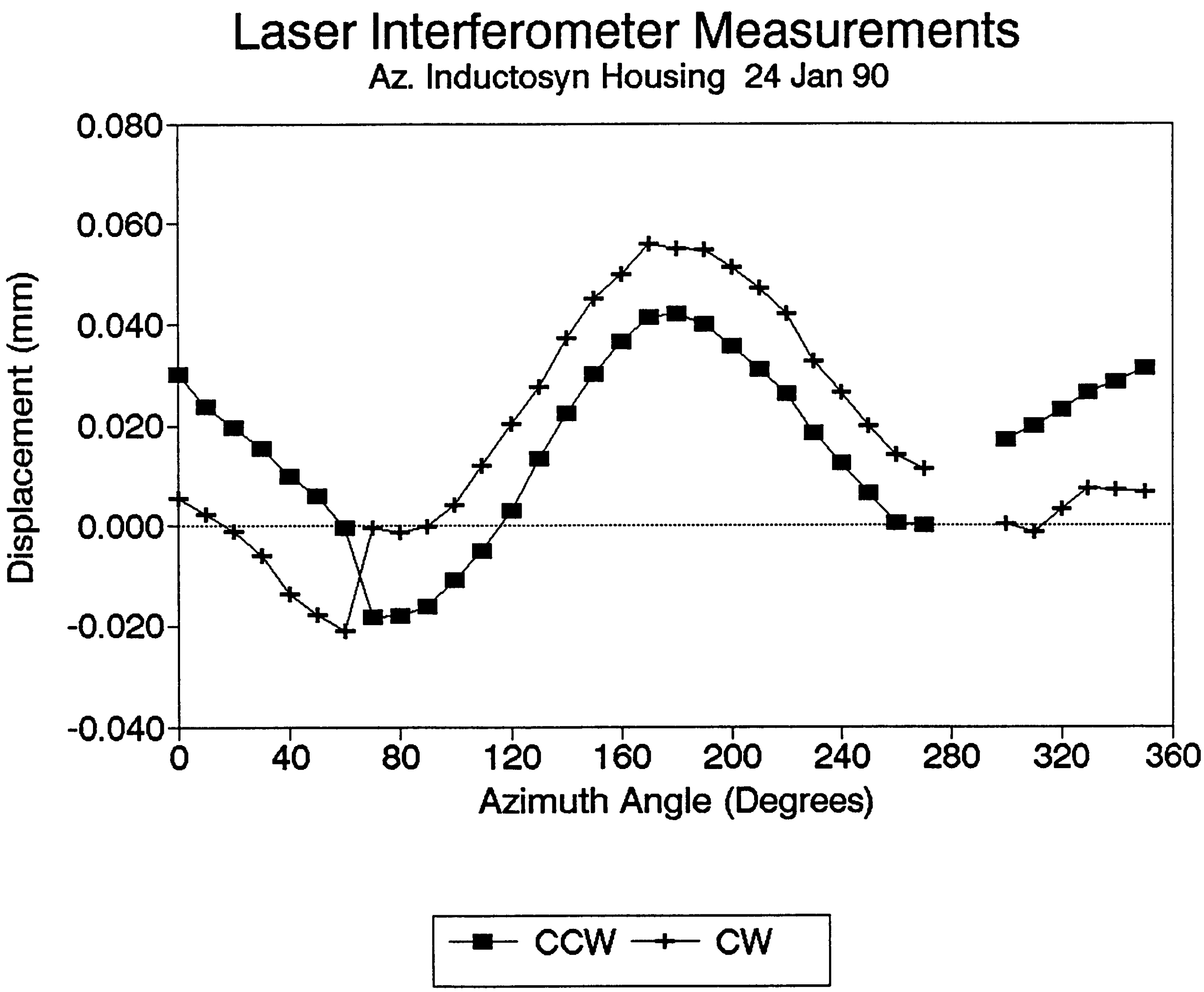

Tilt Measurements on Inductosyn Housing
20 June 1991
fit = 2 sin (Az + 100) + 3 sin (2(Az - 33)) -3.25
Tilt (arcseconds)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
0
40
80
120
160
200
240
280
320
360
Azimuth angle
Inductosyn box tilt
Fit
Residuals

FIG. 6



Laser Interferometer Measurements
Az. Inductosyn Housing 24 Jan 90
0.080
0.060
0.040
0.020
0.000
-0.020
-0.040
Displacement (mm)
0
40
80
120
160
200
240
280
320
360
Azimuth Angle (Degrees)
CCW
CW

