Jones

\# 182

A REVIEW OF VLA POINTING

D.Morris 25 Febuary 1991

SUMMARY

At present, nighttime, slowly varying, pointing errors are about 15 arc seconds RMS in calm conditions. Over shorter periods (4-5 h) they can be as low as 7 arc seconds. Tilt measurements indicate as much as an additional error of about 20 arc seconds during daytime (2"/h).

This suggests that under calm conditions the slowly varying component of the pointing errors can be reduced to below 7 arc seconds RMS by frequent updates of the offsets - perhaps even in daytime. This would require 10-15 mins of pointing observations on a nearby calibration source every few hours.

Faster changes in pointing due to wind deflections and telescope oscillations can probably only be kept below 7 arc seconds by observing in low winds - for example < 10 mph. Time lost would be approximately 30% in the calm season, 70% in the windy season (Febuary - June).

These are CHEAP solutions which will probably allow good observations at 43 GHz. They can be easily checked by trial observations. The other solutions which involve the use of inclinometers or optical telescopes are quite expensive - of order $10,000 or more per telescope. It may be worthwhile to try to improve the temperature control of the yoke structure and to try to understand the excitation of the 2.2 Hz oscillations.

INTRODUCTION

At present the VLA routinely operates at 22 GHz where the pointing error specification is for an RMS of 15 arc seconds. This is already 1/8 of a primary beam width and must already compromise the dynamic range that can be achieved on sources extended with respect to the primary beam width.

At 43 GHz the effects will be much more pronounced and it seems clear that an improvement of a factor of 2 in the pointing performance must be achieved if the VLA is to work successfully there.

I have tried to explore several possibilities for improving on or circumventing the present limitations.

CLASSIFICATION OF POINTING ERRORS

SLOW VARIATIONS

These change on time scales of minutes or hours and are attributable to:-

Misalignements (errors of construction) - function of azimuth, elevation

Gravitational deformations (sag) - function of elevation

They can be corrected for by a static geometrical model.

Temperature differences - function of time, solar heating, wind.

Steady wind deflections - function of wind speed, direction, elevation.

In principle these effects could be corrected by a "slow" dynamic model which used input from tilt sensors and or measured temperatures in the telescope structure. A detailed structural model would be needed and to my knowledge such a model has not yet been successfully used in practice.

FAST VARIATIONS

With time scales of seconds or less due to:-

Wind Gusts - actual deformations of the antenna structure

Servo errors - incomplete correction for wind gusts for example

Oscillations (E.G. 2 Hz) - induced by wind or telescope motion.

EFFECTS OF POINTING ERRORS ON APERTURE SYNTHESIS

The main effects are due to the associated uncertainties in the gain of the individual antenna gains near the edge of their primary beams. This variation in antenna gain over the synthesized field cannot be corrected for by current self calibration techniques.

1) Constant pointing offsets of all antennas

This leads to errors in overall shape and calibration of extended sources.The dynamic range of the synthesized maps is not effected.

2) Slow variations during an extended synthesis

Gain errors are now a function of position in the primary beam and self calibration is not effective.The dynamic range is degraded and becomes progressively worse away from the field center.Thus the dynamic range depends on the source angular size in comparison with the primary beam.

3) Fast variations compared with the basic integration time

Such very fast pointing changes have the effect of smoothing the primary beam. If the statistics of the variations are constant during the synthesis then the effect may not be severe - the primary beam is a little wider than expected.If the statistics of the pointing errors changes during the synthesis then the effective antenna gain becomes a function of time and position in the field and the dynamic range must suffer.

A related effect due to the motion of the phase centers of the individual telescopes (during oscillations of the pedestal for example) will reduce the effective antenna gain.This can be corrected for by the self calibration process.

PRESENT PERFORMANCE

I have used data taken during routine pointing runs over a period of 3 months to assess the present performance.These pointing runs are made at night in calm conditions (< 10 mph wind) and typically take 4-5 hours to observe about 20 sources.They thus represent the "best" performance of the VLA.Each determination consists of 5 observations of 20 seconds (10 seconds integration, 10 seconds moving time).Up to 5 determinations are made on each source at C band.Under good weather conditions I found a peak to peak reproducibility of the determination of the pointing offsets of the order of 6 arc seconds.

The standard reduction program PEEK fits a simple model,with 6 terms,to the measured pointing offsets (see Table 4).It gives an assessment of the measurement errors of the individual measured offsets - typically 1.5 arc seconds - and the RMS residuals between the fit and the measurements.The residuals are calculated twice,"prefit" (using the old parameters),and "postfit" using the "new" parameters.These results are given in Table 1.

The prefit residuals give a measure of the RMS pointing error to be expected on a typical calm night,randomly selected.The postfit residuals give an estimate of the minimum errors to be expected over a period of 4-5 hours. Table 1 shows that under good weather conditions (90OCT29 and 90DEC05) the prefit residuals are about 15 arc seconds which is therefore an estimate of the present average pointing accuracy of the VLA antennas - the long term stability of the pointing model.These values are close to those (18") given by Newell (1983).The postfit residuals are about 9.5 arc seconds RMS - which is an estimate of the short term (4-5 hours) stability of the model.

