NATIONAL RADIO ASTRONOMY OBSERVATORY
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INVESTIGATING the USE of TILTMETERS to CORRECT VLA ANTENNA POINTING
Part I. INITIAL MEASUREMENTS AND ANALYSIS

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I. INTRODUCTION

Tiltmeters have been mounted on two VLA antennas for a long time. Various attempts have been made to suggest uses and to understand measurements made with them so as to correct radio pointing problems (von Hoerner, VLA Test Mem. 132, 1981 ; von Hoerner, VLA Test Mem. 135 , 1982 ; Newell, VLA Test Mem. 138 , 1982 ; Newell, VLA Test Mem. 142, 1983 ; Carilli and Perley, uncatalogued). However, there have been only a few instances in which tiltmeter measurements have been fully analyzed, and in each case only a small amount of data was used.

The tiltmeters are mounted on the antenna and measure small changes in the inclination (relative to the local vertical) of the structural members to which they are attached. The purpose of making the measurements is to find places on the antenna structure for which variations in tilt correlate well with errors in radio pointing. Ultimately, one would expect to make real-time corrections for these errors. This can only work effectively if the components of tilt which affect radio pointing can be separated from other components of tilt (such as local bending, vibration, changes when the antennas are moved, etc.)

This memorandum outlines methods by which tiltmeter data could be treated, discusses calibration of the tiltmeters, and analyzes an initial series of measurements. This series of measurements is designed primarily to establish whether the tiltmeter readings are repeatable and to look for unsuspected systematic effects.

II. SETTING UP THE TILTMETERS

Figure 1 shows the antenna yoke-structure which is supported by the azimuth bearing and which in turn supports the elevation bearings. A single tiltmeter had been mounted near the azimuth bearing and another pair had been mounted on the encoder side of the yoke near one of the elevation bearings. The tiltmeter near the azimuth bearing appeared to be registering considerable local bending which was thought not to apply to the yoke as a whole. During the summer of 1986 a pair of tiltmeters was located on the waveguide side of the yoke, approximately symmetrically disposed to the pair on the encoder side of the yoke. There were several intents: to check the "tracking" (i.e. symmetrical behaviour) of the two sides of the yoke; to get redundant information from the two pairs of tiltmeters; to find out just how much of the non-planar distortions found near the azimuth bearing are transmitted to the top of the yoke. In principle, since all deflections below the mounting points of the tiltmeters will be registered, they should be placed as high as possible on the structure. It is at this point that feedback to radio pointing corrections would be most direct.

As illustrated in figure 1, there are now 4 tiltmeters. They are labelled the XW, YW, XE, and YE tiltmters and are currently mounted only on antenna 22.

The tiltmeters used here are made by Schaevitz Engineering. They are sensitive to tilt in 1 direction only. A pair is needed to instantaneously measure the direction of the normal to a plane relative to the local vertical They are a small, sealed modular unit (about 3.5 by 1.6 inches). They operate by means of an enclosed pendulum which is kept in place by a torque-inducing coil which offsets the gravitational torque in a closed-loop feedback system. They will operate over about a 1 degree range over which the internal electronics provides about 10 volts of output swing into a 5 Kohm impedance. Obviously, they are designed to operate only in a static situation. Other specifications are given in Appendix I. At the VLA they are used in an operational amplifier circuit which can control the gain and time constant of the output.The output of this circuit is digitized (12-bits) and a sample sent through the waveguide system every 800 ms to one of the system monitor points.

The gain of the tiltmeters has been readjusted to about 10 mvolt per arcsec. This allows a range of about ±17 arcmin with a resolution of 0.5 arcsec for a 1-bit change in the A/D converter. About ±12 arcmin of range is needed to accomodate the gravitational deflection at the antenna positions farthest from the center of the array (see below).

Several competing factors limit the range of time constants for the tiltmeter circuit: a) The time constant of the tiltmeter, itself, is about 2 seconds b) The antenna-structure/control- system has a natural frequency of about 2.5 Hz c) There is a noise component plus a spurious 250 kHz output which should be kept as low as possible. d) The time constant should be short enough to allow a tiltmeter reading to be made quickly after antennas stop slewing. The final electronic time constant has been adjusted to about 10 seconds but further tests will be required to optimize it.

Appendix II contains the system information required to access the tiltmeter readings for antenna 22. Information on software is likely to change when new Modcomp control computers are installed.

III. MEASURING TILT AS A FUNCTION OF AZIMUTH AND ELEVATION

A considerable number of simple measurements are needed to check the repeatability of both the tiltmeter measurements and the antenna, itself. This can be most easily checked by moving the antenna at intervals in azimuth around a complete circle at a constant elevation. A measurement series of this type is known at the VLA as a "box run". Figure 2 is a sample plot of the tilt measurements taken at 22.5 degree intervals in azimuth for an elevation of 90 degrees.

Individual tiltmeter readings at a fixed antenna position are combined in a weighted average as follows: When the antenna stops slewing it waits for 50 seconds before using any readings. The output, $\bar{x}$ (initially set to the first reading), is updated according to the recursive relation:

$$\bar{x}_{new} = \frac{1}{8}x + \frac{7}{8}\bar{x}_{old} \ .$$

This is continued for 25 readings (sampled every 800 ms for 20 s), having the effect of a time constant of about 7 s. The final value of $\bar{x}$ is retained.

At present, the easiest way to handle the data is to have it printed one of the on-line printers attached to the MODCOMPS. However, it must then be re-typed on a VAX. Since there are only 136 numbers for each box run, this is still easier for this amount of data than recording it as a disk file and then trying to negotiate the tortuous path to a VAX computer.

It is important to determine the long-term stability of the tiltmeters and to have a way of checking the gains while they are in service. A computer programme has been written to fit a sinusoid to each of the four data records independently. Providing that the antenna and the tiltmeters are stable throughout the box run, the tiltmeters can be calibrated in situ. In the following section, equations for the tiltmeter gain and two angular parameters related to the orientation of the tiltmeters are derived. (It will eventually be shown, however, that there are rapid changes in the antenna which may make in situ calibration impractical.)

IV. IN SITU CALIBRATION

Each tiltmeter is associated with three parameters, two of which describe its mounting orientation with respect to the antenna:

G = gain (mvolt of output per arcsec of tilt),

h = angular offset of the mounting plane from horizontal (constant tilt) (see figures 1, 3 and 4),

δ = rotation in the horizontal plane from its intended reference direction (see figures 1, 3 and 4).

The tiltmeters can respond only to structural changes below their mounting points near the elevation bearings. The main variation in tilt is sinusoidal with one cycle in 360 degrees of azimuth. This can be calculated in two parts as follows:

1. The radio pointing measurements are done in conditions which are as ideal as possible (i.e. no sun and no wind). These measurements are averaged over many positions on the sky and fitted to a simple model of the antenna. Radio pointing measurments yield, as one of the fitted parameters, the direction of the azimuth axis from the VLA tangent plane (i.e. the plane tangent to the Earth's surface at the array centre). The responses of the E tiltmeters (figure 3) are given as:

$$T_{xz} = -E_{1z}\sin(Az) - E_{2z}\cos(Az)$$

$$T_{yz} = E_{2z}\sin(Az) - E_{1z}\cos(Az)$$

where

E_{1z} = E-W component of azimuth axis tilt - top of the azimuth axis towards East is positive.

E_{2z} = N-S component of azimuth axis tilt - top towards North is positive.

2. The second component is due to the direction of the local vertical with respect to the VLA tangent plane. The responses of the E tiltmeters to this component are given as (figure 4):

$$T_{xs} = 32.3R_s\cos(Az - Az_{arm})$$

$$T_{ys} = -32.3R_s\sin(Az - Az_{arm})$$

where Rs is the distance of the antenna from the array centre in km and the E's are in arcsec. This can be expanded in in-phase/quadrature form as:

$$T_{xs} = -E_{1s}\sin(Az) - E_{2s}\cos(Az)$$

$$T_{ys} = E_{2s}\sin(Az) - E_{1s}\cos(Az)$$

where

$E_{1s} = -32.3R_s\sin(Az_{arm})$

$E_{2s} = -32.3R_s\cos(Az_{arm})$

The signs of E_{1s} and E_{2s} are the same as for E_{1z} and E_{2z}.

The total responses of the E tiltmeters are therefore:

$$T_x = T_{xs} + T_{xz}$$

$$T_y = T_{ys} + T_{yz}$$

In amplitude and phase form:

$$T_x = -A_x\sin(Az + \phi_x)$$

$$T_y = -A_y \cos(Az + \phi_y)$$

where

$$A_x = A_y = \sqrt{(E_{1z} + E_{1s})^2 + (E_{2z} + E_{2s})^2}$$

$$\phi_x = \phi_y = tan^{-1}(-\frac{E_{2z} + E_{2s}}{E_{1z} + E_{1s}})$$

The measurements are fitted to the same form of equations:

$$T_{xf} = -E_{1f} \sin(Az) - E_{2f} \cos(Az)$$

$$T_{yf} = E_{2f} \sin(Az) - E_{1f} \cos(Az)$$

The usual minimization of

$$\epsilon = \Sigma(T - T_i)^2$$

yields

$$E_{1f} = \frac{-\Sigma T_i \sin(Az)\Sigma \cos^2(Az) + \Sigma T_i \cos(Az)\Sigma \sin(Az)\cos(Az)}{\Delta}$$

$$E_{2f} = \frac{-\Sigma \sin^2(Az)\Sigma T_i \cos(Az) + \Sigma \sin(Az)\cos(Az)\Sigma T_i \sin(Az)}{\Delta}$$

where $\Delta = \Sigma \sin^2(Az)\Sigma \cos^2(Az) - (\Sigma \sin(Az)\cos(Az))^2$

The corresponding fitted amplitudes and phases respectively are:

$$A_{xf} = A_{yf} = \sqrt{E_{1f}^2 + E_{2f}^2}$$

$$\phi_{xf} = \phi_{yf} = \tan^{-1}(\frac{E_{2f}}{E_{1f}})$$

These equations apply to the E tiltmeters. The equations for the W tiltmeters are the same except that the signs of E_{1f} and E_{2f} are reversed. Also, of course, the signs of the amplitude and phase equations for the W tiltmeters are reversed. The data from each tiltmeter are fitted separately. The expected amplitude and phase from the above equations are compared with the fitted sinusoids to yield G, h, and δ as follows (Figure 5 shows the geometry for δ):

$$G = \frac{A_f}{A} 10 \text{ (mvolt/arcsec)}$$

where A_f is the fitted amplitude and A is the calculated ampliude.

$$\delta = \phi_f - \phi$$

where ϕ_f is the fitted phase and ϕ is the calculated phase.

$$h = \text{the mean of the residuals}$$

Figure 6 shows the sine/cosine wave fitted to the measurements of figure 2. In the case of the other tiltmeters the expressions for G and h are the same.

The accuracy with which the tiltmeter parameters must be known depends upon how they will be used. If peak residuals of the order of 20 arcsec will be fed back as corrections, accuracies of about

1-2 arcsec should be sufficient. Maximum tiltmeter deflections of about 700 arcsec are expected at stations near the outer part of the array. Therefore, gain errors of less than ($\Delta G/G$) of 0.14% are required for antennas near the outer part of the array. The parameters h and δ should be known to corresponding accuracies of about 1 arcsec and 5 arcmin respectively. For antennas near the inner part of the array, the 1-2 arcsec condition requires much less stringent percentage accuracies but the same absolute accuracies.

V. THE RESULTS OF A SERIES OF MEASUREMENTS

A series of 20 box runs were made between early August, 1986 to December, 1986 on antenna 22. In all cases the nearest radio pointing measurements (see Table 1) were used to derive the expected tiltmeter parameters. During this time the antenna was not moved from station N4 (radius, 134.9 m ; array azimuth, 355°).

1. THE FITTED PARAMETERS

Table 2 shows the derived parameters for all the runs. Tables 3 to 6 show the same data rearranged to list the parameters for each tiltmeter individually. In these tables each run is labelled in the leftmost column in the format DATE.ELEVATION.

It is immediately obvious from inspection of the tables that the fitted parameters are not very stable. I first examine apparent gain changes in the tiltmeters. Since groups of measurements have been made covering a range of elevations in a few hours, it is straightforward to check for a systematic elevation dependence. The tiltmeter gain is plotted in figures 7 and 8 as a function of elevation for the X and Y tiltmeters respectively. The shape of the elevation-gain curve is neither simple nor constant. Even the two sets of measurements taken in December are not the same. It appears, therefore, that the gain changes are not elevation dependent.

Could the gain changes be a result of sytematic measurement error or to drift in the tiltmeter instrumentation? Figure 9a is a plot of the gains of the X tiltmeters on the opposite sides of the antenna yoke against each other. There is a very strong correlation between the XE and XW readings. However, a similar plot (figure 9b) of the X versus Y gains on one side yields a much weaker correlation. Consider the following possibility: the X and Y tiltmeters are contained in the same instrument package at the same temperature. Since the tiltmeters would be expected to have a similar temperature dependence, the gain changes could, therefore, be temperature-induced. But if this were correct, then XW and YW gains would be more correlated than the XW and XE gains. Similar arguments can be made to rule out the effect of changes in components of the system which are common to all tiltmeters (e.g. a common A/D converter, common dataset, etc.).

It must be concluded, then, that the amplitude variations cannot be interpreted as gain changes in the measuring system, but rather as actual changes in the antenna structure.

The parameter labelled CONSTANT TILT in the tables (h in the previous section) might be expected to have an elevation dependence if there is an unbalance between the reflectors and the counterweights. Figure 10 shows h versus elevation as measured by the two X tiltmeters. Figure 11 shows the same thing for the Y tiltmeters. Although the repeatability of the measurements is not very good, it is fairly clear that the X tiltmeters indicate a tilt toward the reflector of about 9 arcsec going from 90° to 15° elevation. Since the antennas are supposed to be counter-weight heavy, this result bears some scrutiny, particularly as to the sign of the variation. The Y tiltmeters do not show as much variation, but the measurements of 861117 are mysteriously discordant. The Y tiltmeters would not be expected to vary as a result of reflector/counterweight imbalance.

2. THE RESIDUALS

Figure 12 shows a sample of residuals for the XW tiltmeters taken from a series of runs on

861205. The residuals are not random. They clearly all have similar forms even at different elevations indicating that higher order fits are possible. However, the shape of the residual curve is not really constant and the higher order terms resulting from the fits would be time variable.

Figure 13 shows a comparison of XW and XE residuals from the same series. Apart from a change in sign, the E and W tiltmeters usually track each other within about 1-2 arcsec, indicating that the individual measurements are reliable to within a few arcsec. This also indicates that there is very little evidence for differential bending of the yoke (i.e. twisting). In the absence of significant yoke-distortion, then the E and W measurements are quasi-independent measurements of a tilt which must originate below the yoke.

There is sometimes a serious "turn-around" error which somtimes occurs during the box run when the measurements are repeated at the same azimuths with the rotation in the opposite sense. In several cases the error occurs for only one or two points after the reversal of direction, but in the worst cases the effect is present over large ranges in azimuth. Figure 14 shows examples. Figure 15 simply shows that the tiltmeters on the two sides of the antenna give the same results even when these "turn-around" errors are present.

3. ERROR ANALYSIS

Since there are 3 independent parameters (degrees of freedom) being derived from the data, the expected errors of A, phi and h are given approximately by:

$$\sigma = \sqrt{3/34}\,\sigma_{residuals}.$$

$\sigma_{residuals}$ is typically 6 arcsec. Using this relation for each of G, δ and h in turn, corresponding formal errors in these measurements are about 0.4 , 2. degrees and 2. arcsec respectively.

The rms variations in G, δ and h are given in Table 7. They are about 3 times larger than expected from the residuals, giving further credence to the idea that significant shifts in the orientation of the azimuth axis are occurring.