FIG. 7

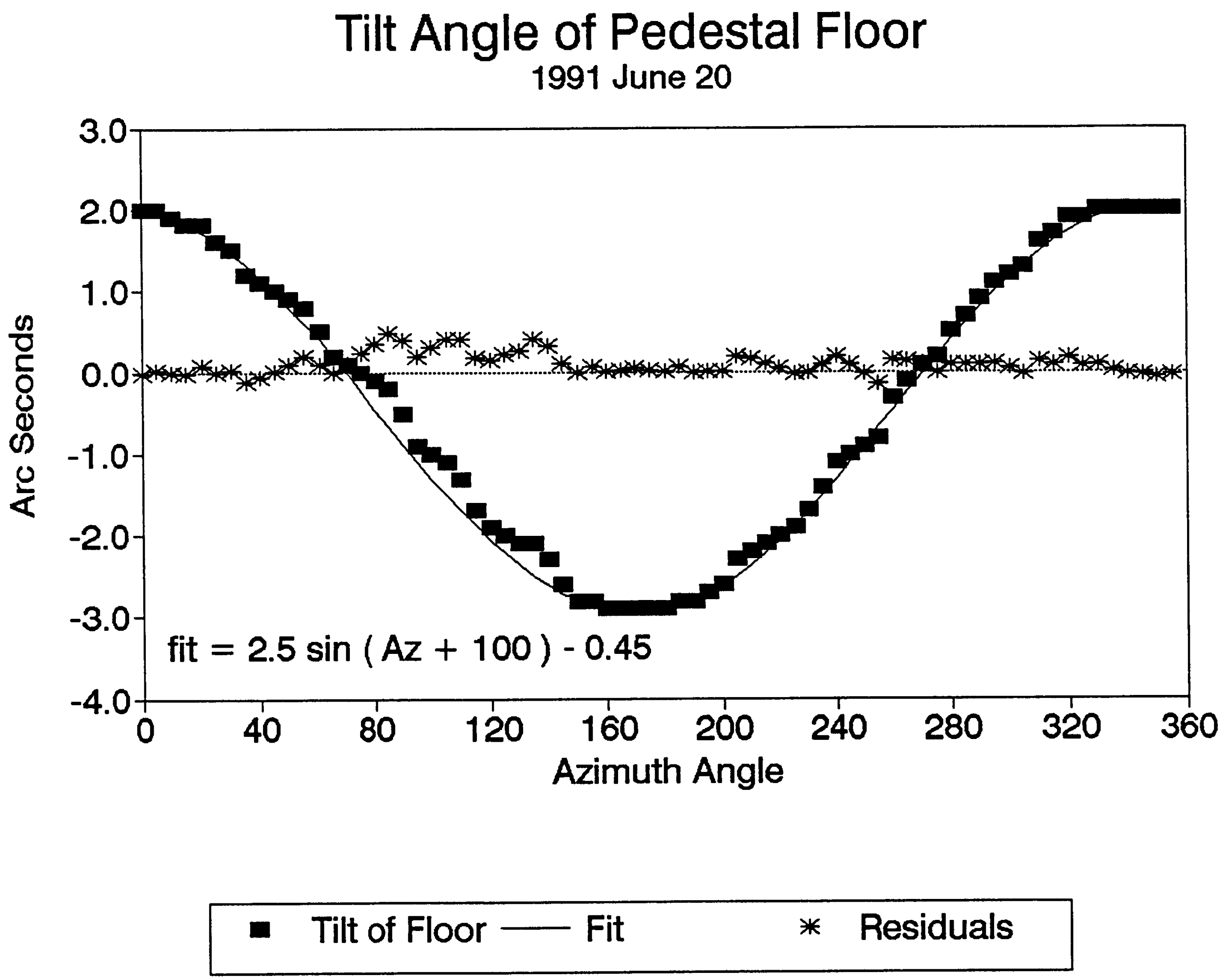

Tilt Angle of Pedestal Floor
1991 June 20
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
Arc Seconds
fit = 2.5 sin (Az + 100) - 0.45
0
40
80
120
160
200
240
280
320
360
Azimuth Angle
Tilt of Floor
Fit
Residuals