It would thus appear that the initial specifications of 15 arc seconds RMS pointing errors for the VLA antennas are met at night in light wind.

Daytime pointing would be expected to be considerably worse.The tiltmeter data of C.Janes (4 Dec 1990),taken with the antennas in the zenith position, in winter,show tilts of up to 20 to 25 arc seconds from dawn to midday.This might be expected to increase the RMS pointing error from 15 to 20 or more arc seconds.There are however reports from earlier epochs of comparable performance at day and night.Newell (1982) reports errors of about 15 and 16 arc seconds for summer day and night respectively.This unexpected good daytime performance is hard to explain but may be the result of the partial shading of the pedestal and fork by the mirror when the sun is at high elevations (in summer).

POSSIBLE REDUCTIONS IN SLOW POINTING ERRORS

An examination of the postfit residuals (from the standard 6 term model),as a function of azimuth and of elevation shows,for many antennas, systematic variations indicative of missing geometrical terms in the model.For example Figures 1-5 (top) show a pronounced oscillation in both azimuth and elevation residuals as a function of azimuth - with period 360 degrees (first harmonic). Such a periodicity has a well known physical cause - a miscentering of the encoders on the telescope axes (Wade 1990).

Hence I decided to experiment with a model containing several more terms.I included 3 additonal terms for miscentering in azimuth and elevation (one is already included in the "sag" term),a term to take account of the non perpendicularity of the azimuth and elevation axes,and an elevation term with a third harmonic variation in azimuth.This latter term had previously been seen in tiltmeter measurements and represents the effects of a "weak" support for the azimuth bearing.Most of these terms had been already discussed by Wade (1990).The details are in Table 4.The postfit residuals using this model (PEEK1) are shown in the bottom half of Figures 1-5.For most antennas no remaining systematic variations can be seen,within the limits imposed by the noise level.When the residuals are plotted as a function of time however, there are suspicions of slow drifts - see for example Figures 6-9.These slow drifts are presumably to be attributed to residual temperature changes in the antenna structures.

A summary of the improvement in the residuals incurred by using PEEK1 (with 12 terms) is given in Table 1.Including 12 terms reduced the RMS residual, averaged over 27 antennas,from about 9 arc seconds to 7 arc seconds.In a few cases of particularly small measurement errors the residuals are reduced by a factor of 2 to about 3 arc seconds (Figure 3).

Some antennas show a second harmonic term in the elevation residuals as a function of azimuth.This may also be due to a defect in the azimuth bearing or its support.Figure 10 shows that the effect for antenna 2 for example is stable over a 2 month interval.Thus a future model should probably include this term also.

It thus appears that small but significant improvements can be made in the static pointing model.Several of the terms can be expected to be constant for a given antenna and could be determined accurately once and for all.Then subsequent routine pointing determinations could solve for a reduced number of constants.

A DYNAMIC REAL TIME POINTING MODEL ?

It is clear that even with the present (6 term) static model,the slowly varying pointing errors are dominated by time variations in the parameters of the model.Deformations of the telescope structure due to temperature differences in the various members seem to be the most likely cause.The expected changes in pointing due to temperature changes in various parts of the telescope are summarized in Table 2.

INCLINOMETERS

It has been repeatedly pointed out that tiltmeters mounted on the top of the fork arms could in principle be used to correct for wind or temperature induced tilts in the pedestal and fork (Van Hoerner ,Newell).However,azimuth errors due to twisting of the fork,for example,would remain.Averaging the the outputs from the pairs of inclinometers (Figure 13) should remove any sensitivity to motions about the azimuth axis.Then the present parameters describing the tilt of the azimuth axis and the perpendicularity of the azimuth and elevation axis could be replaced by inclinometer readings.The Schaevitz inclinometers,in their temperature stabilized box,have peak to peak errors of about 3 arc seconds (Janes and Sittler 1989) and seem quite adequate for the job.This proceedure would work in real time but could be tested off line by including the inclinometer measurements in the pointing fitting program.Then one could test for lower residuals and for parameters which were more stable than those of the conventional fitting process.I have modified the PEEK program to read inclinometer measurements (PEEK2) and done a trial fit to data taken on 21 Nov 1991.The results are dissappointing with large residuals (about 13 arc seconds).The reason is made quite clear by Figure 11 which displays the inclinometer reading as a function of time for antenna 6.During normal observations the inclinometers show an RMS of a few arc seconds but during the pointing run peak to peak variations of 90 arc seconds occurr.This we attribute to large 2.2 Hz oscillations of the telescope which are excited by the fast telescope motions during the pointing run.The data aquisition system takes samples every 80 seconds during normal operations and so samples the 2.2Hz waveform randomly - giving the impression of noise.The form of the oscillations is indicated in Figure 14 - under conditions of normal tracking of a source at the sidereal rate.Unknown factors induce damped oscillations of several tens of arc seconds amplitude.Slewing motions or high winds are an additional exciting factors.