4. INTERPRETATION OF MEASUREMENTS ASSUMING PERFECT TILTMETERS

If the tiltmeters are assumed not to need calibration, the readings can be interpreted directly to give the direction of the azimuth axis with respect to the gravity vector. A correction for the variation in the local vertical over the array can be done using the following relation:

$$T'_x = T_{xf} - T_{xs}$$

$$T'_y = T_{yf} - T_{ys}$$

In amplitude and phase form for the E tiltmeters:

$$T'_x = -A'_x \sin(Az + \phi'_x)$$

$$T'_y = -A'_y \cos(Az + \phi'_y)$$

where A' and ϕ' discribe the orientation of the azimuth axis with respect to the tangent plane of the array. A' is the angle between the normal to the array tangent plane and the azimuth axis. ϕ' is the angle in the tangent plane between the projection of the azimuth axis on the tangent plane and the centre-line of the tiltmeter (which is assumed to be mounted on a line of symmetry of the antenna).

The gravitational correction is quite small for the cases investigated here. Therefore, these numbers are essentially re-scaled gains, and the variations in A' and ϕ' will be similar to those for the gains and azimuth offsets discussed above. Table 8 is a list of the amplitudes and orientations for the azimuth axis. The orientations are referenced to individual tiltmeters (i.e. The angles reported are analogous to δ.)

The size of the amplitude variations are much larger than changes measured by radio pointing methods (see Table 1). One would expect these changes to be easily observable in the routine pointing observations unless the variations are so rapid that they are removed by the averaging process which is inherent in the routine pointing determinations. This could be the case. Inspection of Table 8 shows large changes in amplitude in box runs taken one after the other. For example, the amplitudes of the XW tiltmeter readings were 20, 33, 42, 44, 29, and 46 arcsec in adjacent runs on 861217 going from elevations of 15° to 90°.

On the other hand, there could just as easily be some other deflection of the antenna structure which causes the apparent changes seen here. The problem with interpreting the changes as changes in the orientation of the azimuth axis is that there should be equally good correlation between XW and XE and between XW and YW. But as shown in figure 9, this is not the case. There is still some correlation between XW and YW, leaving open the possibility that there is more than one effect present.

VI. DISCUSSION

Final conclusions cannot be reached until a combination of radio pointing measurements and tiltmeter measurements are made. This is the next step in the investigation. The following will be some of the aims of subsequent work:

a) To establish that the variations seen in the tiltmeter readings can be replicated while observing a source. This may require a radio pointing measurement followed by slewing back and forth to mimic the box runs and then returning to radio pointing.

b) To compare the stability of the tiltmeter readings and the radio pointing measurements while the antennas are tracking (small movements instead of gross movements).

c) To try these tests (box runs and radio pointing runs) either on a different antenna or the same antenna on a different pad (or both).

d) To continue to persue an adequate calibration method for the tiltmeters. If independent measurements could establish that the drift time-scale for the tiltmeter gains were sufficiently long, a bootstrapping technique might be available. The initial values of tiltmeter gains might be used to get improved values of E_1 and E_2. These could in turn could be used in conjunction with further box runs to get improved values of tiltmeter gain.

Some way of giving the tiltmeters a known tilt is another possibility for calibration that should not be ignored. A mechanical device in the tiltmeter instrument package might be adequate. Using a peizoelectric translator is a method which has not yet been investigated. The tiltmeters are about 10 cm long. A stable calibrating device which raises one end by about 50 μm would produce a tilt of approximately 100 arcsec.

e) Assuming that the tiltmeters are eventually proved to be appropriate for correcting the pointing problems, to examine the details of using the tiltmeter signals in real time to correct the pointing.

TABLE 1

VLA ANTENNA POINTING PARAMETERS
ANTENNA 22

Before Aug, 1986

STATION N4: R = 0.13487 Km

A1 = -0.76	A2 = -0.05	A6 = -1.58	A7 = 3.97
E1 = 0.76	E2 = -0.05	E3 = 0.46	E5 = 0.55

Changed Aug, 1986

STATION N4: R = 0.13487 Km

A1 = -0.62	A2 = -0.13	A6 = -1.50	A7 = 3.91
E1 = 0.62	E2 = -0.13	E3 = 0.59	E5 = 0.55

Changed Sept 28, 1986

STATION N4: R = 0.13487 Km

A1 = -0.78	A2 = -0.13	A6 = -1.51	A7 = 3.73
E1 = 0.78	E2 = -0.13	E3 = 0.09	E5 = 0.68

TABLE 2

DERIVED TILTMETER PARAMETERS

		GAIN(mvolt/arcsec)	AZ OFFSET(degrees)	CONST TILT(arcsec)
860806.90	XW	9.04	0.94	3.90
	YW	7.36	-6.43	27.80
	XE	9.05	-4.58	20.59
	YE	7.09	-7.21	-26.32
860813.90	XW	11.41	8.65	1.54
	YW	7.95	15.45	27.42
	XE	12.40	11.40	21.37
	YE	7.98	15.88	-23.63
860819.90	XW	8.67	13.34	2.89
	YW	7.11	-6.00	26.08
	XE	8.29	9.08	20.56
	YE	6.77	-6.12	-23.33
861117.22	XW	9.42	12.68	11.59
	YW	8.48	-0.73	16.88
	XE	9.33	8.61	16.27
	YE	8.51	-0.35	-32.34
861117.30	XW	10.91	8.61	10.59
	YW	9.05	2.71	18.25
	XE	10.91	6.18	17.58
	YE	8.99	3.00	-32.53
861117.45	XW	9.97	7.86	8.31
	YW	8.45	0.60	17.77
	XE	10.08	4.06	17.42
	YE	8.38	0.97	-32.06
861117.60	XW	9.96	1.27	5.91
	YW	8.74	-1.11	18.57
	XE	9.72	6.93	17.69
	YE	8.42	-1.73	-33.88
861117.90	XW	11.79	0.61	-0.8
	YW	11.53	0.84	22.85
	XE	11.93	-2.90	27.30
	YE	11.49	0.13	-35.21
861205.15	XW	9.00	9.77	12.06
	YW	8.64	-0.54	16.07
	XE	9.01	4.91	14.60
	YE	8.59	0.16	-32.36
861205.30	XW	8.43	11.62	12.33
	YW	8.13	-2.06	14.83
	XE	8.49	6.57	14.47
	YE	8.18	-1.42	-32.00
861205.45	XW	9.16	10.09	9.34
	YW	8.51	-0.05	13.82
	XE	9.20	5.18	17.53
	YE	8.60	0.51	-34.90
861205.60	XW	8.03	14.76	8.72
	YW	7.51	-2.99	12.94
	XE	7.98	8.14	17.08

	YE	7.53	-0.33	-34.14
861205.75	XW	9.42	10.60	4.66
	YW	8.36	0.93	13.84
	XE	9.46	5.89	20.14
	YE	8.41	1.79	-34.76
861205.90	XW	7.88	16.72	3.61
	YW	6.35	-0.48	14.18
	XE	8.00	10.58	20.16
	YE	6.29	0.05	-32.73
861217.15	XW	4.31	0.64	10.91
	YW	7.85	-8.72	15.91
	XE	4.97	-16.85	10.61
	YE	7.85	-8.85	-32.55
861217.30	XW	7.00	4.33	11.98
	YW	8.09	-7.29	14.72
	XE	7.32	-3.81	10.82
	YE	8.10	-6.44	-34.31
861217.45	XW	8.73	6.69	9.38
	YW	8.50	-5.03	12.84
	XE	8.78	1.03	13.21
	YE	8.58	-4.12	-35.66
861217.60	XW	9.27	6.03	6.65
	YW	8.74	-3.51	11.63
	XE	9.36	2.09	13.73
	YE	8.82	-1.84	-35.98
861217.75	XW	6.04	3.71	2.76
	YW	6.93	-19.57	14.00
	XE	6.09	-10.05	14.51
	YE	6.17	-17.25	-35.39
861217.90	XW	8.27	6.89	5.72
	YW	8.85	-1.98	12.74
	XE	9.70	1.30	18.66
	YE	9.01	-1.54	-35.86

TABLE 3

DERIVED TILTMETER PARAMETERS FOR THE XE TILTMETER

	GAIN(mvolt/arcsec)	AZ OFFSET(degrees)	CONST TILT(arcsec)
860806.90	9.05	-4.58	20.59
860813.90	12.40	11.40	21.37
860819.90	8.29	9.08	20.56
861117.22	9.33	8.61	16.27
861117.30	10.91	6.18	17.58
861117.45	10.08	4.06	17.42
861117.60	9.72	6.93	17.69
861117.90	11.93	-2.90	27.30
861205.15	9.01	4.91	14.60
861205.30	8.49	6.57	14.47
861205.45	9.20	5.18	17.53
861205.60	7.98	8.14	17.08
861205.75	9.46	5.89	20.14
861205.90	8.00	10.58	20.16
861217.15	4.97	-16.85	10.61
861217.30	7.32	-3.81	10.82
861217.45	8.78	1.03	13.21
861217.60	9.36	2.09	13.73
861217.75	6.09	-10.05	14.51
861217.90	9.70	1.30	18.66

TABLE 4

DERIVED TILTMETER PARAMETERS FOR THE XW TILTMETER

	GAIN(mvolt/arcsec)	AZ OFFSET(degrees)	CONST TILT(arcsec)
860806.90	9.04	0.94	3.90
860813.90	11.41	8.65	1.54
860819.90	8.67	13.34	2.89
861117.22	9.42	12.68	11.59
861117.30	10.91	8.61	10.59
861117.45	9.97	7.86	8.31
861117.60	9.96	1.27	5.91
861117.90	11.79	0.61	-0.81
861205.15	9.00	9.77	12.06
861205.30	8.43	11.62	12.33
861205.45	9.16	10.09	9.34
861205.60	8.03	14.76	8.72
861205.75	9.42	10.60	4.66
861205.90	7.88	16.72	3.61
861217.15	4.31	0.64	10.91
861217.30	7.00	4.33	11.98
861217.45	8.73	6.69	9.38
861217.60	9.27	6.03	6.65
861217.75	6.04	3.71	2.76
861217.90	8.27	6.89	5.72

TABLE 5

DERIVED TILTMETER PARAMETERS FOR THE YE TILTMETER

	GAIN(mvolt/arcsec)	AZ OFFSET(degrees)	CONST TILT(arcsec)
860806.90	7.09	-7.21	-26.32
860813.90	7.98	15.88	-23.63
860819.90	6.77	-6.12	-23.33
861117.22	8.51	-0.35	-32.34
861117.30	8.99	3.00	-32.53
861117.45	8.38	0.97	-32.06
861117.60	8.42	-1.73	-33.88
861117.90	11.49	0.13	-35.21
861205.15	8.59	0.16	-32.36
861205.30	8.18	-1.42	-32.00
861205.45	8.60	0.51	-34.90
861205.60	7.53	-0.33	-34.14
861205.75	8.41	1.79	-34.76
861205.90	6.29	0.05	-32.73
861217.15	7.85	-8.85	-32.55
861217.30	8.10	-6.44	-34.31
861217.45	8.58	-4.12	-35.66
861217.60	8.82	-1.84	-35.98
861217.75	6.17	-17.25	-35.39
861217.90	9.01	-1.54	-35.86

TABLE 6

DERIVED TILTMETER PARAMETERS FOR THE YW TILTMETER

	GAIN(mvolt/arcsec)	AZ OFFSET(degrees)	CONST TILT(arcsec)
860806.90	7.36	-6.43	27.80
860813.90	7.95	15.45	27.42
860819.90	7.11	-6.00	26.08
861117.22	8.48	-0.73	16.88
861117.30	9.05	2.71	18.25
861117.45	8.45	0.60	17.77
861117.60	8.74	-1.11	18.57
861117.90	11.53	0.84	22.85
861205.15	8.64	-0.54	16.07
861205.30	8.13	-2.06	14.83
861205.45	8.51	-0.05	13.82
861205.60	7.51	-2.99	12.94
861205.75	8.36	0.93	13.84
861205.90	6.35	-0.48	14.18
861217.15	7.85	-8.72	15.91
861217.30	8.09	-7.29	14.72
861217.45	8.50	-5.03	12.84
861217.60	8.74	-3.51	11.63
861217.75	6.93	-19.57	14.00
861217.90	8.85	-1.98	12.74

TABLE 7

ERRORS IN DERIVED TILTMETER PARAMETERS

	XE	XW	YE	YW
Gain (mvolts/arcsec)	1.73	1.73	1.14	1.05
Gain excluding 90°*	1.59	1.74	0.70	0.55
Azimuth Offset (degrees)	7.21	4.82	6.24	6.44
Constant Tilt (arcsec) **	-	-	3.76	5.00

* The Y tiltmeters show much better repeatability if 90° elevation is excluded.

** The XE and XW tiltmeters are excluded because of the systematic variation with elevation.

TABLE 8

DERIVED AZIMUTH AXIS ORIENTATION

		AMPLITUDE (arcsec)	ORIENTATION (degrees)
860806.90	XW	41.32	-2.23
	YW	33.02	-8.41
	XE	40.97	-7.87
	YE	31.72	-8.93
860813.90	XW	44.20	-3.76
	YW	31.14	5.52
	XE	48.30	-1.42
	YE	31.28	5.92
860819.90	XW	33.80	2.73
	YW	26.27	-15.56
	XE	31.99	-1.22
	YE	24.93	-15.24
861117.22	XW	45.62	3.69
	YW	40.02	-9.30
	XE	44.87	-0.34
	YE	40.22	-8.93
861117.30	XW	52.51	-1.13
	YW	43.04	-6.15
	XE	52.34	-3.59
	YE	42.79	-5.81
861117.45	XW	47.92	-1.45
	YW	40.01	-7.91
	XE	48.15	-5.35
	YE	39.67	-7.47
861117.60	XW	47.34	-8.14
	YW	41.26	-9.86
	XE	46.63	-2.26
	YE	39.67	-10.28
861117.90	XW	56.22	-9.61
	YW	54.97	-9.27
	XE	56.64	-13.25
	YE	54.71	-9.98
861205.15	XW	43.34	1.03
	YW	40.81	-9.21
	XE	43.04	-3.89
	YE	40.64	-8.45
861205.30	XW	40.73	3.28
	YW	38.24	-10.40
	XE	40.61	-1.85
	YE	38.52	-9.78
861205.45	XW	44.15	1.25
	YW	40.22	-8.62
	XE	43.98	-3.73
	YE	40.72	-8.10
861205.60	XW	39.03	6.72
	YW	35.15	-10.84
	XE	38.30	0.12

	YE	35.48	-8.12
861205.75	XW	45.46	1.60
	YW	39.59	-7.50
	XE	45.31	-3.17
	YE	39.87	-6.65
861205.90	XW	38.44	8.79
	YW	29.78	-7.00
	XE	38.59	2.56
	YE	29.53	-6.37
861217.15	XW	20.06	-1.92
	YW	36.40	-17.09
	XE	21.94	-22.07
	YE	36.38	-17.23
861217.30	XW	33.24	-2.82
	YW	37.69	-15.79
	XE	34.21	-11.52
	YE	37.77	-14.91
861217.45	XW	41.82	-1.90
	YW	39.81	-13.74
	XE	41.60	-7.69
	YE	40.29	-12.86
861217.60	XW	44.38	-2.91
	YW	41.07	-12.34
	XE	44.50	-6.97
	YE	41.61	-10.67
861217.75	XW	28.58	-2.27
	YW	31.20	-27.77
	XE	27.82	-16.65
	YE	27.71	-24.44
861217.90	XW	46.06	-4.09
	YW	41.75	-10.83
	XE	46.11	-7.96
	YE	42.57	-10.49

APPENDIX I

TYPICAL TILTMETER SPECIFICATIONS

Power supply voltages	±15 volts
Power supply Current	10-14 ma
Output impedance	4.99 Kohms
Range of tilt	$\pm 1°$
Full range output voltage	±4.977 volts
Resolution	0.1 arcsec
Noise	0.002 volts rms (1.44 arcsec)
Non-repeatability and hysteresis	0.02 % (1.44 arcsec)
Max deviation from straight line	0.05 % (3.6 arcsec)
Zero offset	0.007 volts (5.0 arcsec)
Scale factor temperature coefficient	0.02 % per $°C$ (error at 12 arcmin = 0.14 arcsec per $°C$)
Null Temperature coefficient	0.05 % FS per $°C$ (3.6 arcsec per $°C$)
Operating Temperature Range	-18$°C$ to 71$°C$

* As used in the present system.