FIG. 8

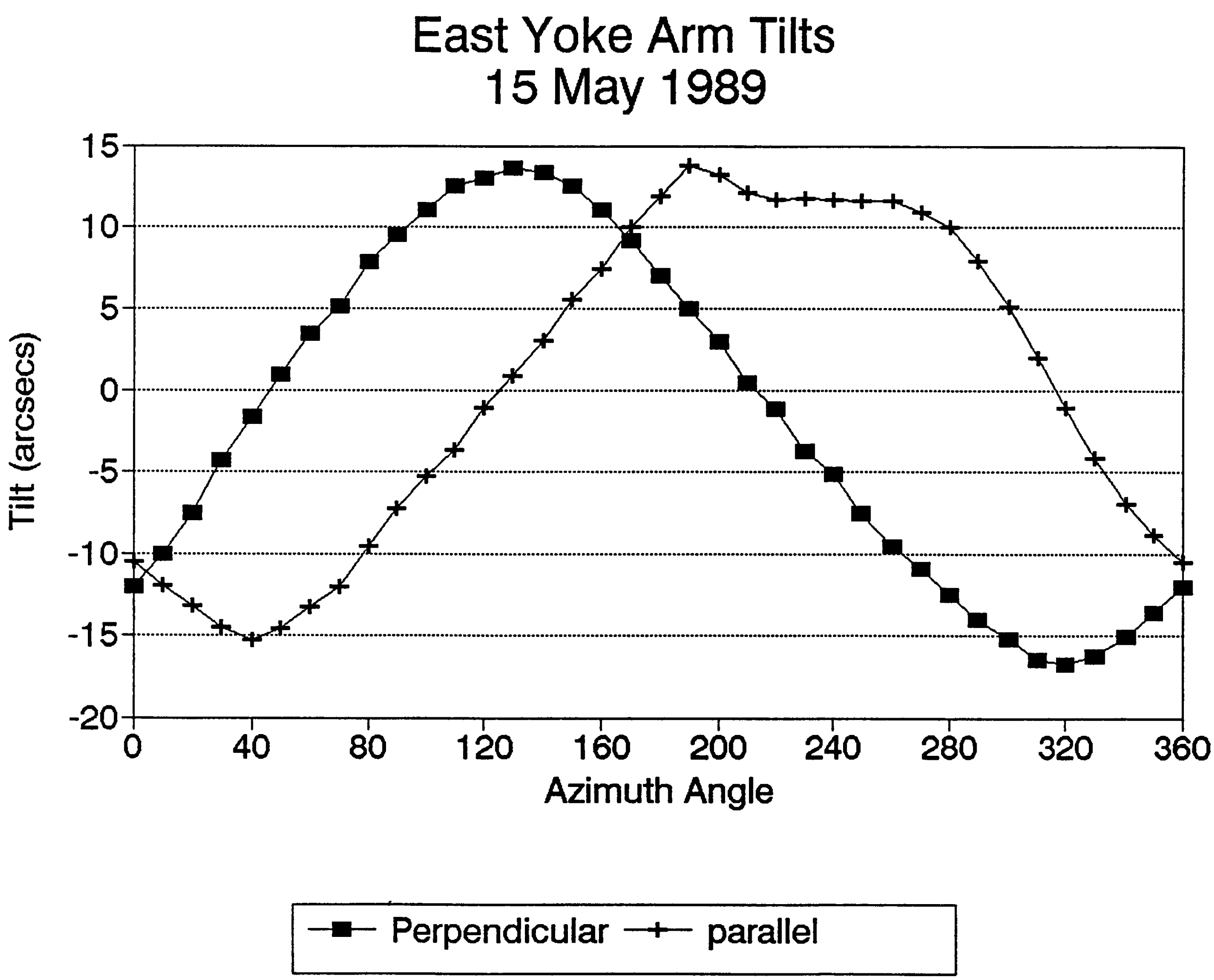
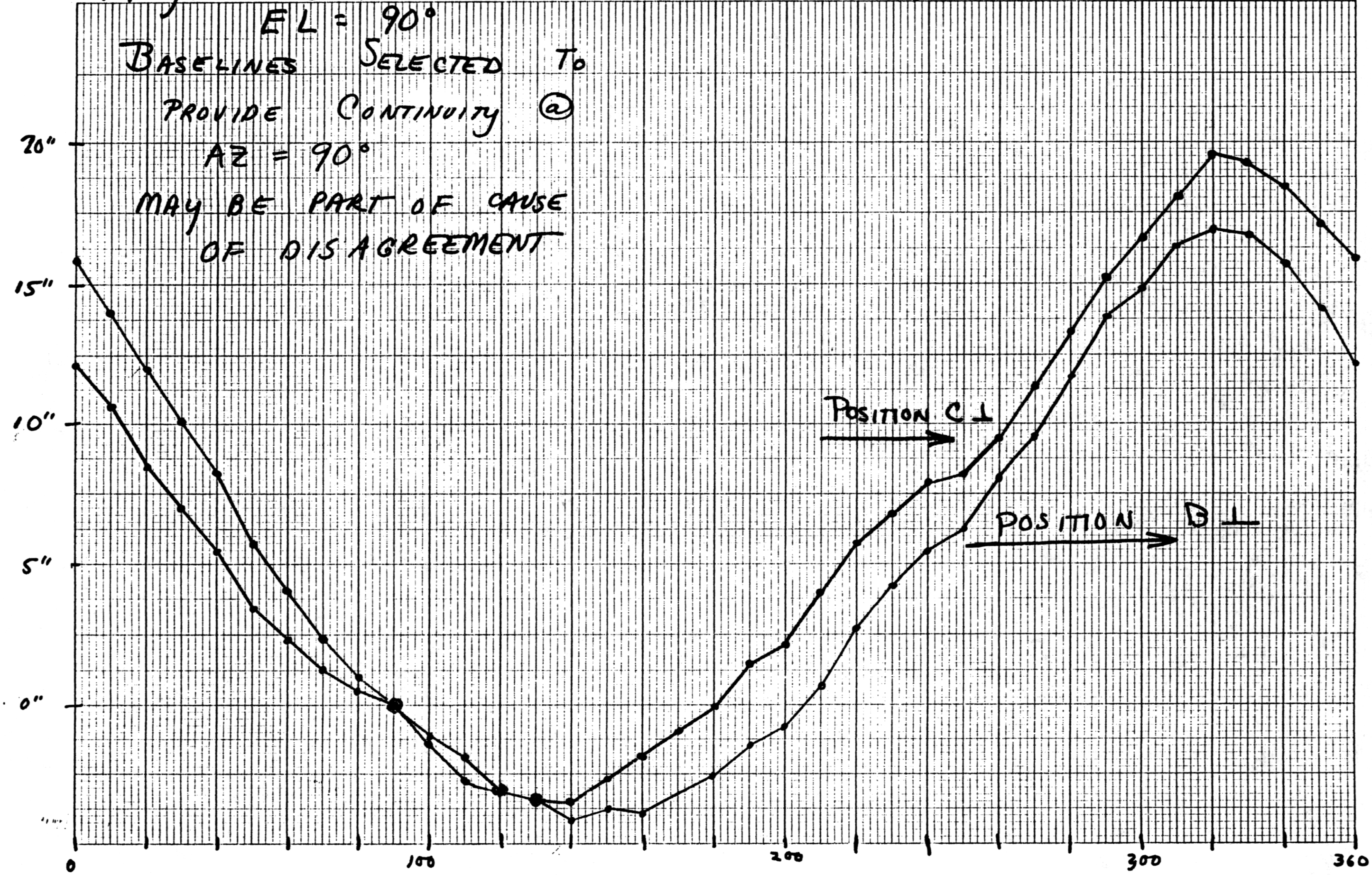