The effect of the fast oscillations could be removed if the inclinometer data were filtered before digitization at the telescope.Then it would be possible to further test the idea of a "slow" dynamic real time model.

TEMPERATURE SENSORS

Another possible dynamic real time pointing model would use an array of calibrated temperature sensors installed at a large number of critical points in the structure.Then given an adequate structural model it would be possible to predict the pointing error in real time as a linear function of all the temperature readings.Such a model would of course not correct for wind induced errors.At present we have neither structural model,nor an adequate number of calibrated (+- 0.1 degree) temperature sensors.

POSSIBLE REDUCTIONS IN FAST POINTING ERRORS.

There seems little chance for reduction of the fast pointing errors due to wind gusts and wind induced and other oscillations of the telescopes.They are mainly dependant on the rigidity of structure.Perhaps the servo performance may be improved by adjustement,but any big improvement would call for a new servo installation with perhaps state controllers.The limited speed of the data transmission over the waveguide system means that the inclinometer readings cannot be included in any real time fast servo loop (Janes Dec 10,1990).

The factors inducing the 2.2 Hz oscillations are not completely understood at the moment.Clearly wind is a large factor and also fast telescope motion seems to be able to excite quite large amplitude oscillations (100 arc seconds peak to peak).Even when tracking,low level oscillations are observed with peak to peak values of some tens of arc seconds (Figure 14,Janes 4 Dec 1990).

The calculated wind induced pointing errors are summarized in Table 3.They come from Van Hoerner (1981,1982).From this tabulation it appears that errors of less than 7 arc seconds could be expected in winds of less than 10 mph.A quick assessment of the inclinometer data (Janes 1990) indicates that the 2.2 Hz oscillations would probably be of the order of 3 arc seconds RMS in this wind.

Thus a possible way to reduce wind effects to a managable level is simply to restrict observing at 43 GHz to times of low wind (< 10 mph).Then Van Hoerner's wind statistics indicate a loss of time of only 30% during the "quiet season" from July to January - but 70% during the windy season!

CONCLUSIONS AND RECOMMENDATIONS

So far it appears from the above that we have no proved method of improving the "blind" absolute pointing of the VLA antennas to guarantee an RMS error of 7 arc seconds or less.The application of the inclinometers may eventually help but this is an expensive solution when applied to 27 antennas.Likewise the use of optical tracking aids would also be expensive and time consuming to install and test.

By far the CHEAPEST and FASTEST technique will be to use frequent updates of the pointing offsets based on the observations of a calibration source near to the source under observation.Such a pointing update need only take 10-15 minutes every few hours.The exact frequency of update will depend on the distance between source and calibrator,on the quality of the pointing model and the rate of thermal deformations (daytime observations may be excluded).Thus there is still some incentive to include more terms in the static model and to understand and improve the thermal properties of the telescopes.

Wind induced pointing errors can be only reduced by restricting observations at 43 GHz to calm periods (< 10mph wind).

Future experimental work could concentrate on reducing the thermally induced errors.Table 2 indicates that the fork is a critical element.Temperature recordings made in the fork (Figure 12) by C.Janes (4 Dec 1990,1991) show an anomolously large temperature differential (about 5 degrees) at the back of the base of the fork.Newell (1983) has suggested that heating by ambiant air rather than solar insolation may be responsible for some of the observed temperature changes.Improved insulation and or forced ventillation may be called for.

Another fruitfull line of enquiry would be to try to understand in more detail how the 2.2 Hz oscillations of the structure are excited and to see if they could be damped in some way.

Although it would be interesting to pursue the application of the inclinometers to a real time model ,the expense of such a solution makes it unlikely to be adopted for 27 antennas.

ACKNOWLEDGEMENTS

The above relies heavily on the measurements taken by C.Janes and A.Sittler. I am indebted to them and also C.Wade and P.Hicks for their help and unstinting cooperation.

TABLE 1

VLA POINTING RESIDUALS (Average over 27 antennas in arc secs)

DATE	PREFIT (6 terms)	POSTFIT (6 terms)	POSTFIT (12 terms)	EL/AZ (12 terms)	WEATHER & TIME(MST)
90NOV21	21.4	16.9	15.1	1.63	50-90% stratus rain 4-8m/s 22h-4h
90OCT20	19.1	14.9	12.9	1.65	50% cumulus 8m/s 2h-7h
90OCT29	14.4	9.5	7.0	1.14	clear calm 2h-6h
90DEC05	16.3	9.13	6.8	1.29	clear 1-4m/s 17h-21h

Typically about 20 sources observed each for up to 5 cycles of 100 seconds
I.E. about 10 mins total observing time per source.Each of 5 positions observed for 10 seconds.
Mean measurement error 1.5 arc seconds (90DEC05) - Optimistic ?