Note: These specifications are drawn from Schaevitz Technical Bulletin 4504C

APPENDIX II

ADDRESSES FOR TILTMETERS

ANTENNA 22 (note 2) - current DCS address = 24 (note 3)

TILTMETER	HARDWARE ADDRESSES Dataset = 2 Multiplexor	SOFTWARE ADDRESSES Pseudodataset = 6 Pseudomultiplexor
XW (note 4)	70	50
YW	71	51
XE	72	52
YE	73	53

Note 1: All addresses here are octal.

Note 2: Antenna 22 is now the only antenna equipped with tiltmeters. The tiltmeters on antenna 6 have been removed to extract another Schaevitz device and to do stability and gain tests in the lab. Presumably antenna 6 is still equipped with the wiring and electronics required to reinstall the tiltmeters, but BEWARE of a wiring swap that was found in the module on antenna 22.

Note 3: This number is mysteriously changed every so often, and is located in a table called CBCOM in the Modcomp computers. (This table begins with the statement "TTL PROTOTYPE SYSTEM CONTROL BLOCKS".) The table also contains the translation from physical dataset and multiplex addresses to pseudo-addresses known only to Modcomp programmes.

Note 4: XW = x coordinate tiltmeter on the elevation axis, Waveguide side.
YW = y coordinate tiltmeter on the elevation axis, Waveguide side.
XE = x coordinate tiltmeter on the elevation axis, Encoder side.
YE = y coordinate tiltmeter on the elevation axis, Encoder side.

The x coordinate is perpendicular to the plane of the yoke ; the y coordinate is in the plane of the yoke. The tiltmeters are installed so that tilts of the elevation axis will be registered with the opposite sign on the two sides of the elevation axis. This applies to both the x and y coordinates.

FIGURE CAPTIONS

Figure 1: The antenna yoke showing the mounting points of the pairs of tiltmeters. In the diagram the back face of the yoke is shown (i.e. the antenna is facing away from the reader). The X tiltmeters measure tilt angles in a plane perpendicular to the elevation axis. The Y tiltmeters measure tilt angles in a plane containing the azimuth and elevation axes. The pair mounted near the elevation encoder are denoted E tiltmeters ; the pair mounted near the waveguide are denoted W tiltmeters. The E pair and W pair respond in the opposite sense to the same tilt.

Figure 2: a) Raw X tiltmeter measurements made by setting the azimuth of the antenna every 22.5 degrees for the full circle (clockwise from above the antenna), stopping, and repeating the measurements while driving the antenna counter-clockwise. b) Raw Y tiltmeter measurents.

Figure 3: Plan views of the antenna used in deriving the signs of the response functions of the tiltmeters. The tiltmeter response is positive when the corresponding arrow points out of the page.

Figure 4: N-S and E-W sections through the array showing the direction of the local vertical relative to the tiltmeter axes.

Figure 5: A plan view of the antenna showing the direction of δ for the XE and YE tiltmeters respectively. Both δ_{xw} and δ_{xe} are positive when the tiltmeters are rotated clockwise with respect to the antenna (looking down on the antenna).

Figure 6: a) X tiltmeter measurements showing the fitted sinusoids. b) Y tiltmeter measurements showing the fitted sinusoids.

Figure 7: a) The derived gain for the XW tiltmeter versus elevation for three sequences of box runs. Several earlier box runs done only at an elevation of 90° are also plotted. b) The same type of plot done for the XE tiltmeter which is on the opposite side of the antenna yoke.

Figure 8: a) Same as figure 7a except the measurements are for the YW tiltmeter. b) Same as for figure 7b except the YE measurements are plotted.

Figure 9: a) The gain of the XE tiltmeter plotted against the gain of the XW tiltmeter. The line is not fitted to the data. It is simply a reference line with a slope of 1. This contains all the points plotted in figure 7. b) The same type of plot as in figure 9a except for the YW and XW tiltmeters. It contains all the points plotted in figures 7a and 8a.

Figure 10: a) The parameter h (so-called constant tilt) plotted as a function of elevation for the XE tiltmeter. The best fit straight line has a slope of 0.10 arcsec per degree of elevation. b) h versus elevation for the XW tiltmeter. In this case the best-fit slope is -0.13 arcsec per degree.

Figure 11: a) h versus elevation for the YE tiltmeter. b) Same as figure 11a for the YW tiltmeter.

Figure 12: The residuals from the XW tiltmter plotted for a series of box runs done on 861205 at the elevations marked on the left.

Figure 13: The XW and XE residuals in comparative plots using tiltmeters on opposite sides of the antenna for 3 different elevations. Note the change in sign between XE and XW (see figures 1 and 3).

Figure 14 a-d) Plots of the residuals in cases selected for strong "turn around" error (poor repeatability of tilt measurements at the same azimuth).

Figure 15: A comparative pair of plots showing the residuals on both sides of the antenna (XE

and XW) when there is a strong "turn around" error. The top panel is the same as in figure 14d.

TILTMETER MOUNTING LOCATIO AND SENSING DIRECTIONS

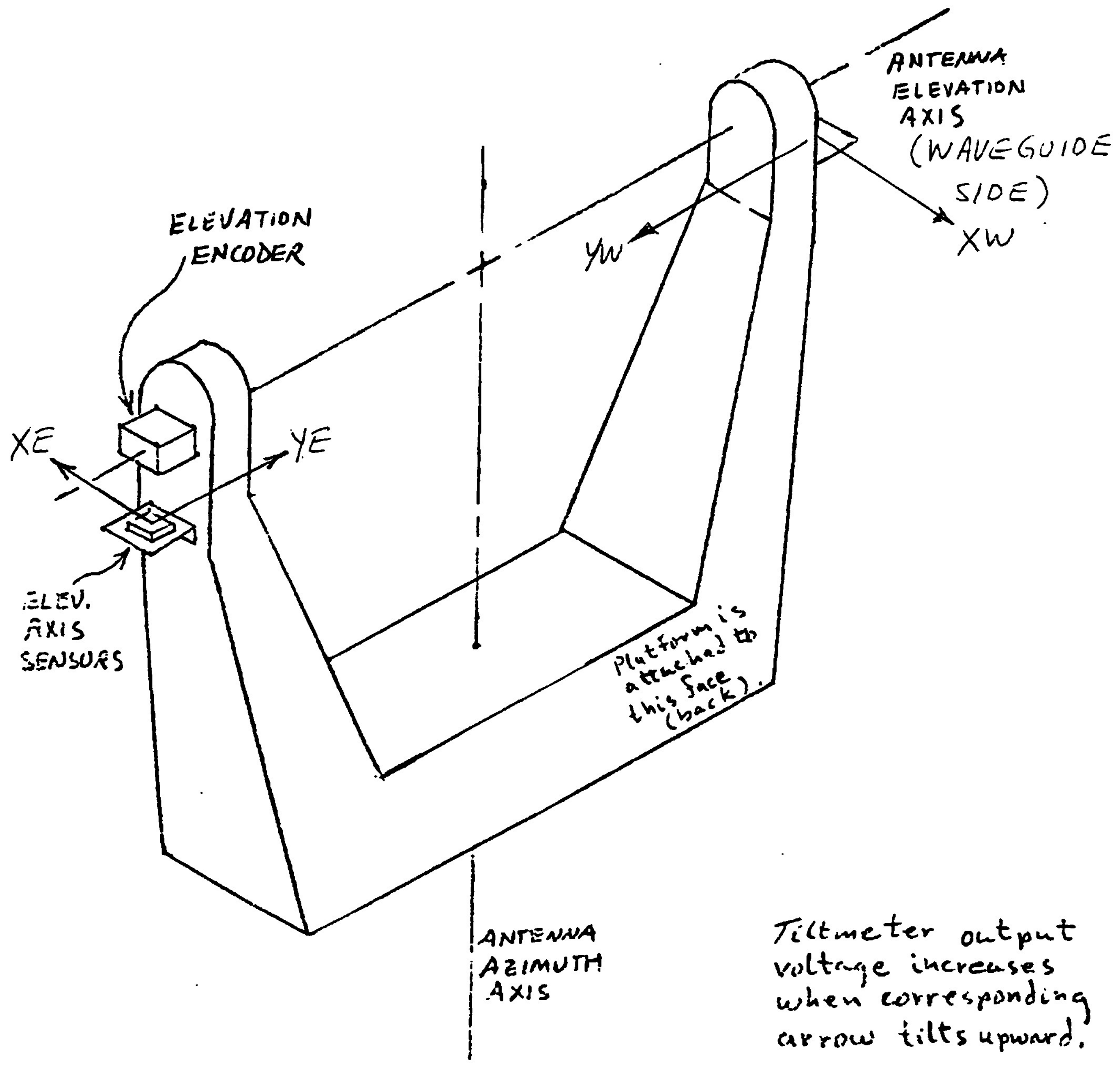


Figure 1: The antenna yoke showing the mounting points of the pairs of tiltmeters. In the diagram the back face of the yoke is shown (i.e. the antenna is facing away from the reader). The X tiltmeters measure tilt angles in a plane perpendicular to the elevation axis. The Y tiltmeters measure tilt angles in a plane containing the azimuth and elevation axes. The pair mounted near the elevation encoder are denoted E tiltmeters ; the pair mounted near the waveguide are denoted W tiltmeters. The E pair and W pair respond in the opposite sense to the same tilt.

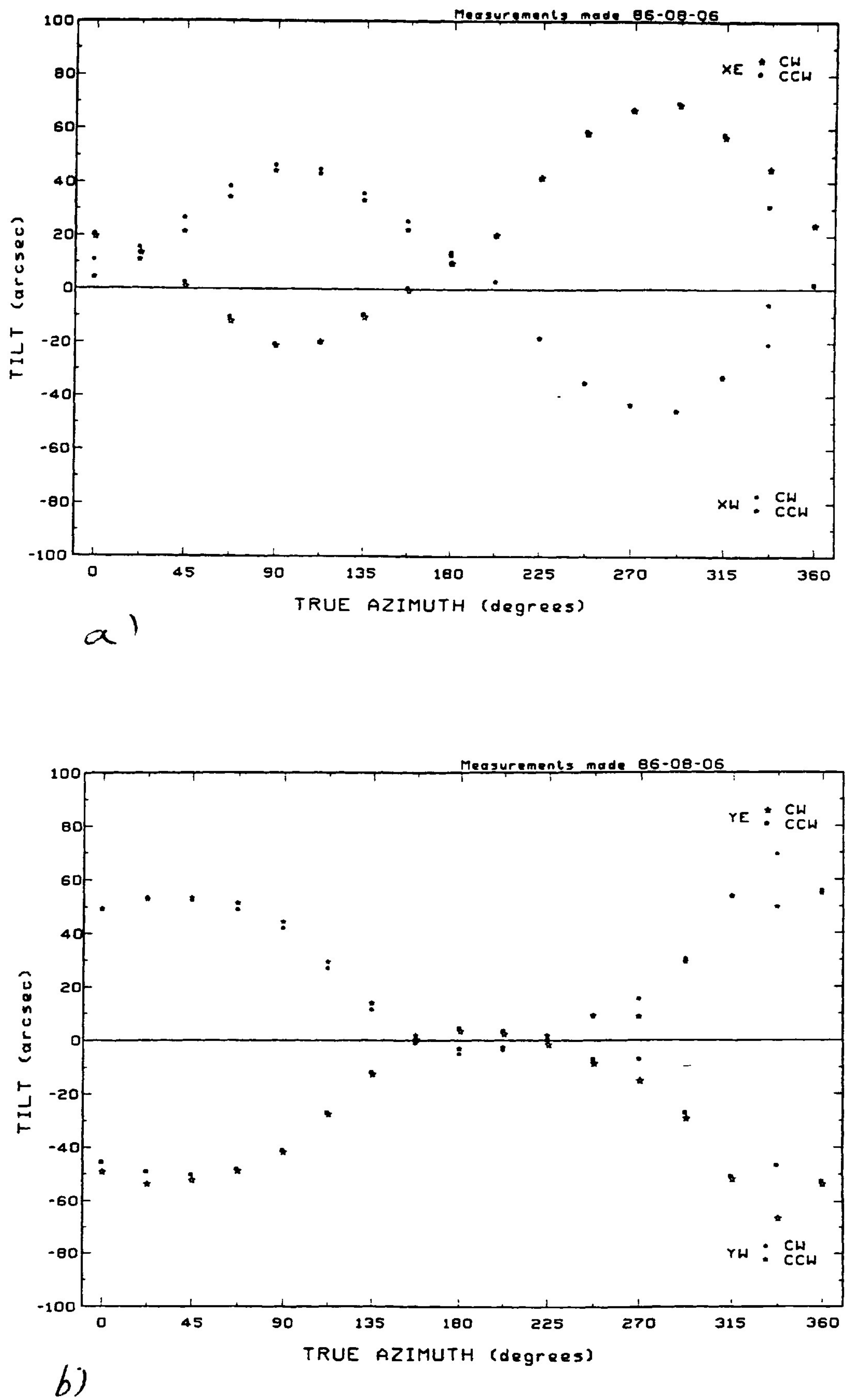


Figure 2: a) Raw X tiltmeter measurements made by setting the azimuth of the antenna every 22.5 degrees for the full circle (clockwise from above the antenna), stopping, and repeating the measurements while driving the antenna counter-clockwise. b) Raw Y tiltmeter measurents.

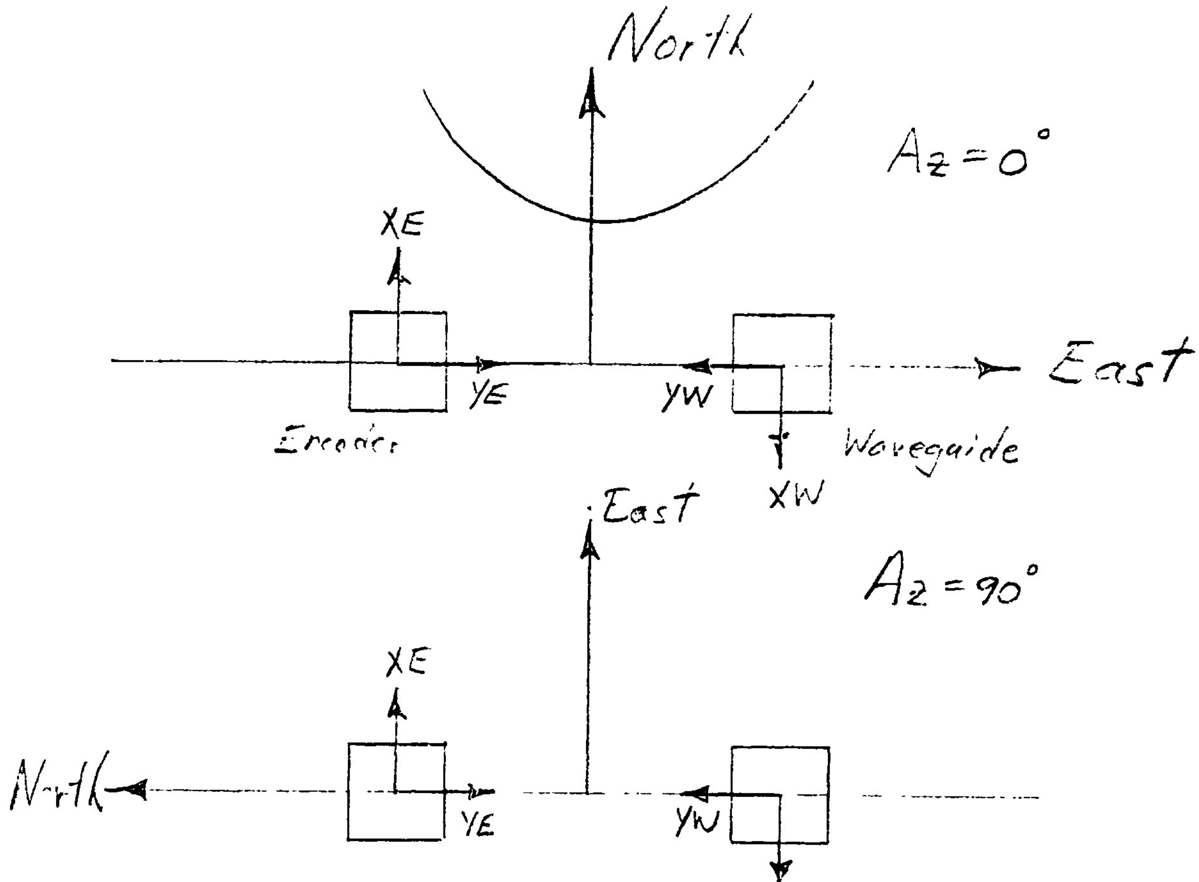


Figure 3: Plan views of the antenna used in deriving the signs of the response functions of the tiltmeters. The tiltmeter response is positive when the corresponding arrow points out of the page.