East Yoke Arm Tilts
15 May 1989
Tilt (arcsecs)
15
10
5
0
-5
-10
-15
-20
0
40
80
120
160
200
240
280
320
360
Azimuth Angle
Perpendicular
parallel

FIG. 9

TALYVEL OUTPUT (POSITIONS B⊥ & C⊥) VS. AZIMUTH - CHARTS # 8 (i) (j)



AZIMUTH

FIG. 10

DATA TAKEN: 7/12

RM 7/18/78

TALYVEL OUTPUT (POSITIONS B11 -and- C11) VS. AZIMUTH - CHARTS # 8 (d) (f)

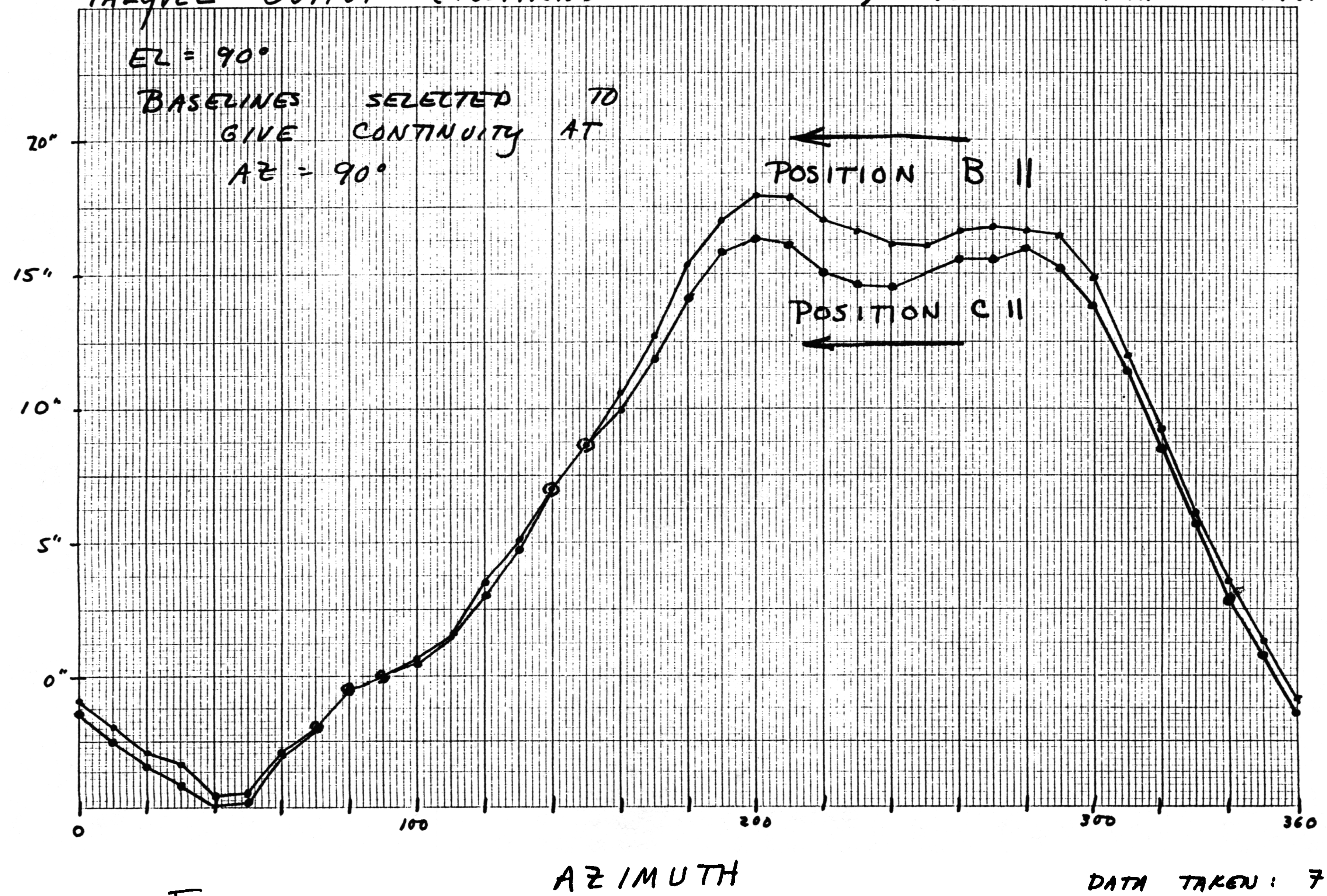


FIG. 11

DATA TAKEN: 7/12
RM 7/12/78

ANGLE (ARCSEC) VS. ELEVATION - 7/20/78 - POSITIONS I⊥, K⊥, K'