TABLE 2

PREDICTED DAY-NIGHT TEMPERATURE EFFECTS (VLA Antennas)

MEMBER	COEFFICIENT (secs/degree)		OBSERVED DELTA T (K)	CONTRIBUTION (arc secs)
I Beam	-0.9		1.5	1.4
Tubes (corner)	4.4	(King)	1.0	4.4
(one side)	1.8	(King)		0.9
Cylinder	0.8	(Van Hoerner)	<=5.0 ??	<=4.0 ??
Yoke Base	2.0	(Morris)	5.0	10.0
Yoke Arms	5.0	(Van Hoerner)	1.5	7.5
Backup Structure	1.6	(Van Hoerner)	<=5.0	<=8.0 ??
Quadrupod	-3.8	(Van Hoerner)	<=0.5	<=-1.9

OBSERVED

Daytime tilts of pedestal + yoke of 20 arc seconds

References

King - quoted by Van Hoerner (1981)

TABLE 3

WIND EFFECTS ON VLA ANTENNAS

About half the calculated deflection occurs in pedestal,half in fork.The contribution of the mirror itself is negligible.

For 18 mph (8 m/s),and angle between telescope axis and wind of A

pointing error = (8 + 20 |Cos A|) arc seconds

= 23 arc seconds for 90% of sky

Wind exceeds 18 mph for 25% of time in windy season (Feb-June)
16% of time in quiet season (July-Jan)

Average wind exceeds 18 mph for 13% of time in windy season
3% of time in quiet season

For 10 mph,pointing error = 7 arc second for 90% of sky

Average wind exceeds 10 mph for 70% of time in windy season
30% of time in quiet season

TABLE 4

GEOMETRICAL TERMS IN VLA POINTING MODELS

DESIGNATION	AZIMUTH (A)	ELEVATION (E)
6 Standard Terms (used by PEEK)		
Tilt	A1 Cos A Sin E	-A1 Sin A
	A2 Sin A Sin E	A2 Cos A
Collimation	A3	
Encoder Zeroes	A4 Cos E	A6
Sag (+ EL decentering)		A5 Cos E
Additional Terms (used by PEEK1)		
Third harmonic		A7 Cos 3A
		A8 Sin 3A
Azimuth decentering	A9 Cos A Cos E	
	A10 Sin A Cos E	
Elevation decentering		A11 Sin E
Axis Perpendicularity	A12 Sin E	
Future possibilities		
Second harmonic		A13 Cos 2A
		A14 Sin 2A

REFERENCES

P.Dewdney,"Investigating the use of tiltmeters to correct VLA antenna pointing Part 1.Initial measurements and analysis",VLA Test Memorandum No. 148, Febuary 1987

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PROGRAMS

The original PEEK (6 constants) together with modified versions PEEK1 (12 constants) and PEEK2 (12 constants + inclinometer inputs) are on VAX1 in the area DISK$RES:[dmorris.astrolab.point].

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30% of time in quiet season

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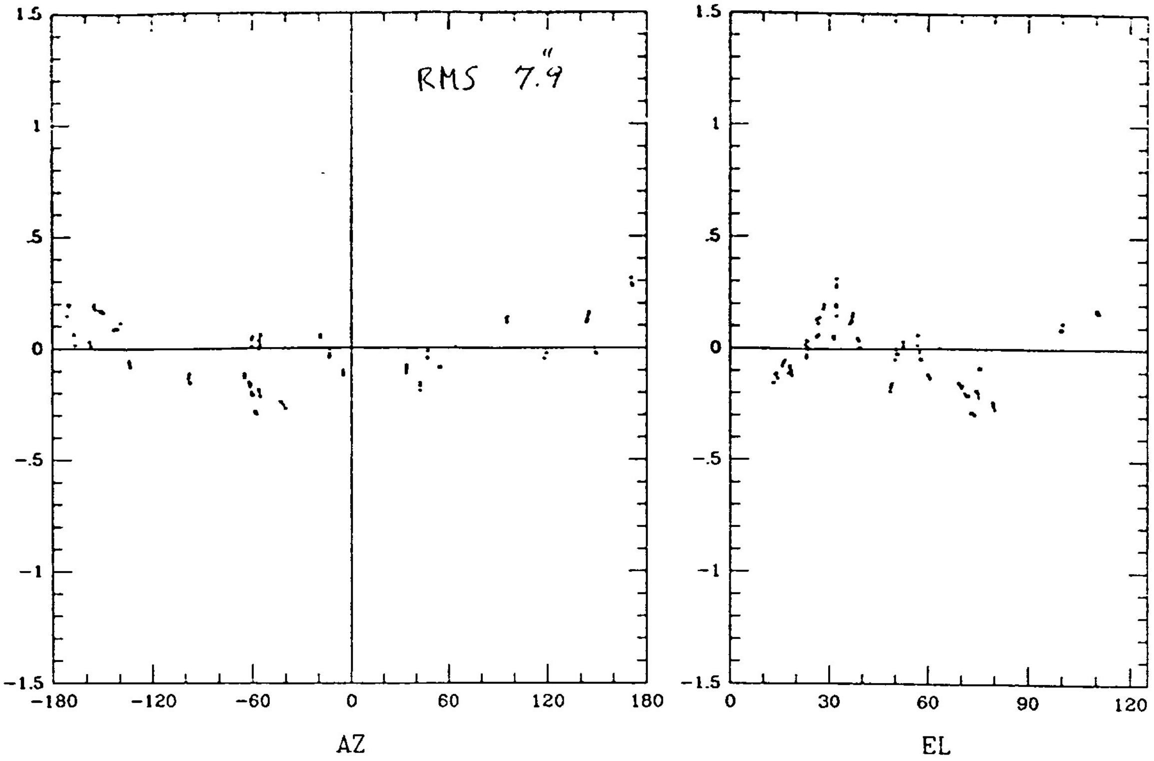
N90DEC05 – Antenna 01 – Azimuth postfit. 6 terms