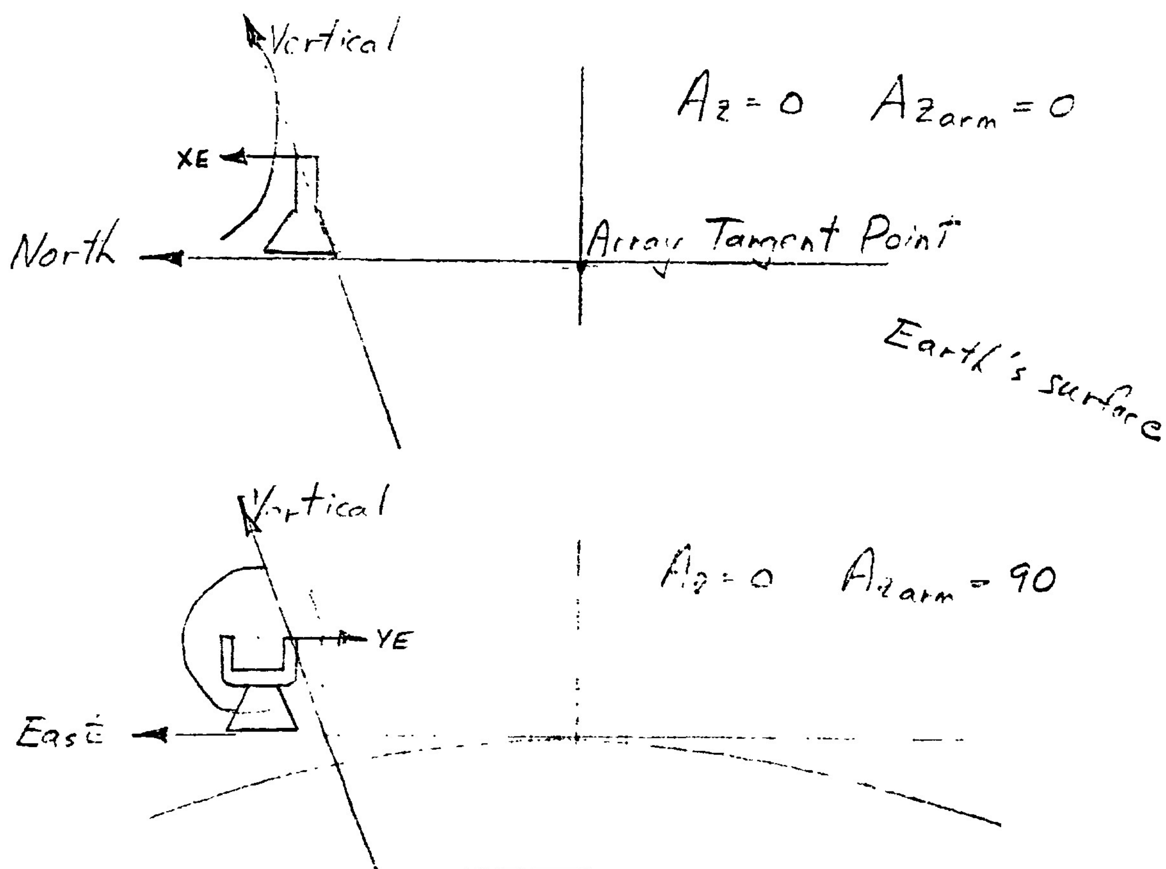


Figure 4: N-S and E-W sections through the array showing the direction of the local vertical relative to the tiltmeter axes.

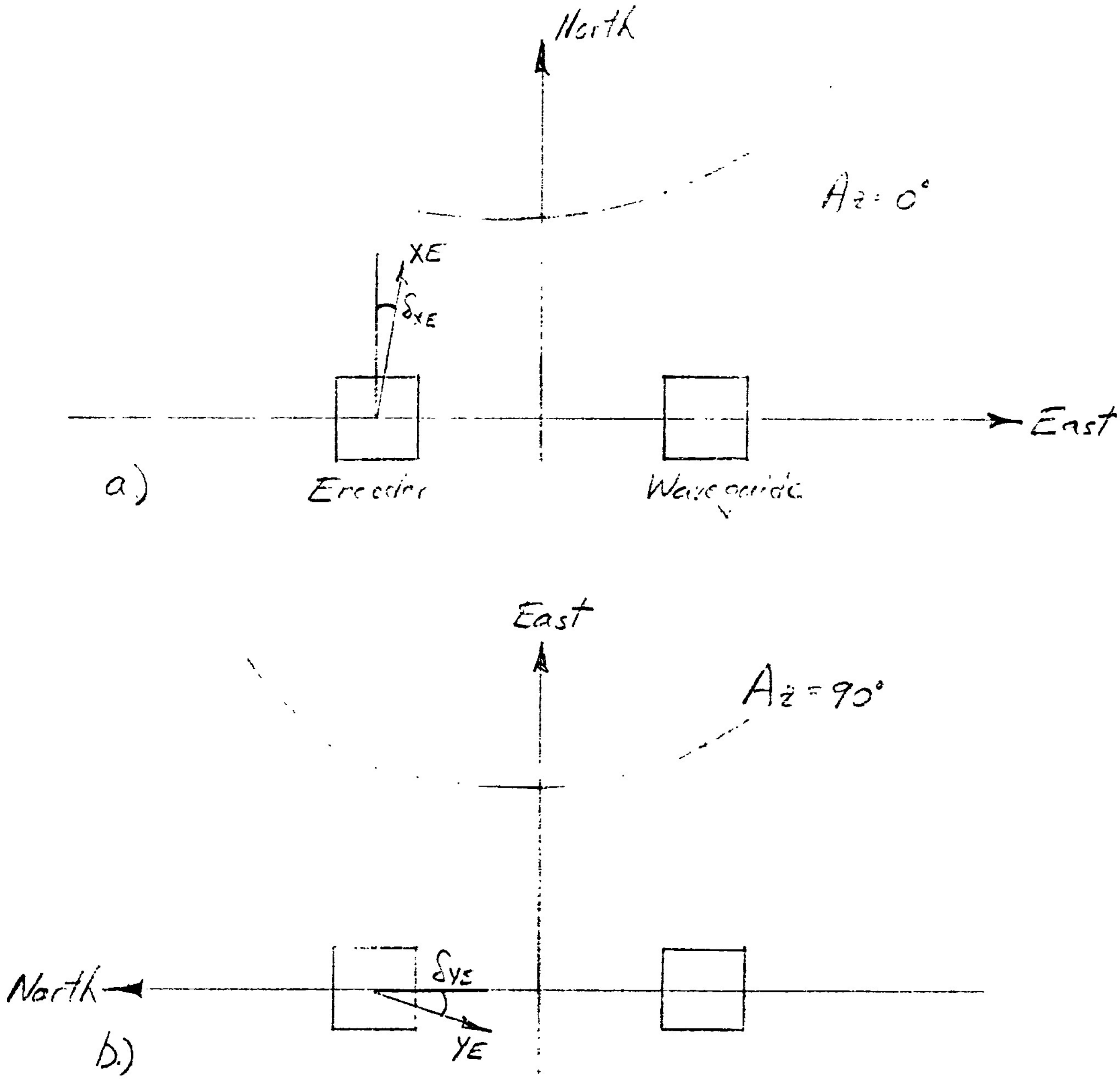
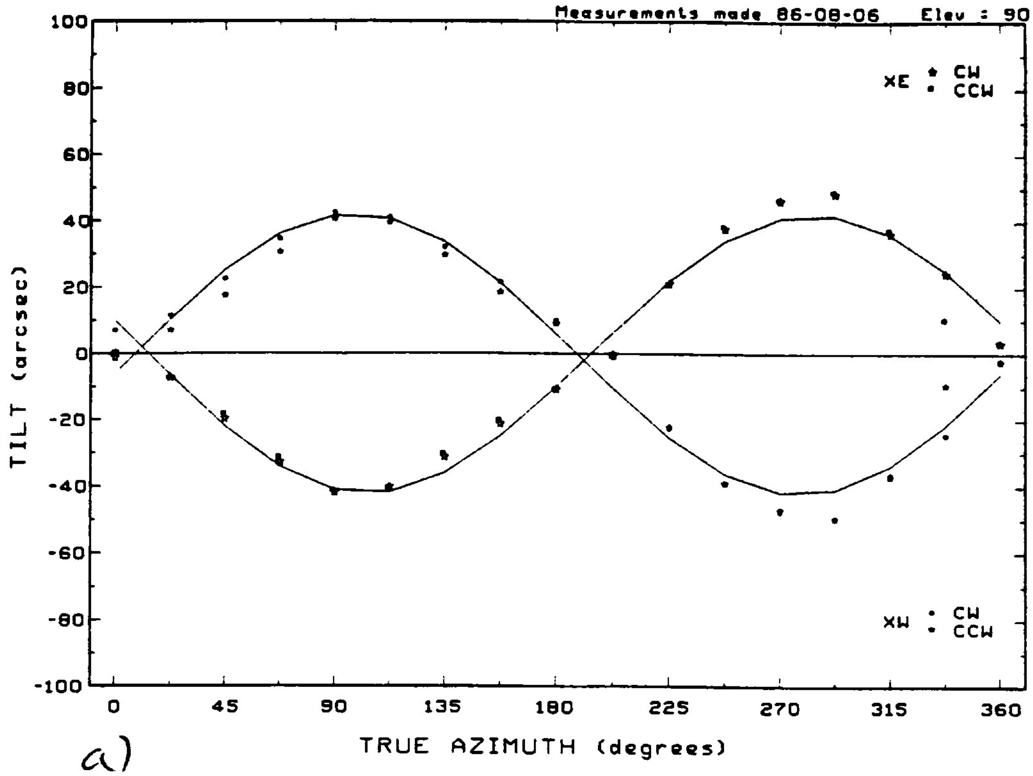


Figure 5: A plan view of the antenna showing the direction of δ for the XE and YE tiltmeters respectively. Both δ_{xw} and δ_{xe} are positive when the tiltmeters are rotated clockwise with respect to the antenna (looking down on the antenna).



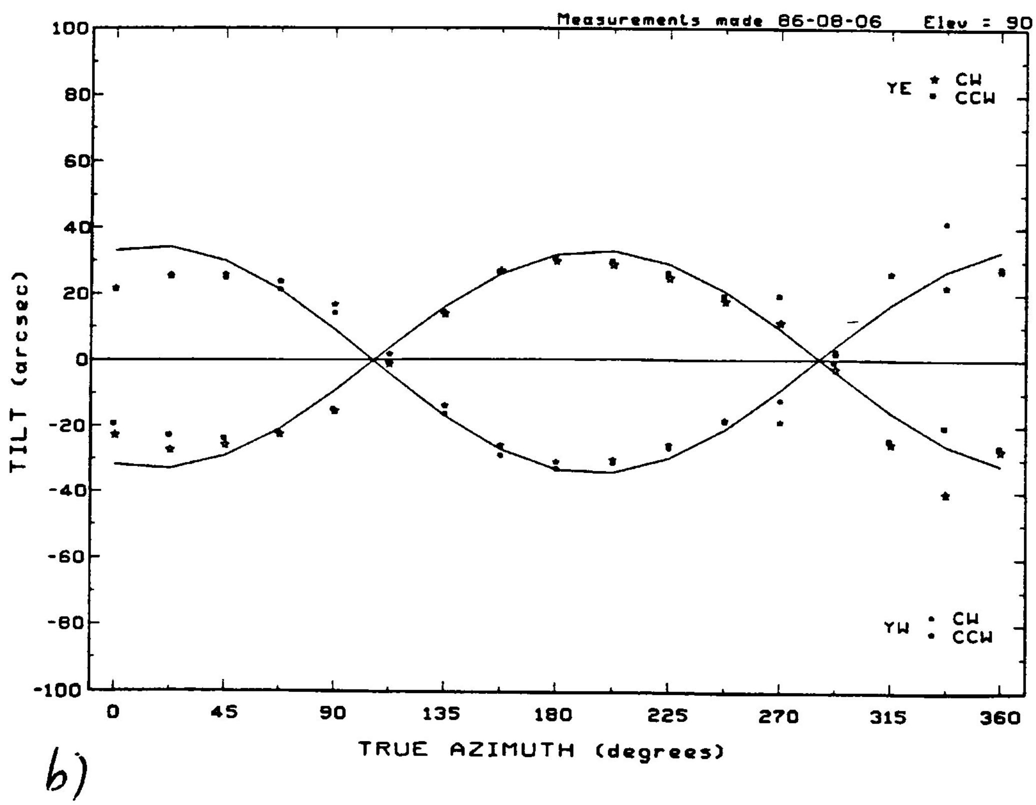
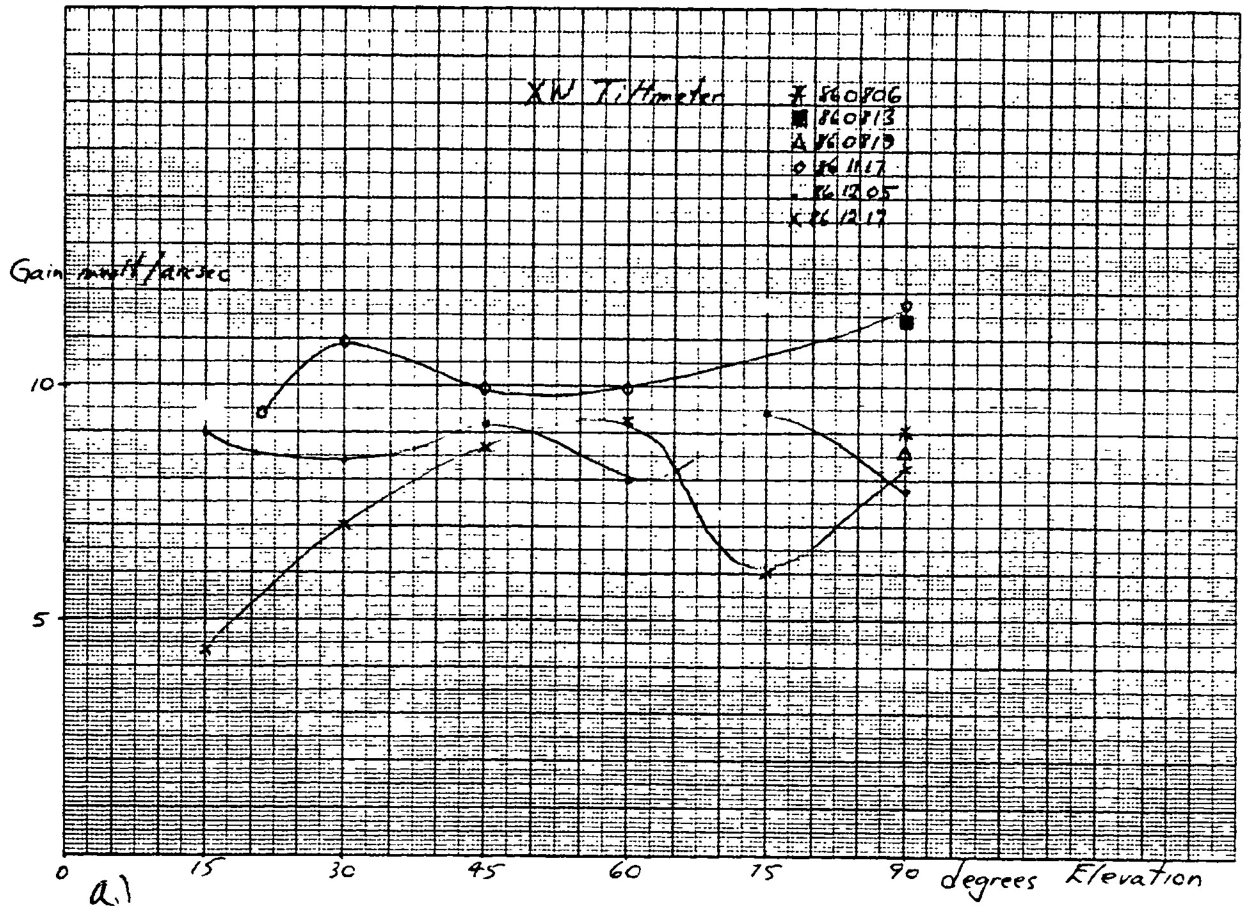


Figure 6: a) X tiltmeter measurements showing the fitted sinusoids. b) Y tiltmeter measurements showing the fitted sinusoids.