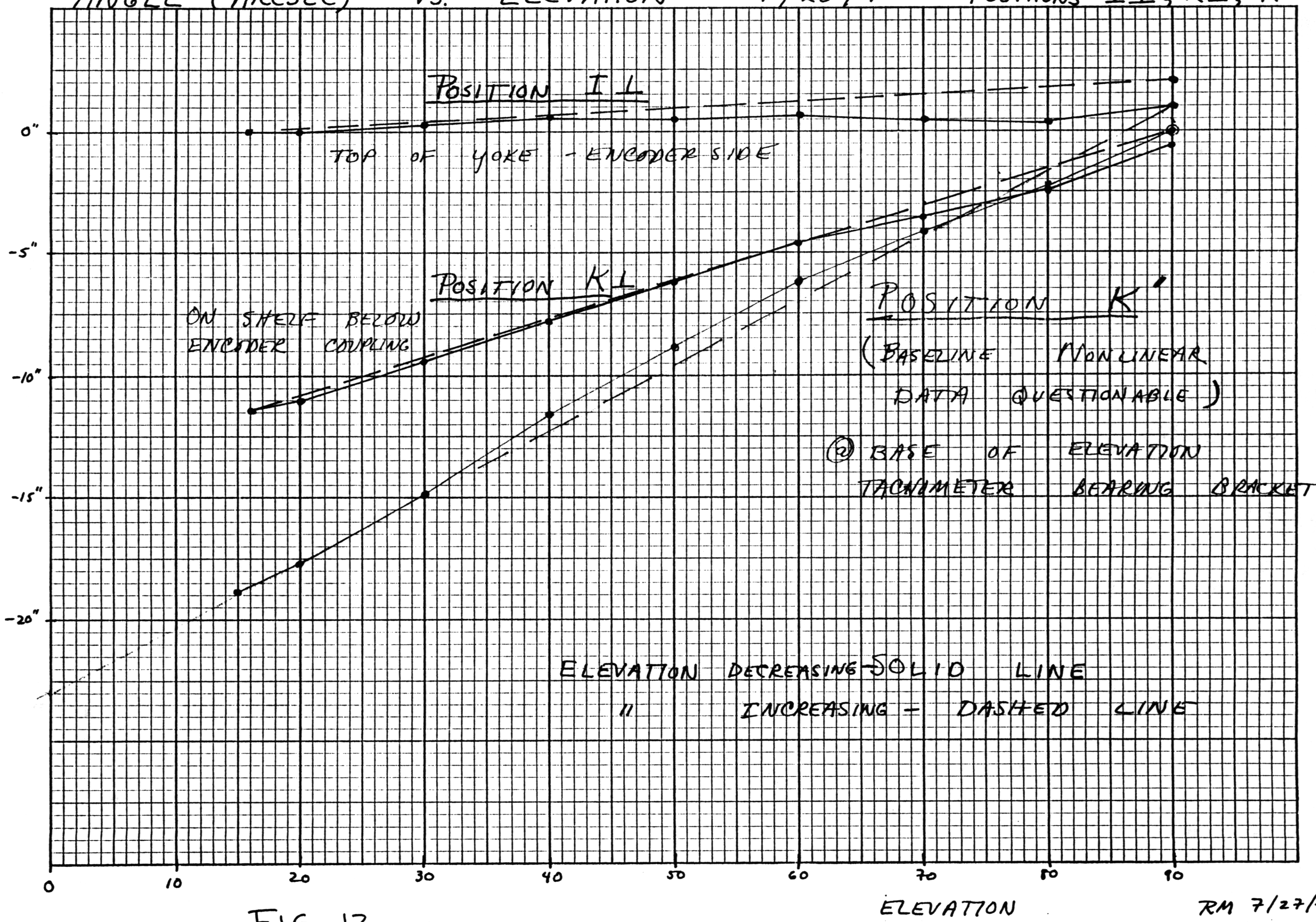


FIG. 12

RM 7/27/78

9/6/78