N90DEC05 – Antenna 01 – Azimuth postfit. 12 terms

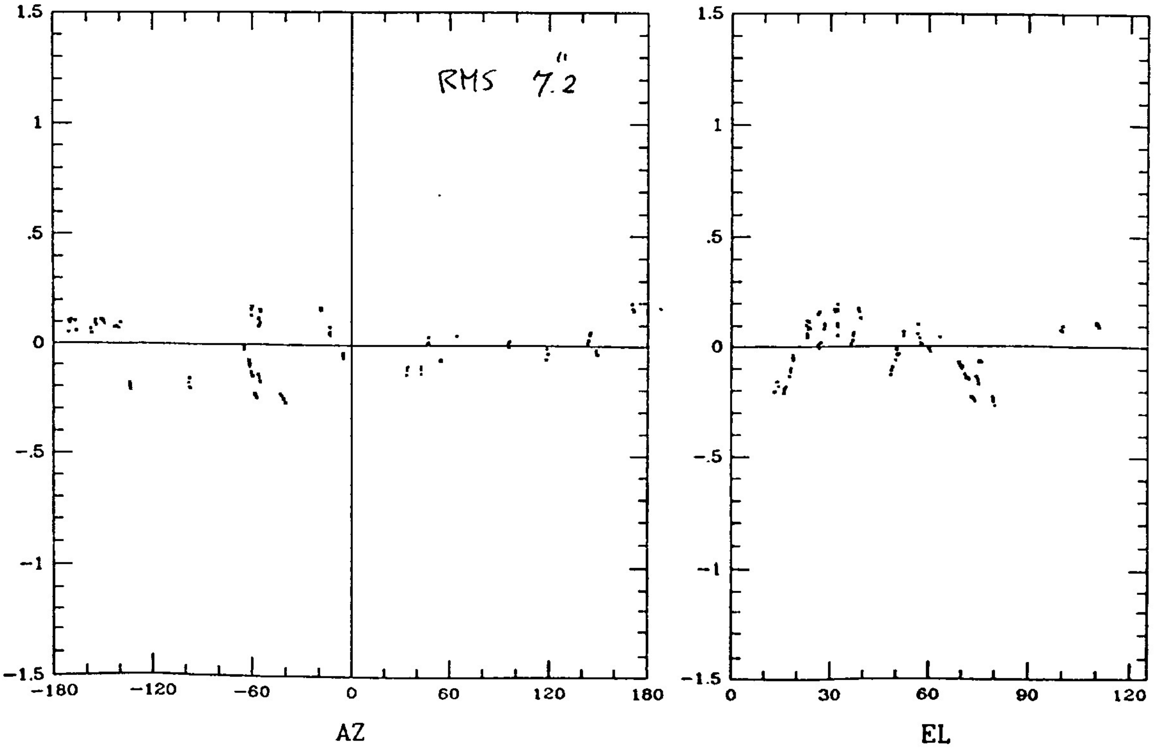