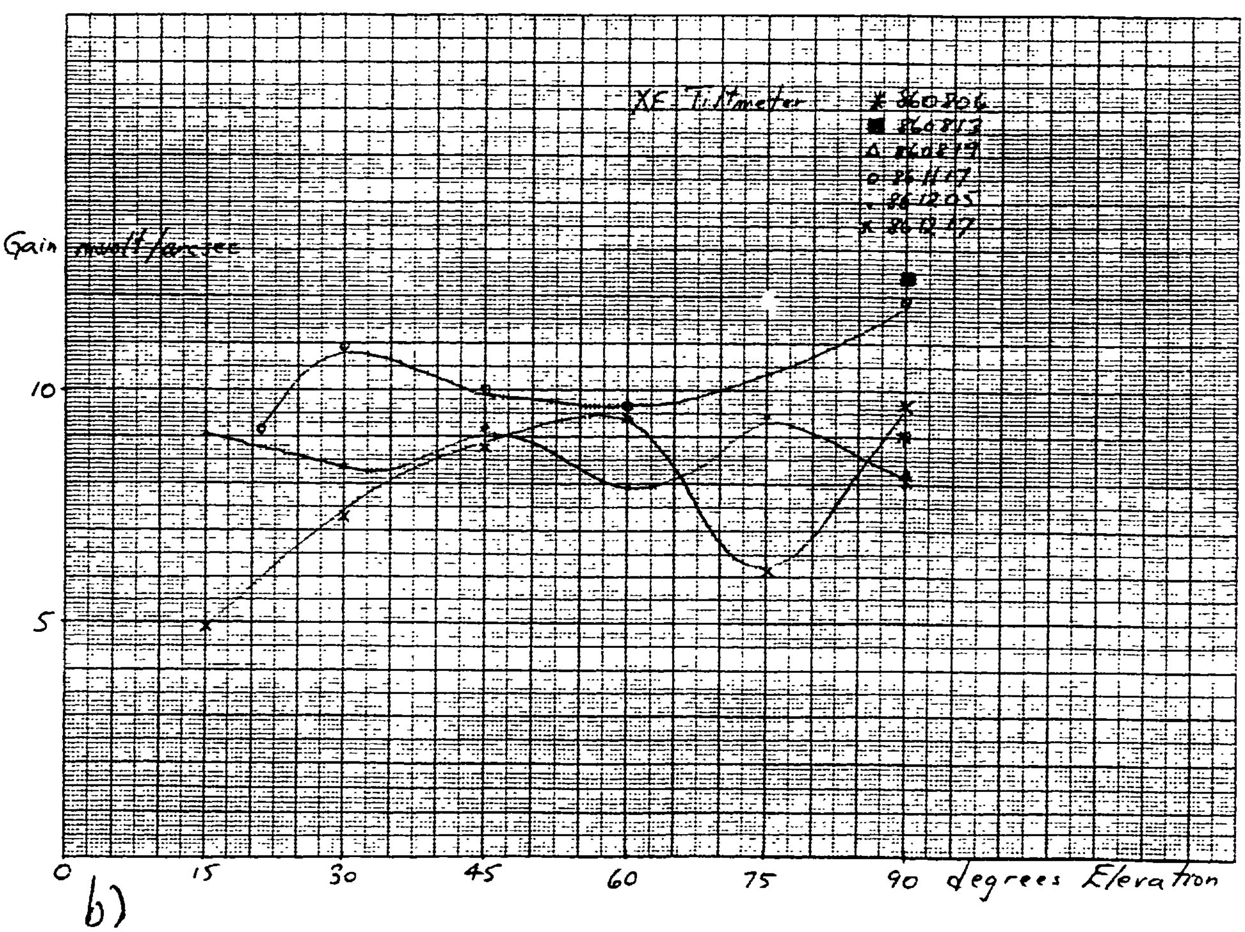
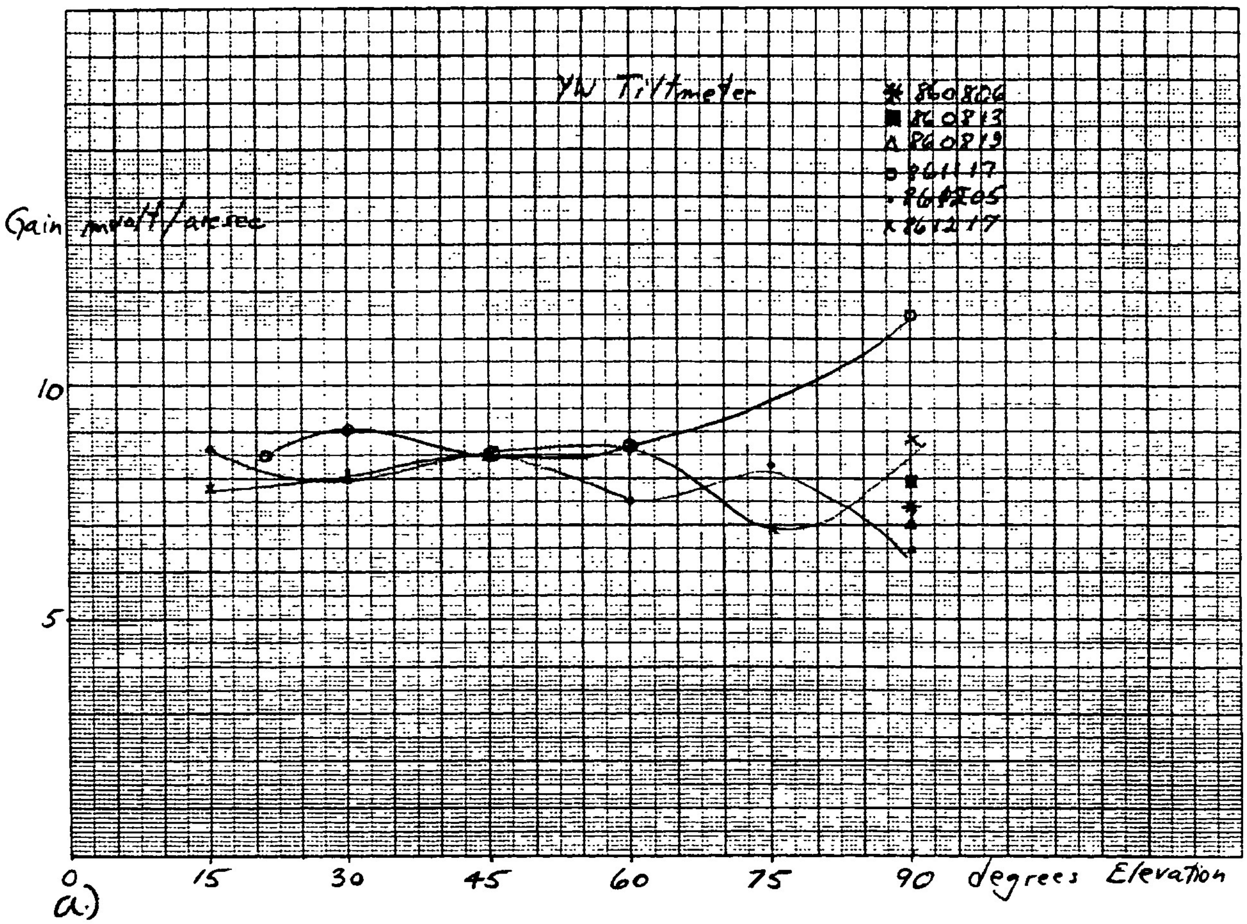


Figure 7: a) The derived gain for the XW tiltmeter versus elevation for three sequences of box runs. Several earlier box runs done only at an elevation of 90° are also plotted. b) The same type of plot done for the XE tiltmeter which is on the opposite side of the antenna yoke.



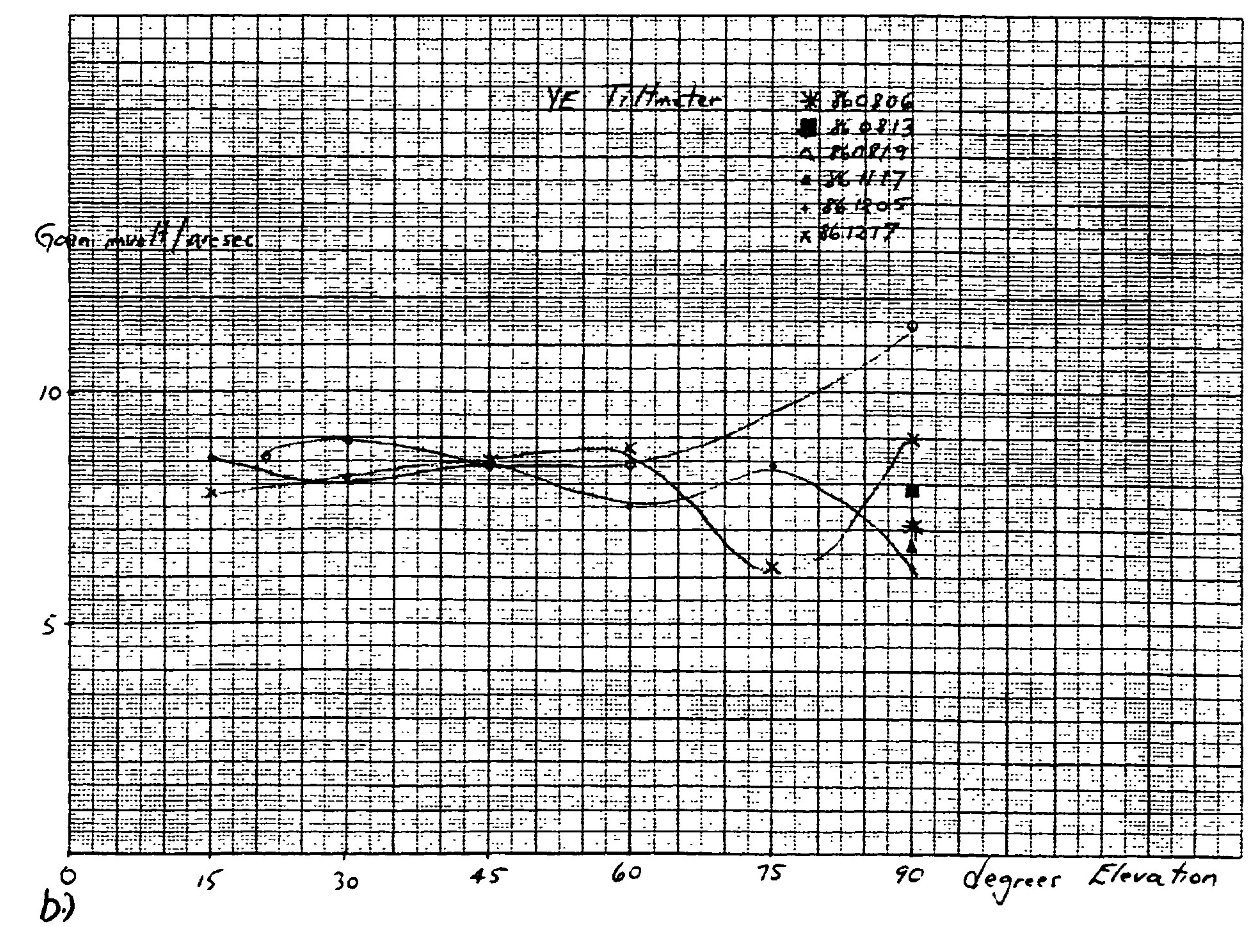


Figure 8: a) Same as figure 7a except the measurements are for the YW tiltmeter. b) Same as for figure 7b except the YE measurements are plotted.

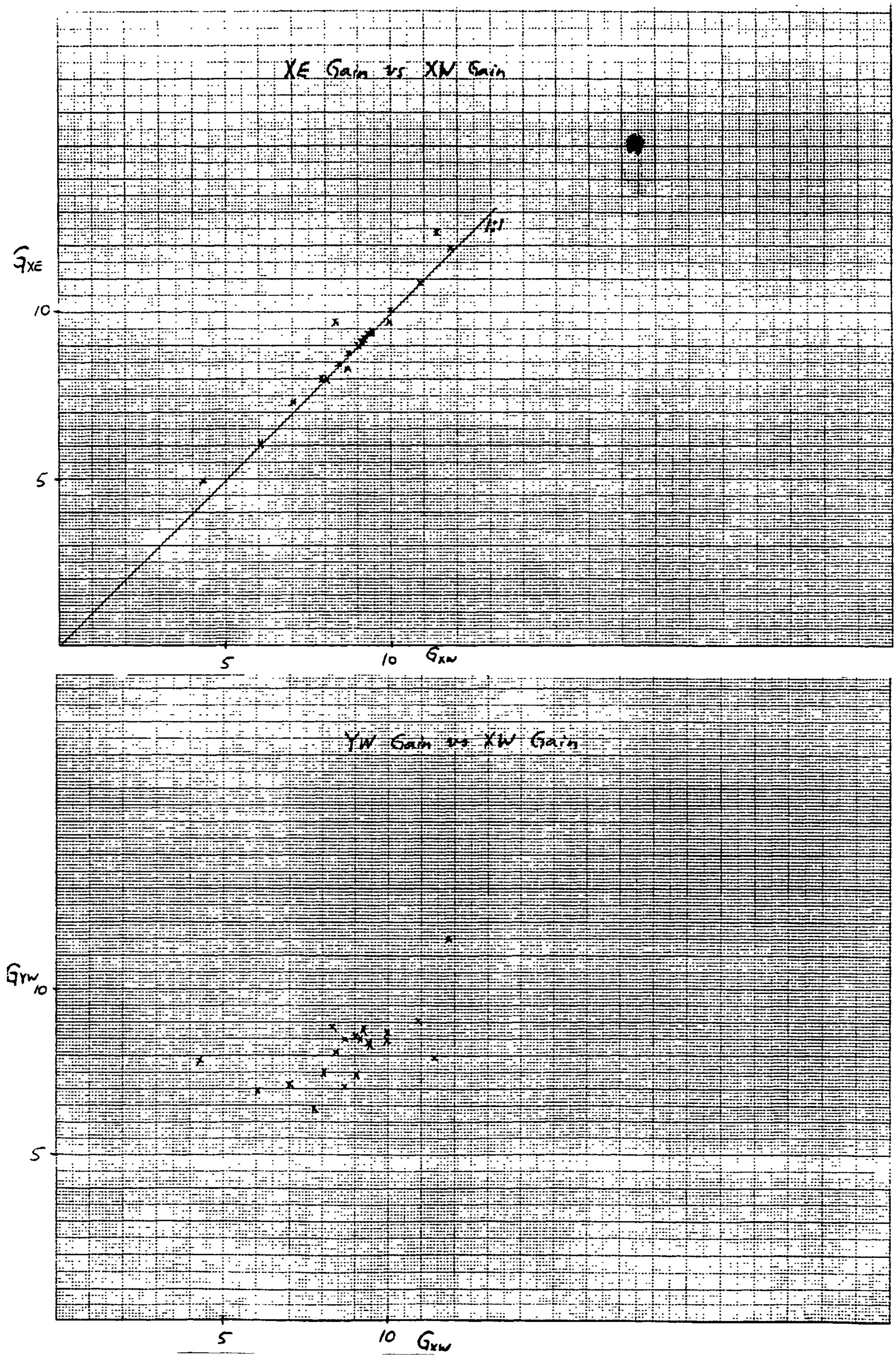


Figure 9: a) The gain of the XE tiltmeter plotted against the gain of the XW tiltmeter. The line is not fitted to the data. It is simply a reference line with a slope of 1. This contains all the points plotted in figure 7. b) The same type of plot as in figure 9a except for the YW and XW tiltmeters. It contains all the points plotted in figures 7a and 8a.