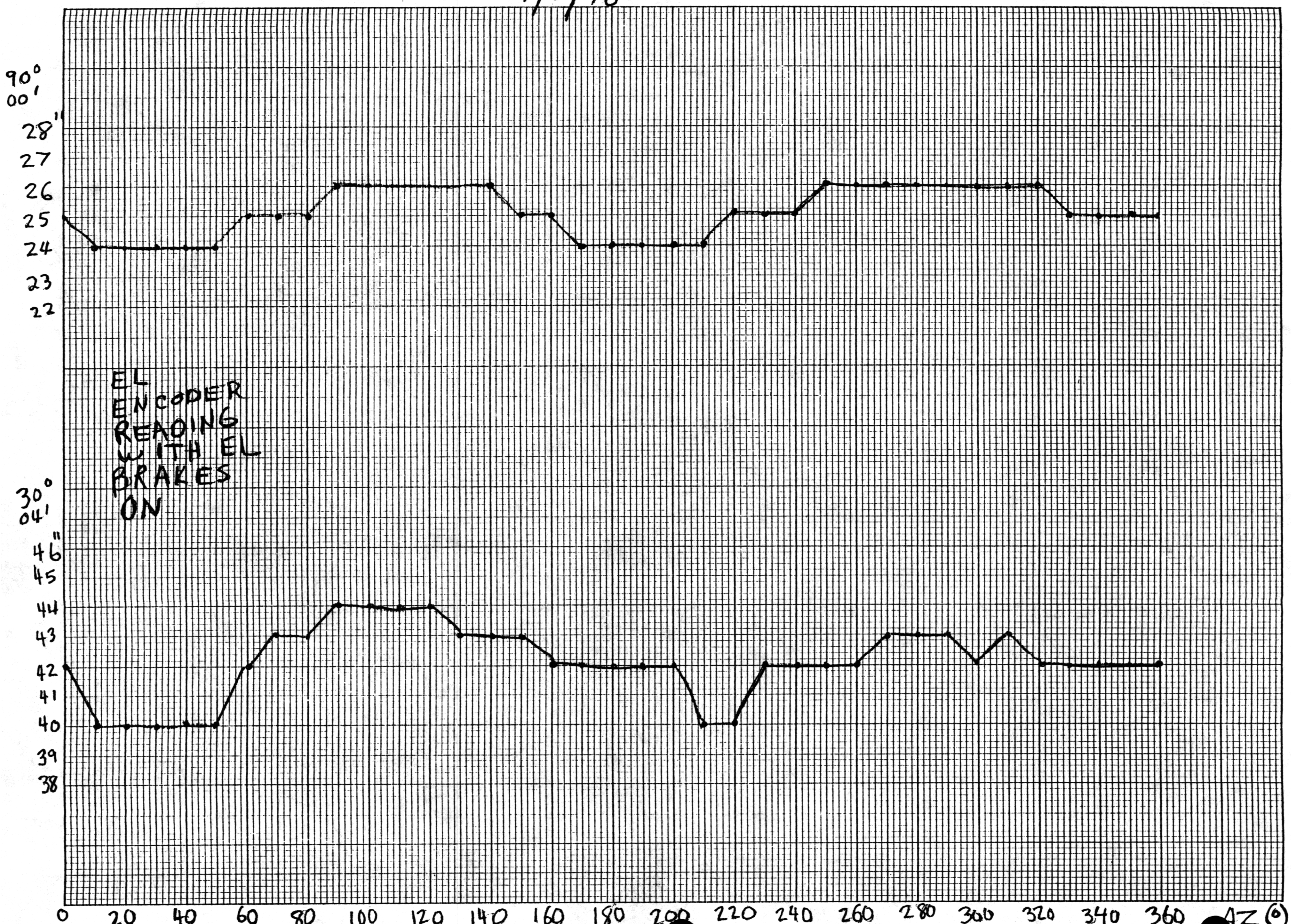
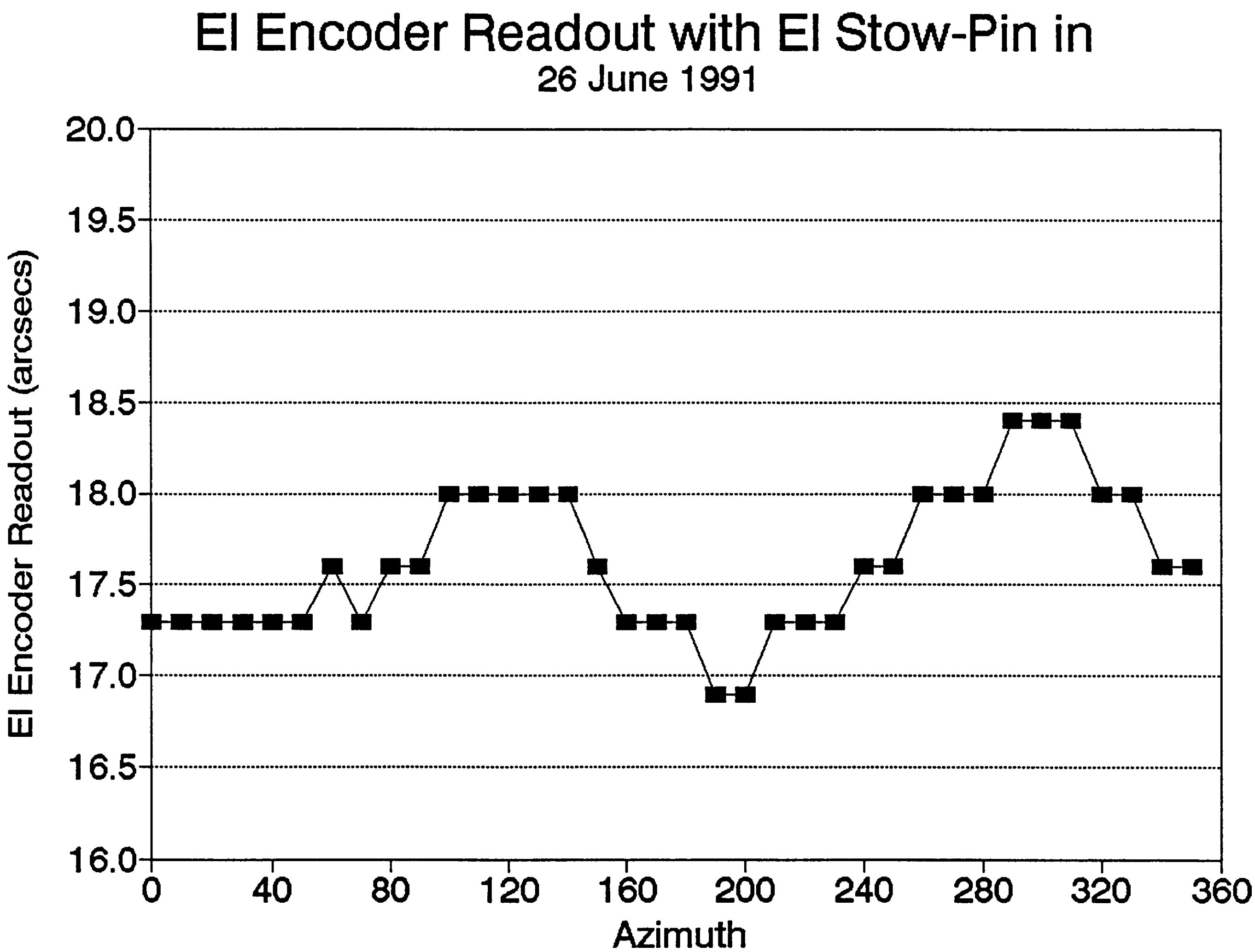