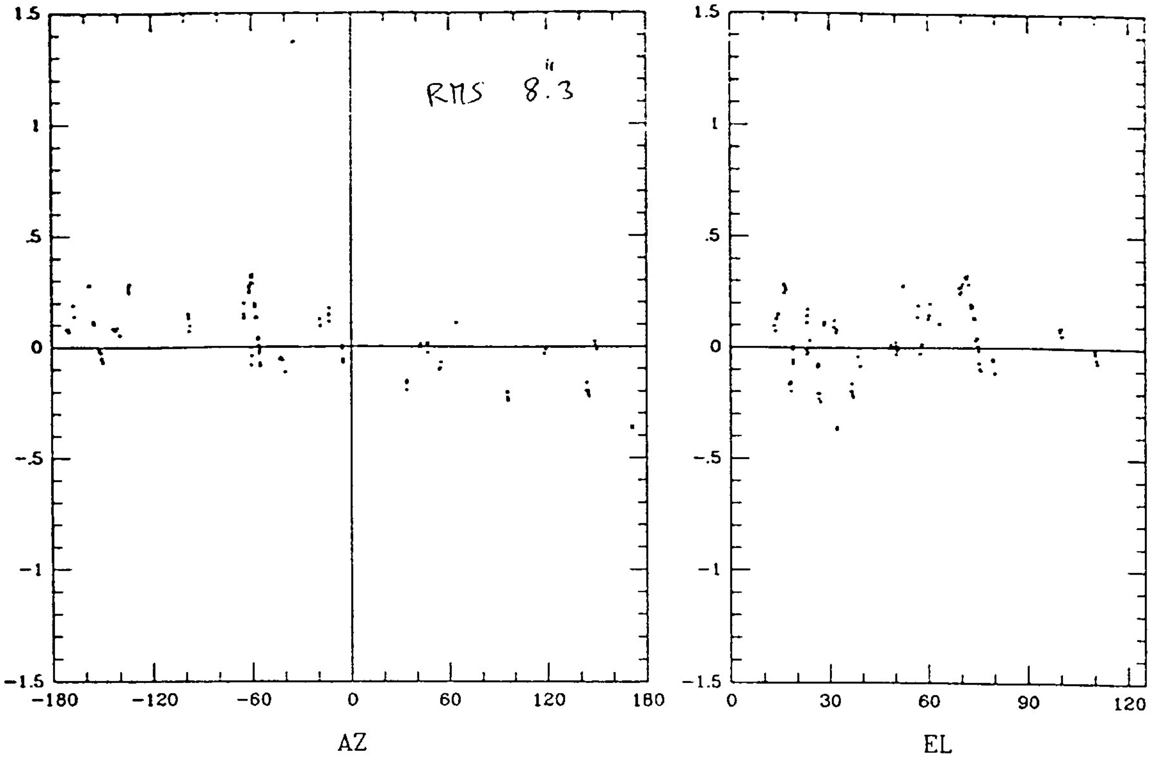
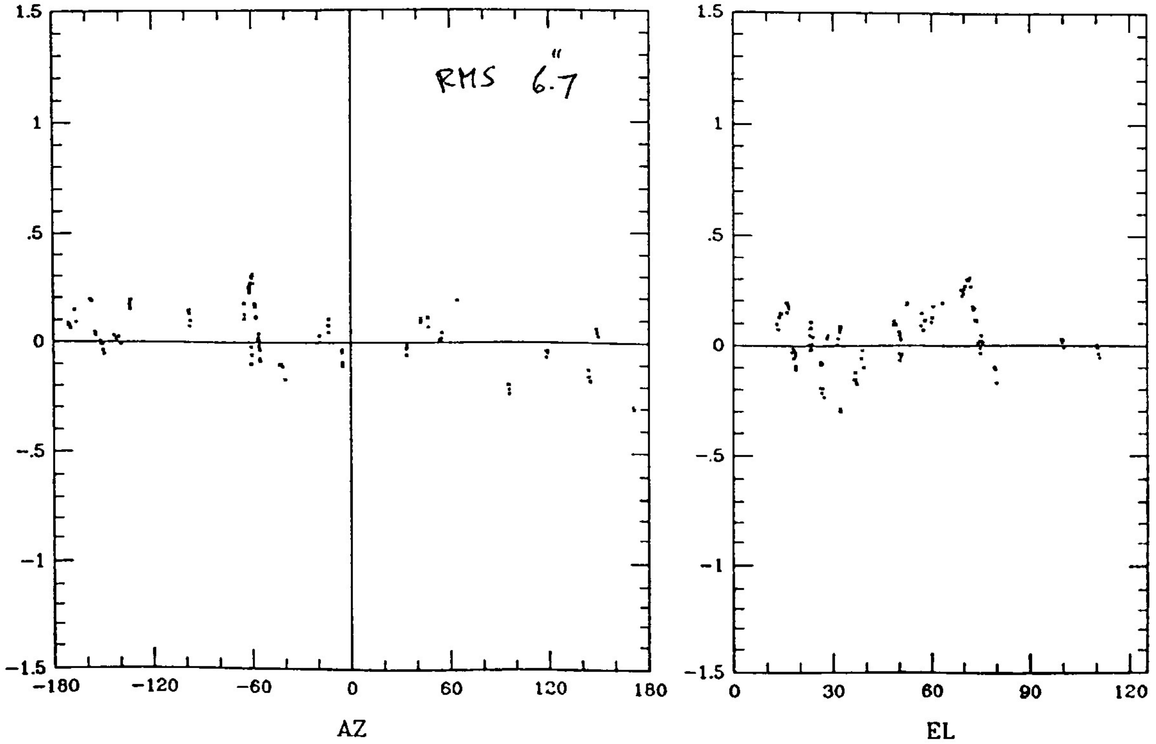