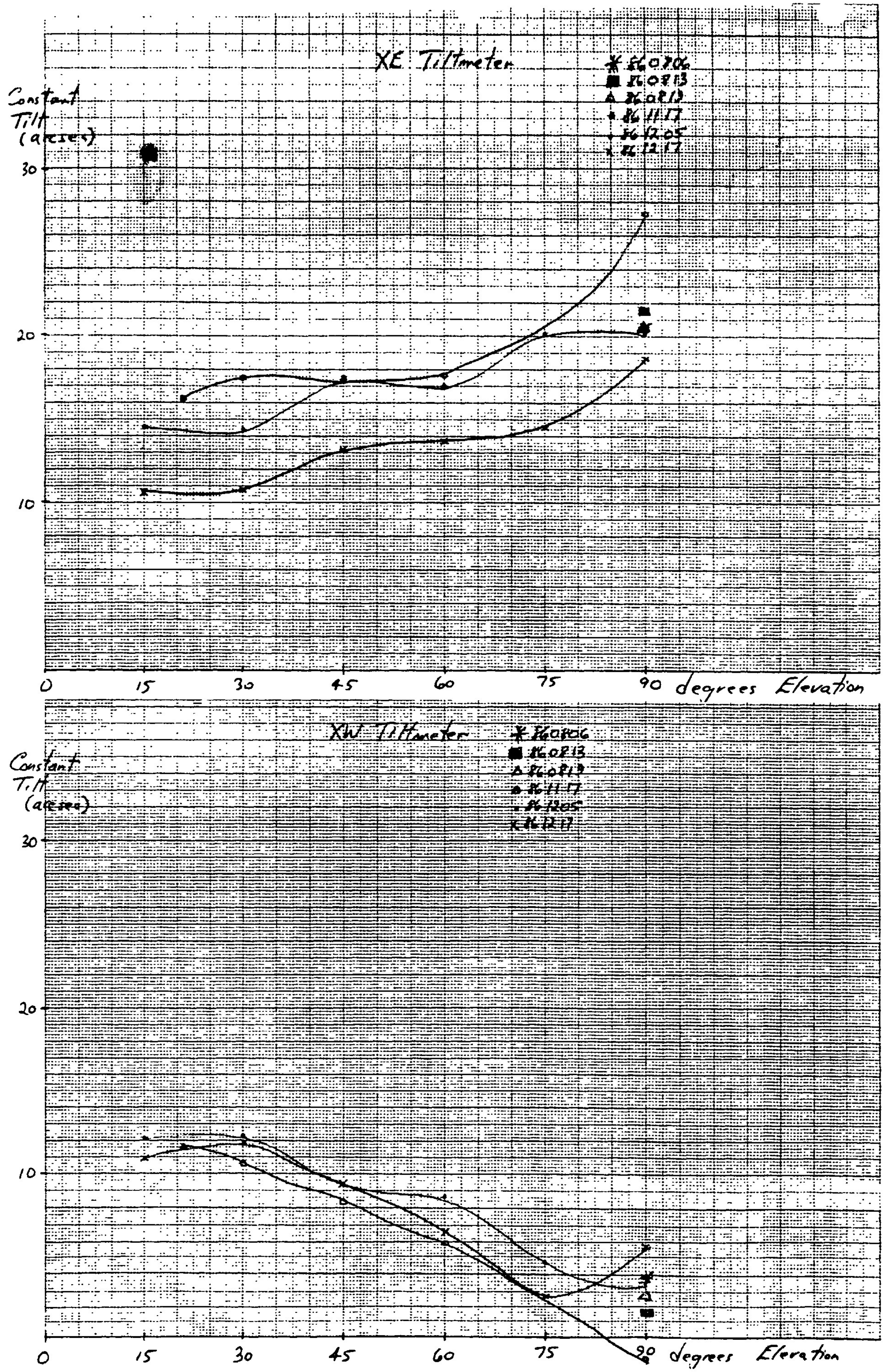
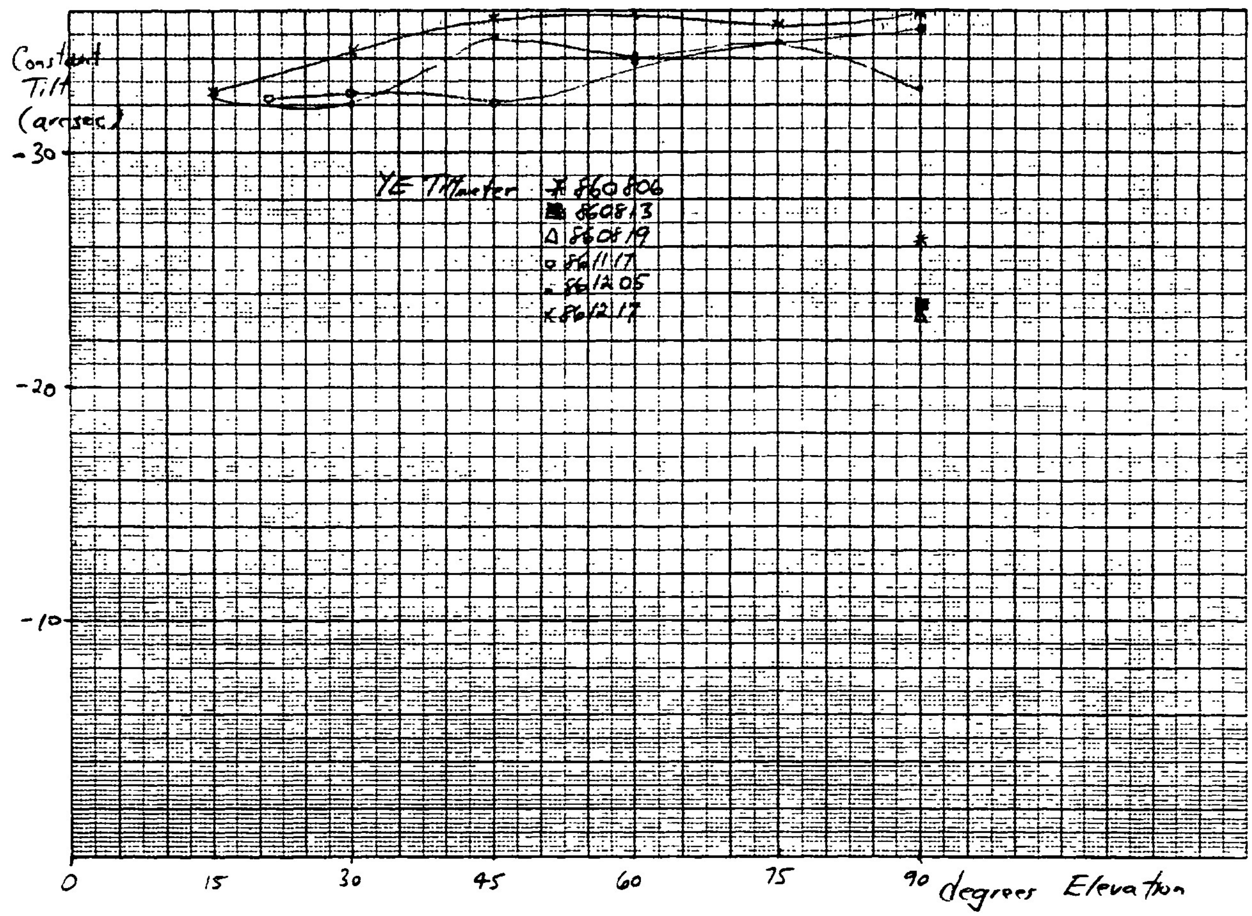


Figure 10: a) The parameter h (so-called constant tilt) plotted as a function of elevation for the XE tiltmeter. The best fit straight line has a slope of 0.10 arcsec per degree of elevation. b) h versus elevation for the XW tiltmeter. In this case the best-fit slope is -0.13 arcsec per degree.



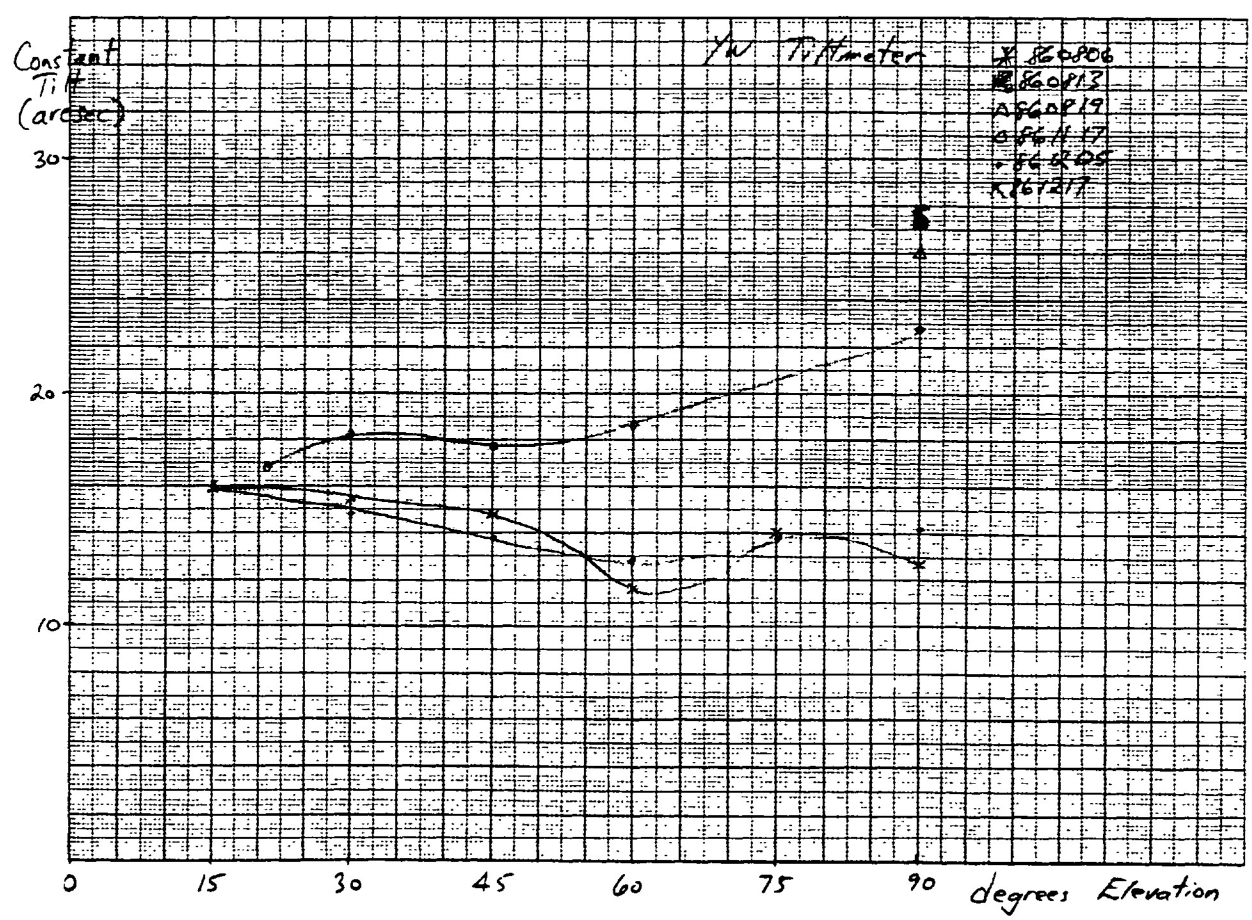


Figure 11: a) h versus elevation for the YE tiltmeter. b) Same as figure 11a for the YW tiltmeter.

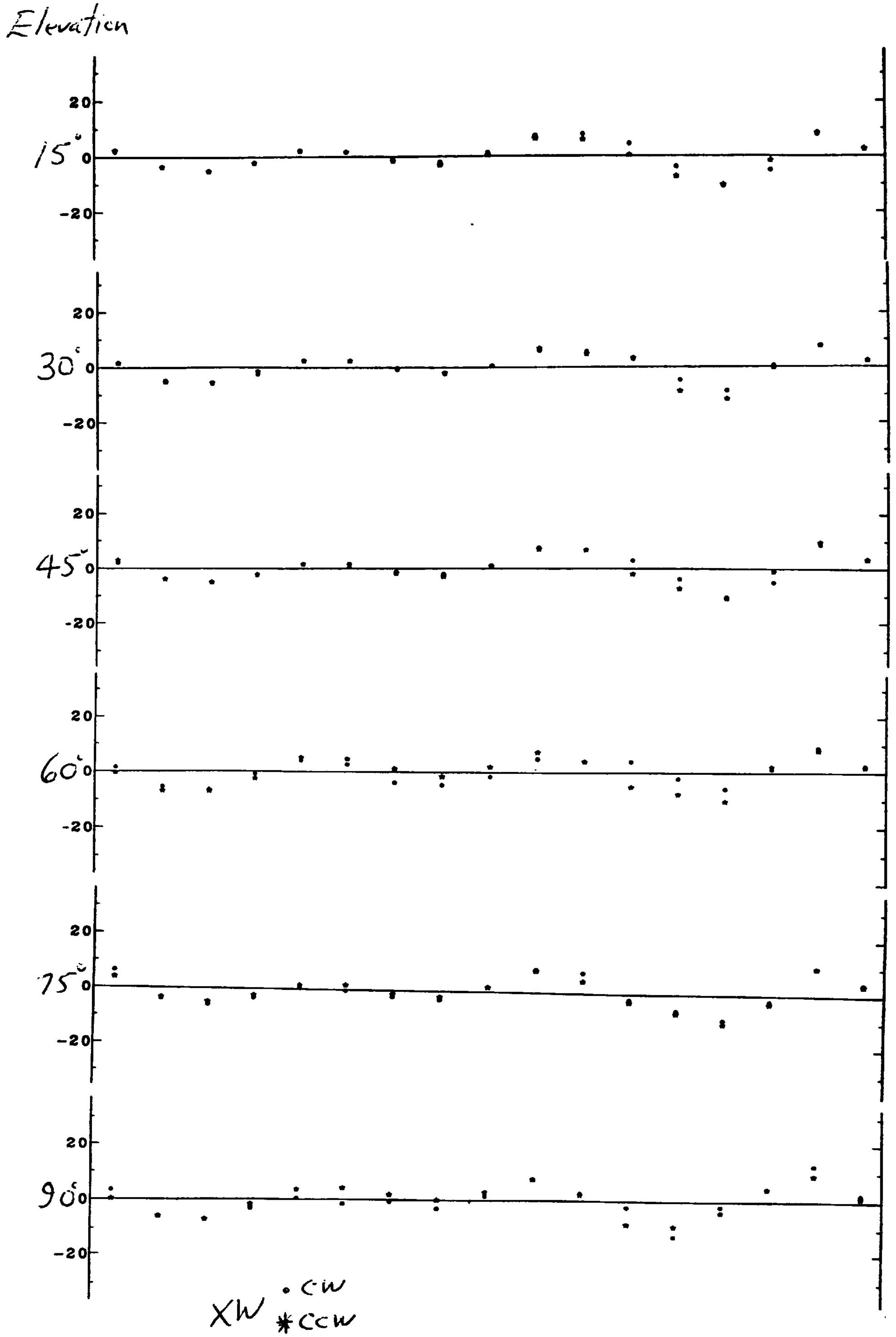


Figure 12: The residuals from the XW tiltmter plotted for a series of box runs done on 861205 at the elevations marked on the left.