90°
00'
28"
27
26
25
24
23
22
EL
ENCODER
READING
WITH EL
BRAKES
ON
30°
04'
46"
45
44
43
42
41
40
39
38
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
AZ (°)

FIG. 13



El Encoder Readout with El Stow-Pin in
26 June 1991
El Encoder Readout (arcsecs)
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
0
40
80
120
160
200
240
280
320
360
Azimuth

FIG. 14

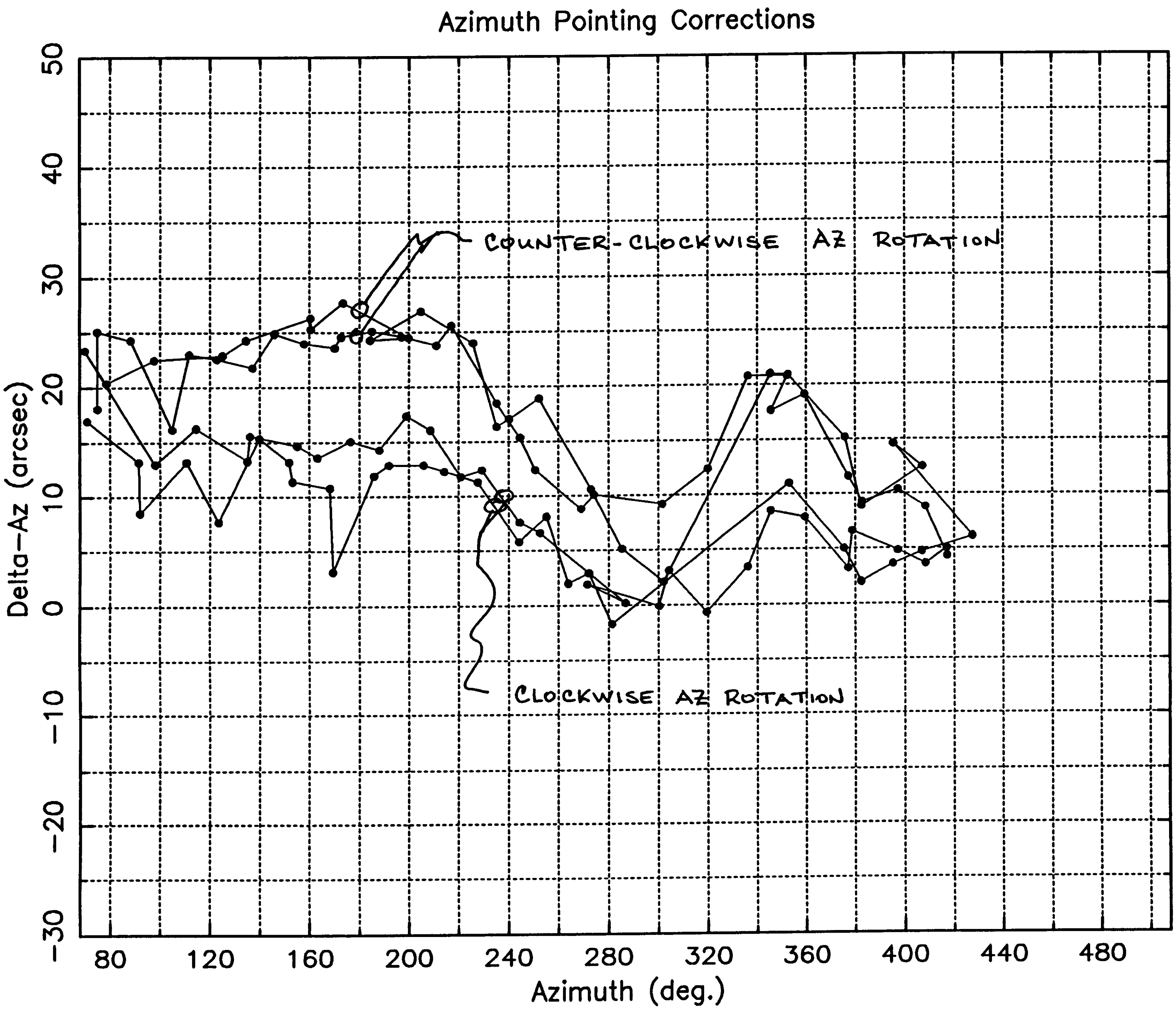


FIG. 15

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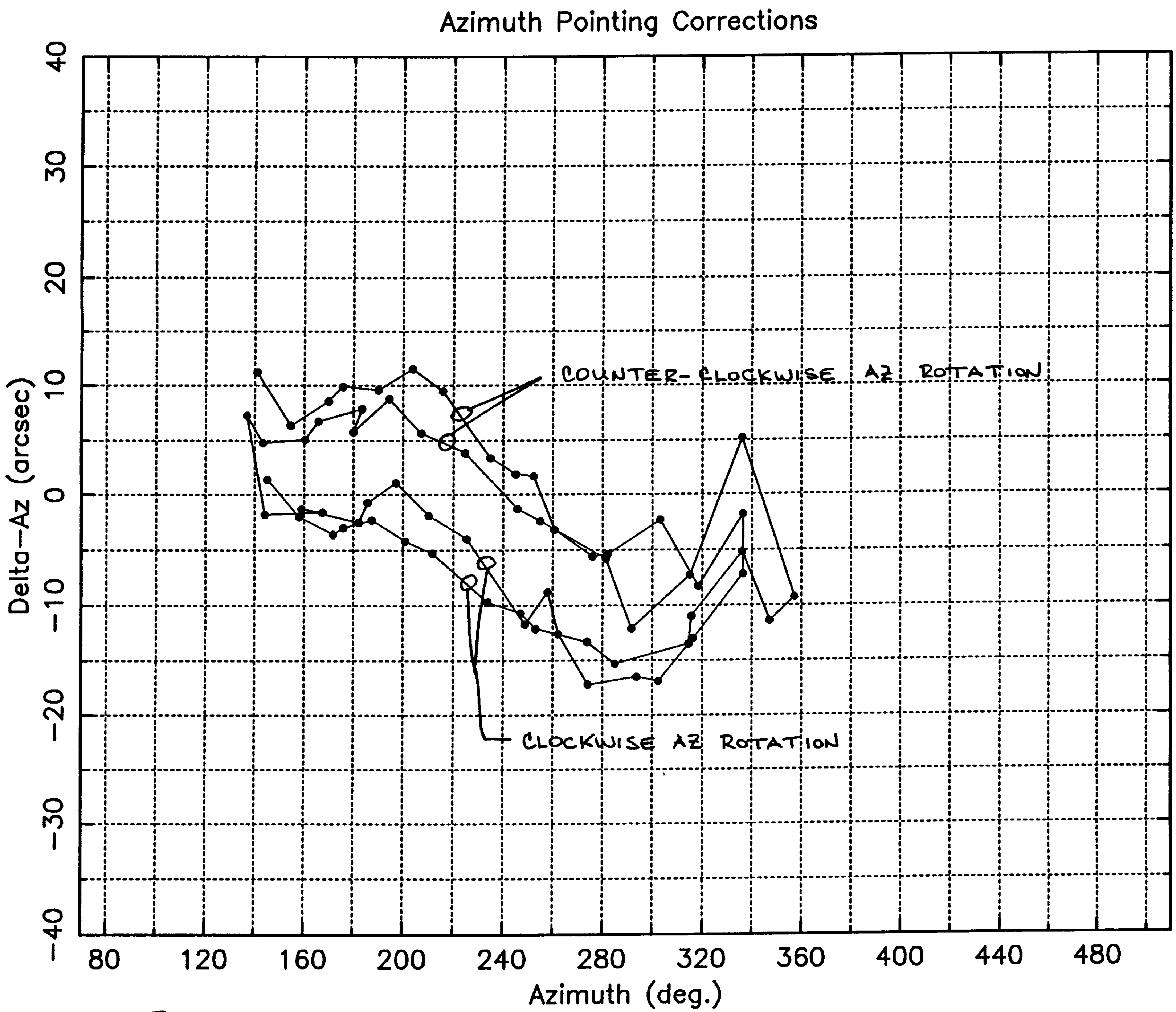

FIG. 16

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