FIGURE 1

N90DEC05 – Antenna 01 – Elevation postfit. 6 Terms



N90DEC05 – Antenna 01 – Elevation postfit. 126 Terms



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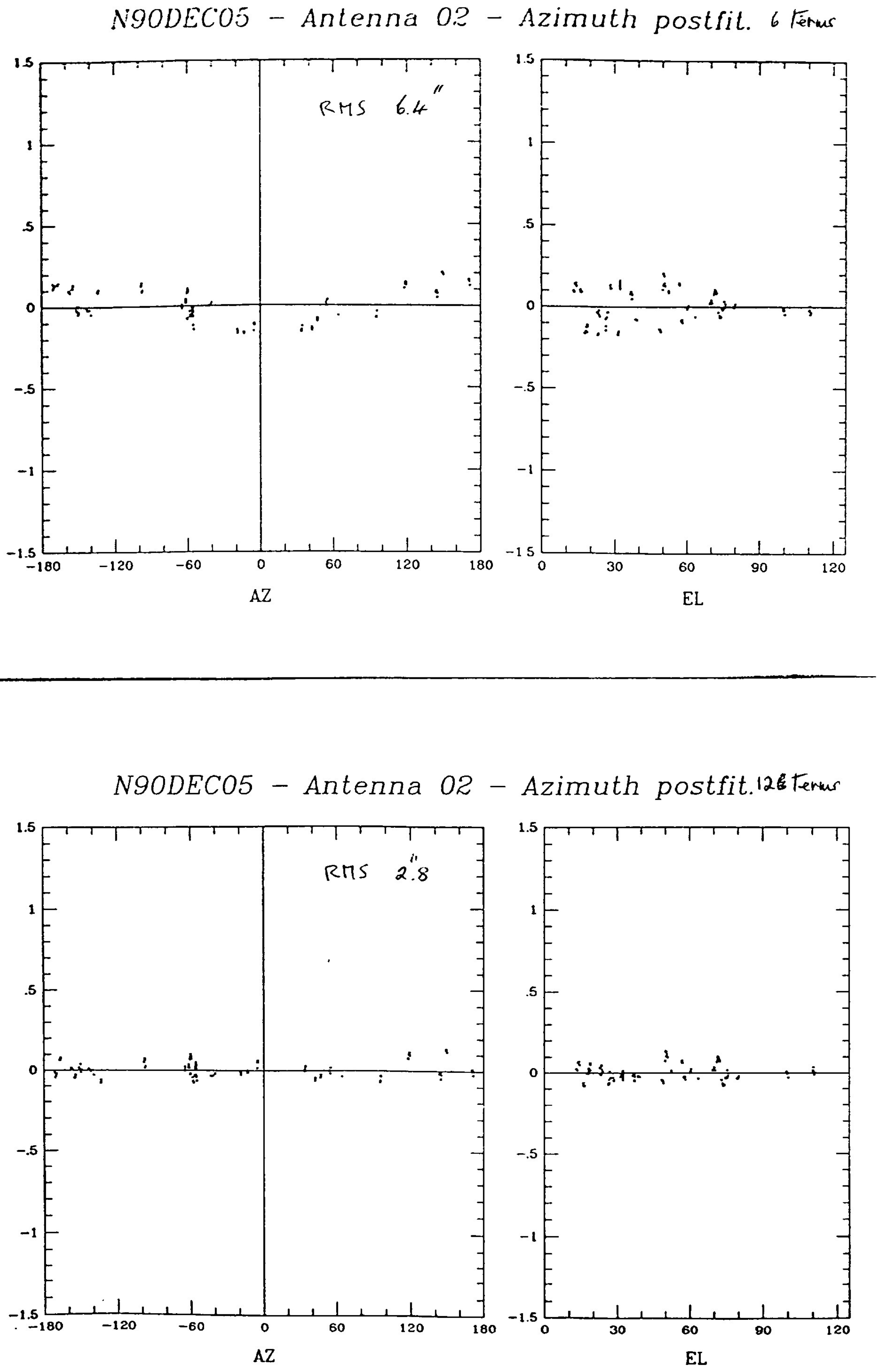
N90DEC05 – Antenna 02 – Azimuth postfit. 6 Terms
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1
.5
0
-.5
-1
-1.5
-180
-120
-60
0
60
120
180
AZ
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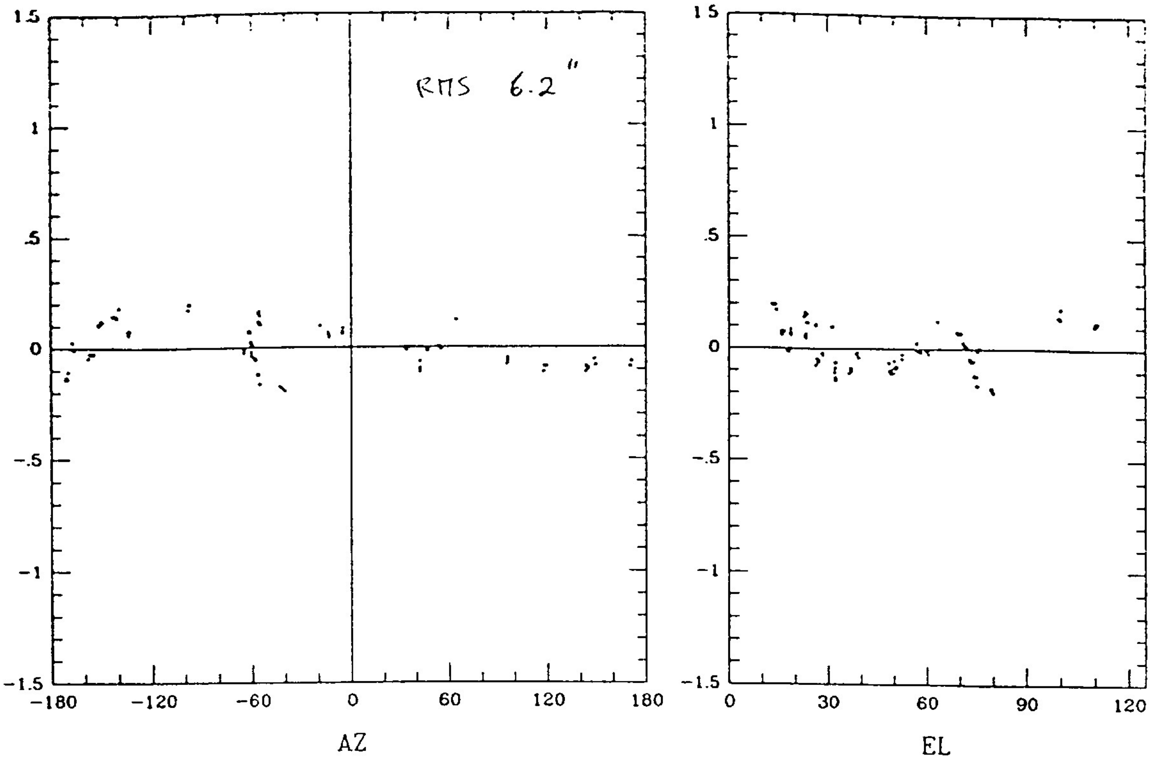
30
60
90
120
EL
N90DEC05 – Antenna 02 – Azimuth postfit. 12 Terms
RMS 2.″8
AZ
EL