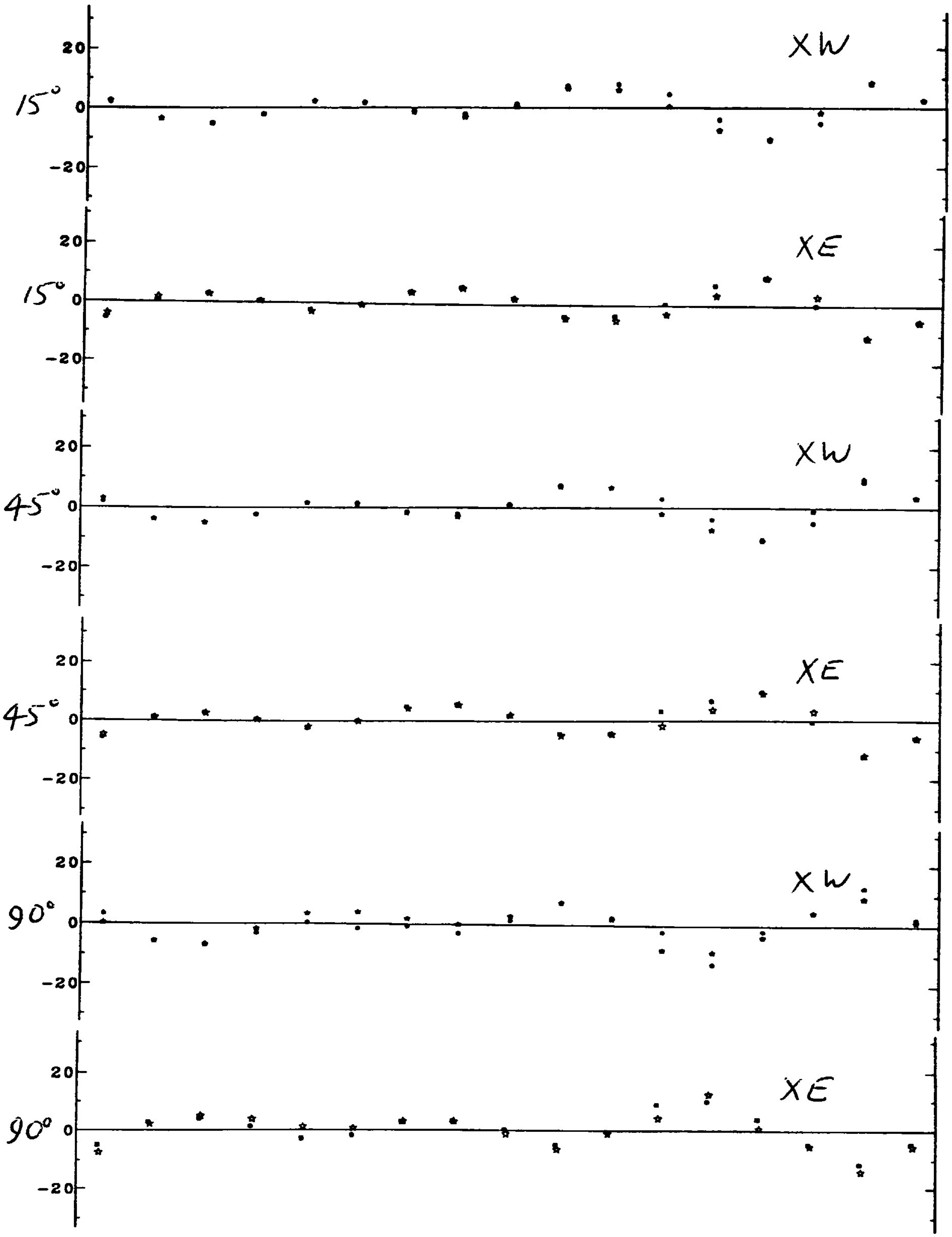
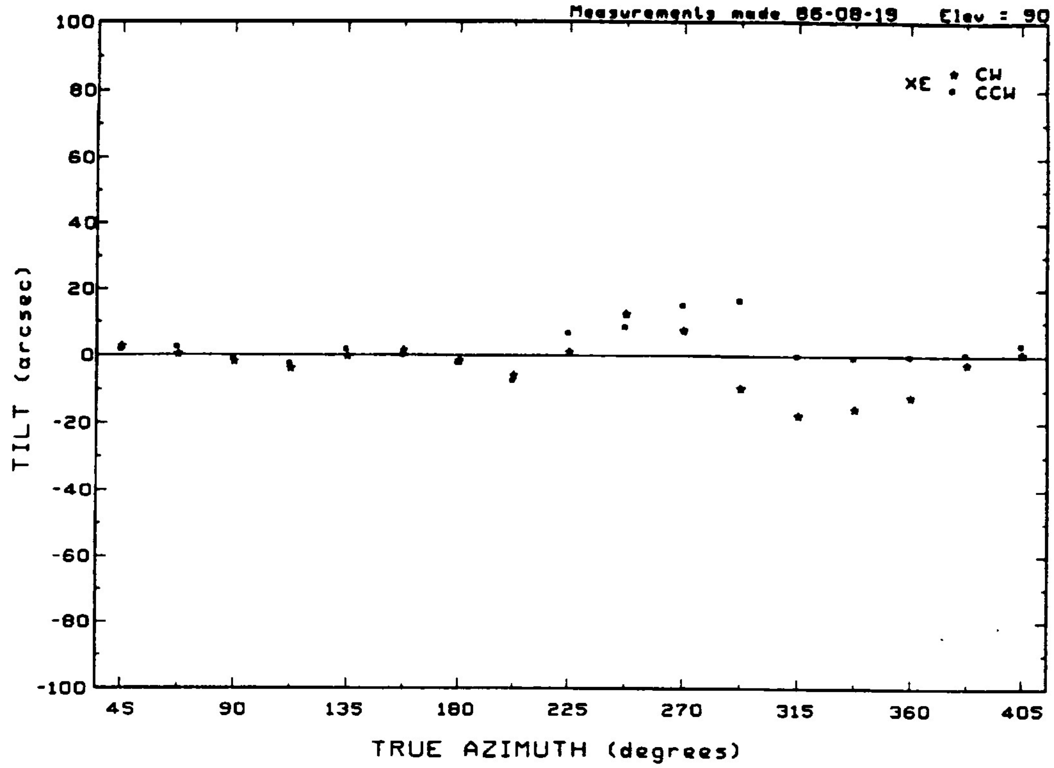


Figure 13: The XW and XE residuals in comparative plots using tiltmeters on opposite sides of the antenna for 3 different elevations. Note the change in sign between XE and XW (see figures 1 and 3).



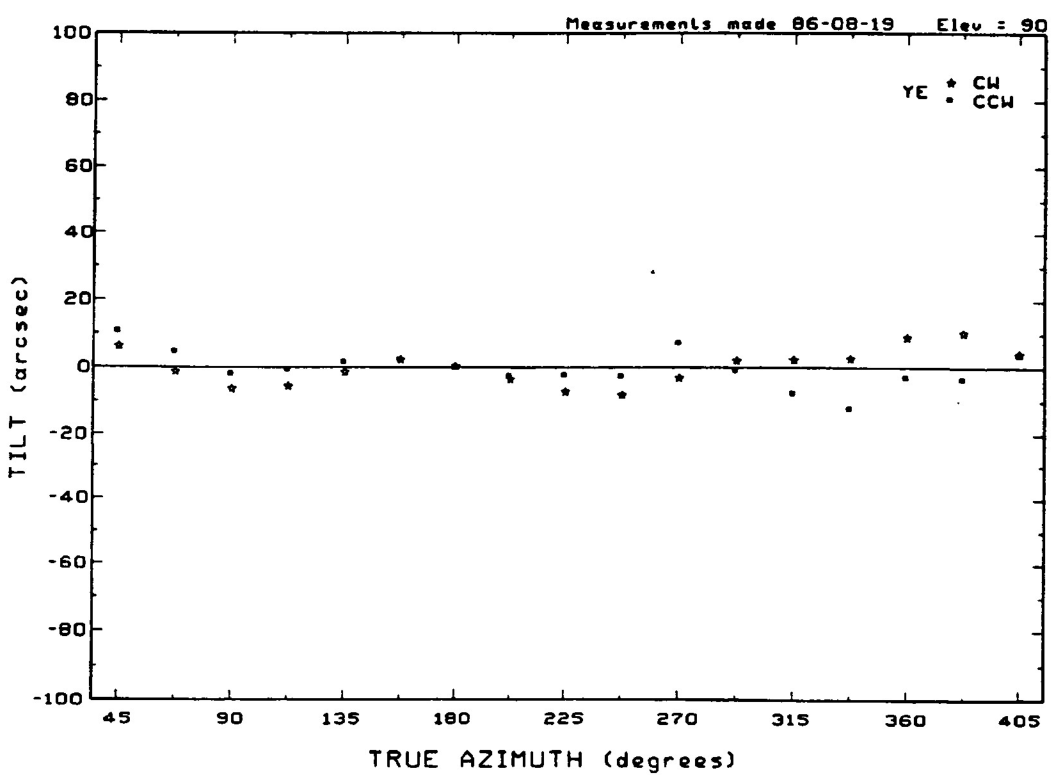
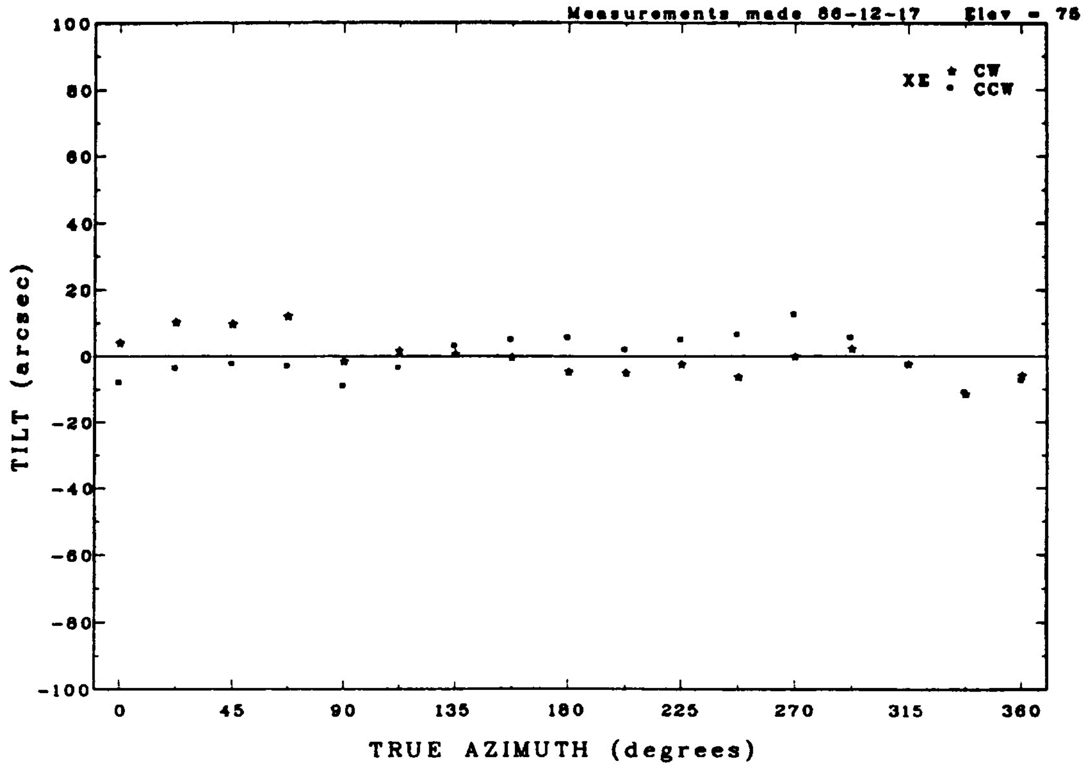


Figure 14 a-d) Plots of the residuals in cases selected for strong "turn around" error (poor repeatability of tilt measurements at the same azimuth).


Measurements made 86-12-17 Elev = 75
XE
* CW
• CCW
TILT (arcsec)
TRUE AZIMUTH (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
45
90
135
180
225
270
315
360

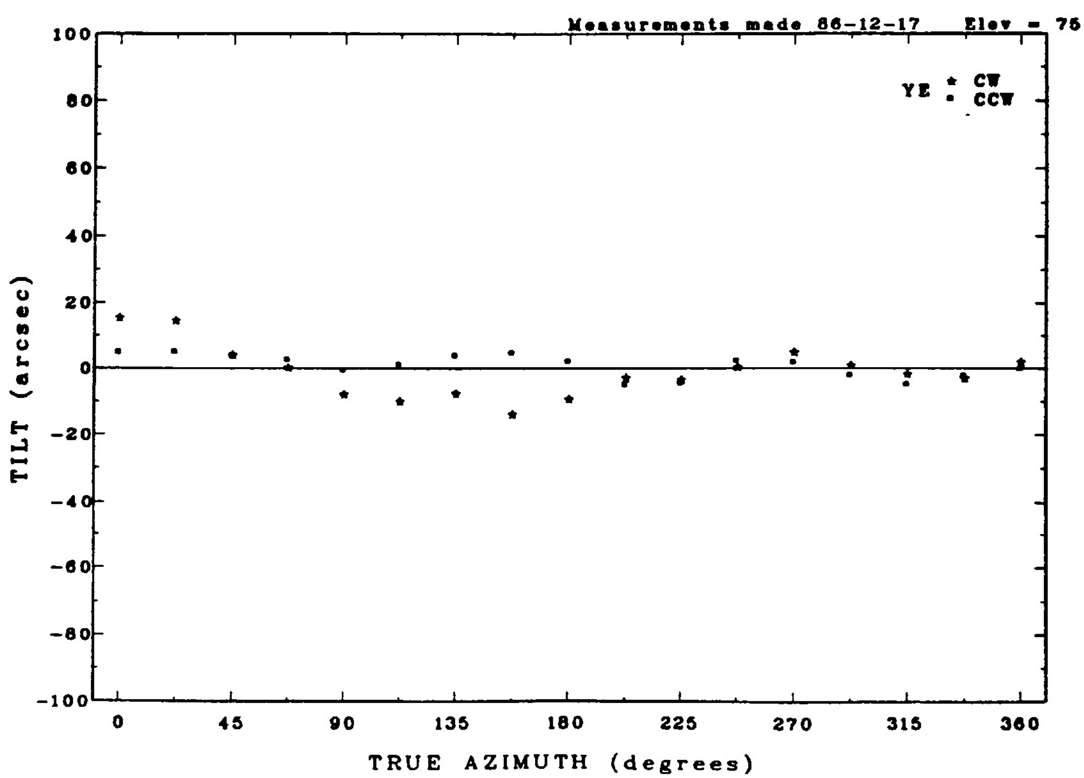
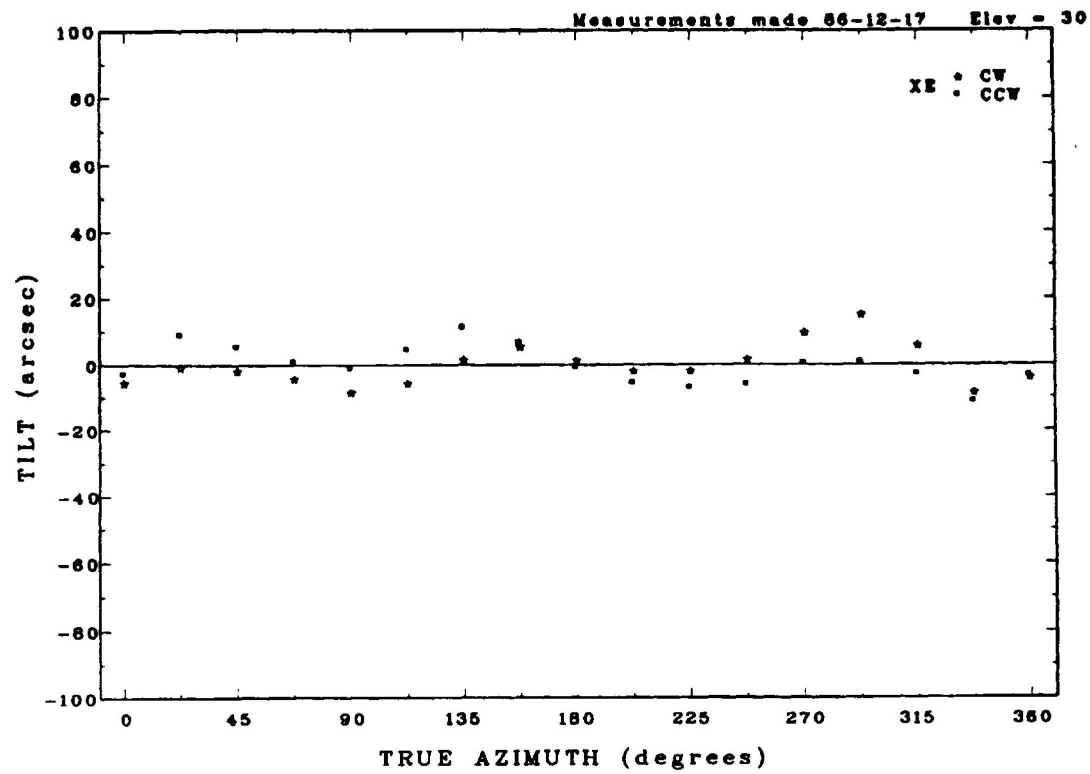

Measurements made 86-12-17 Elev = 75
YE
* CW
• CCW
TILT (arcsec)
TRUE AZIMUTH (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
45
90
135
180
225
270
315
360

Figure 14b


Measurements made 86-12-17 Elev = 30
XE
* CW
* CCW
TILT (arcsec)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
45
90
135
180
225
270
315
360
TRUE AZIMUTH (degrees)

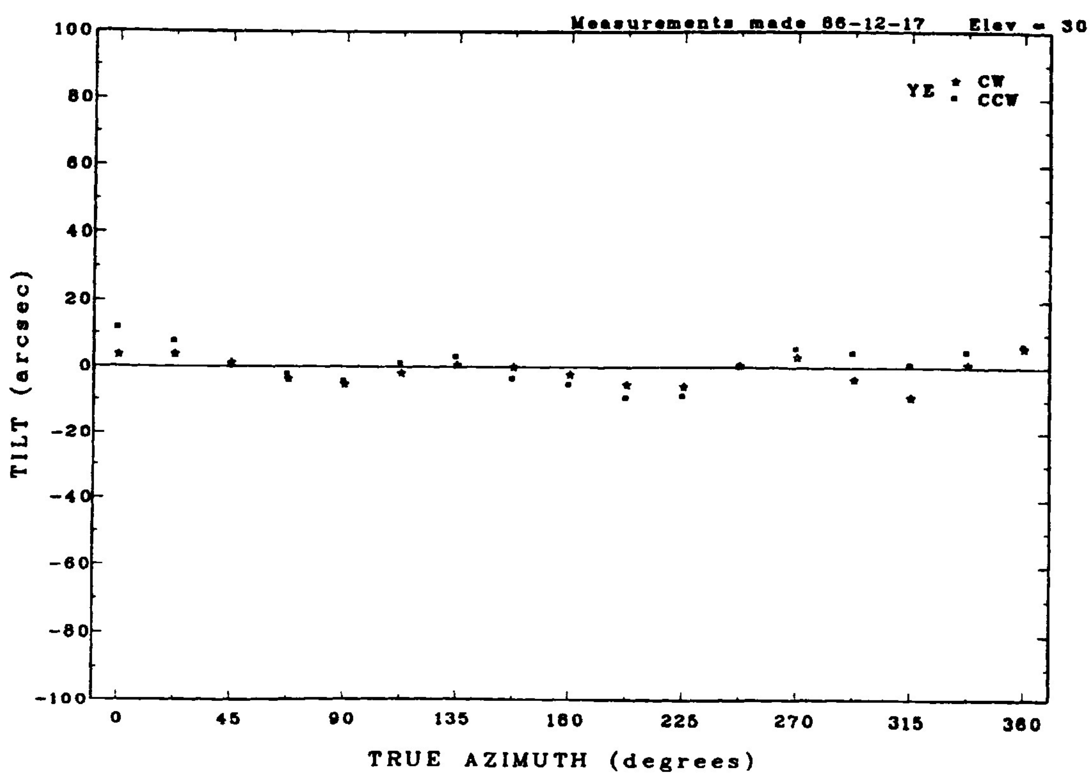
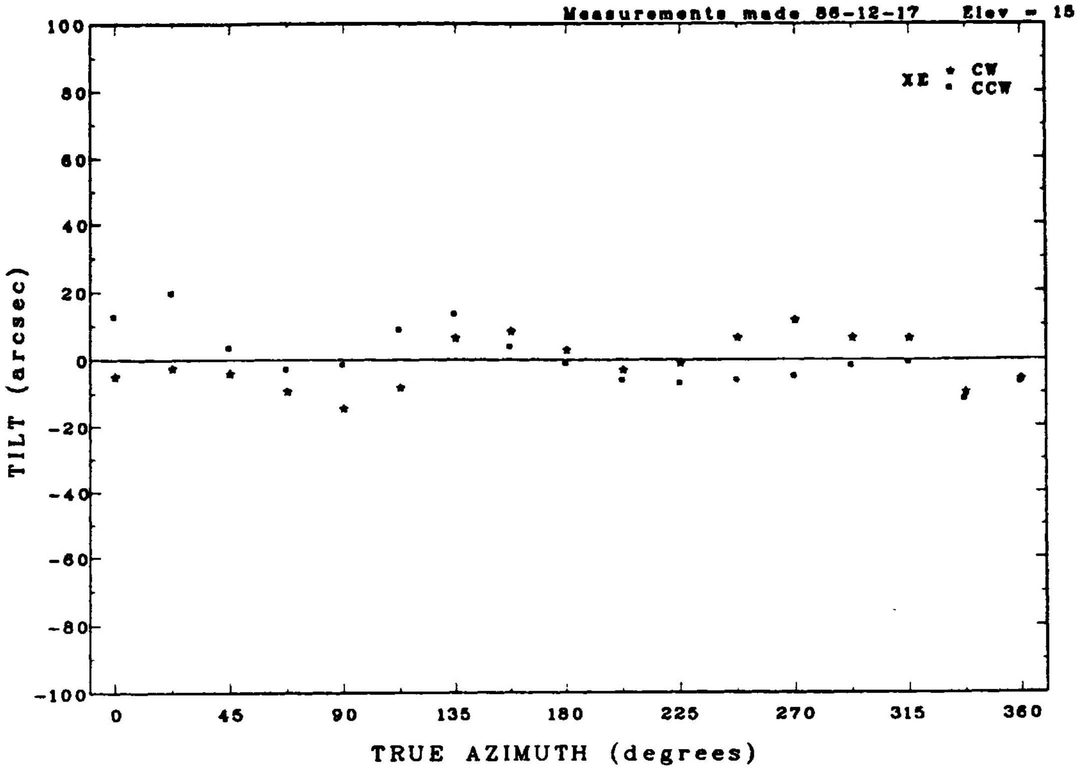

Measurements made 86-12-17 Elev = 30
YE
* CW
* CCW
TILT (arcsec)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
45
90
135
180
225
270
315
360
TRUE AZIMUTH (degrees)

Figure 14C


Measurements made 86-12-17 Elev = 15
XE * CW
. CCW
TILT (arcsec)
TRUE AZIMUTH (degrees)

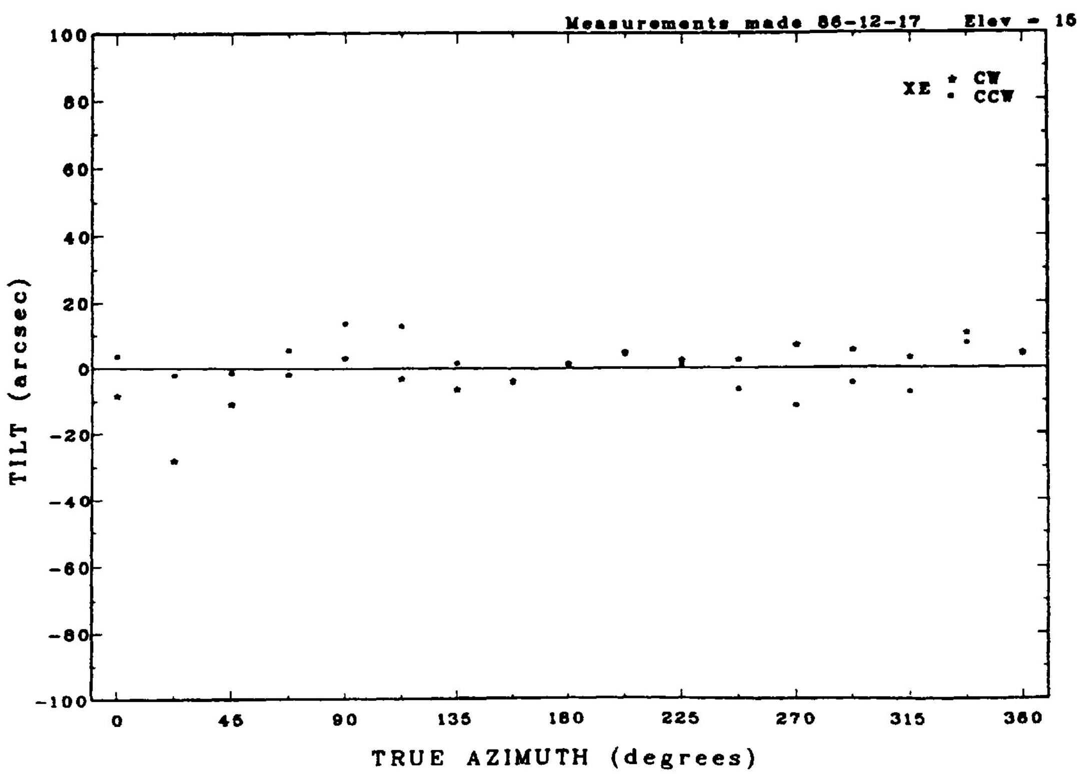
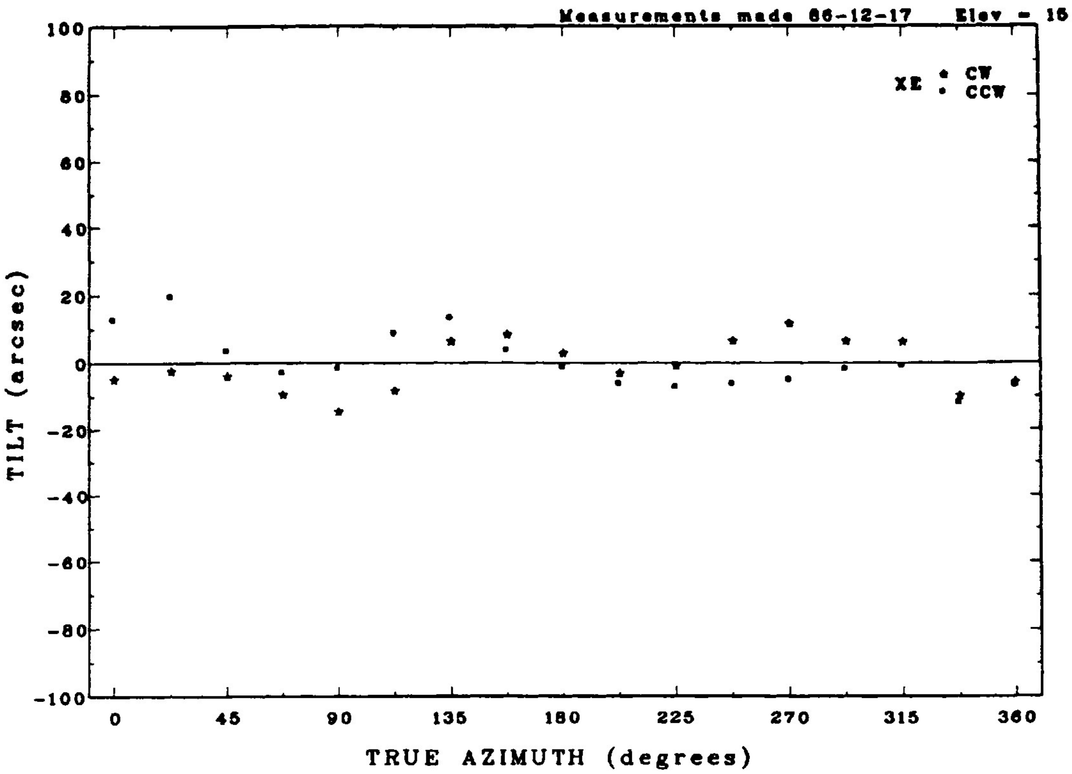

Measurements made 86-12-17 Elev = 15
XE * CW
. CCW
TILT (arcsec)
TRUE AZIMUTH (degrees)

Figure 14d



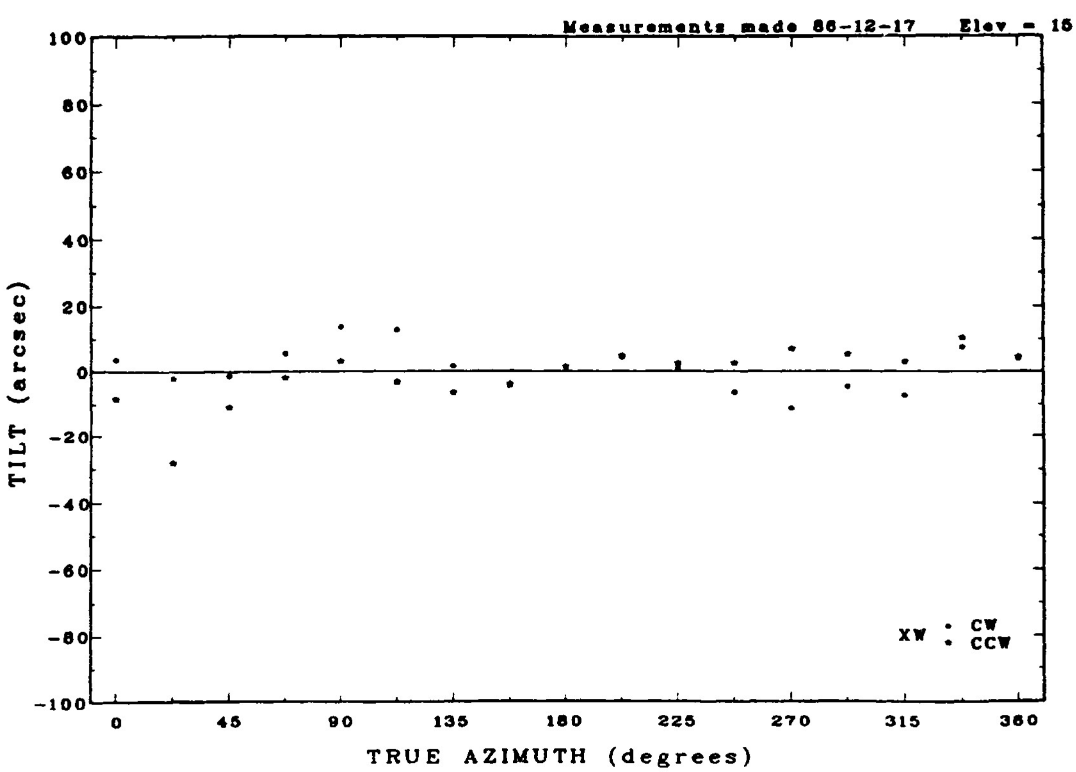


Figure 15: A comparative pair of plots showing the residuals on both sides of the antenna (XE and XW) when there is a strong "turn around" error. The top panel is the same as in figure 14d.