FIGURE 3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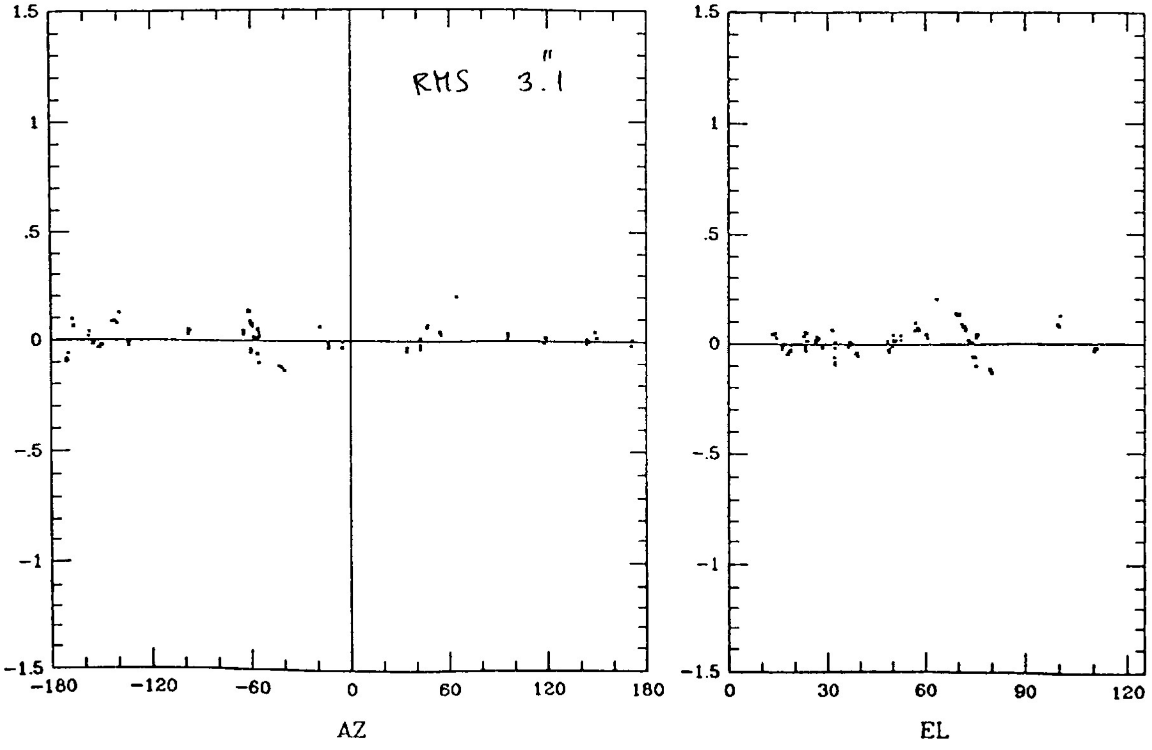
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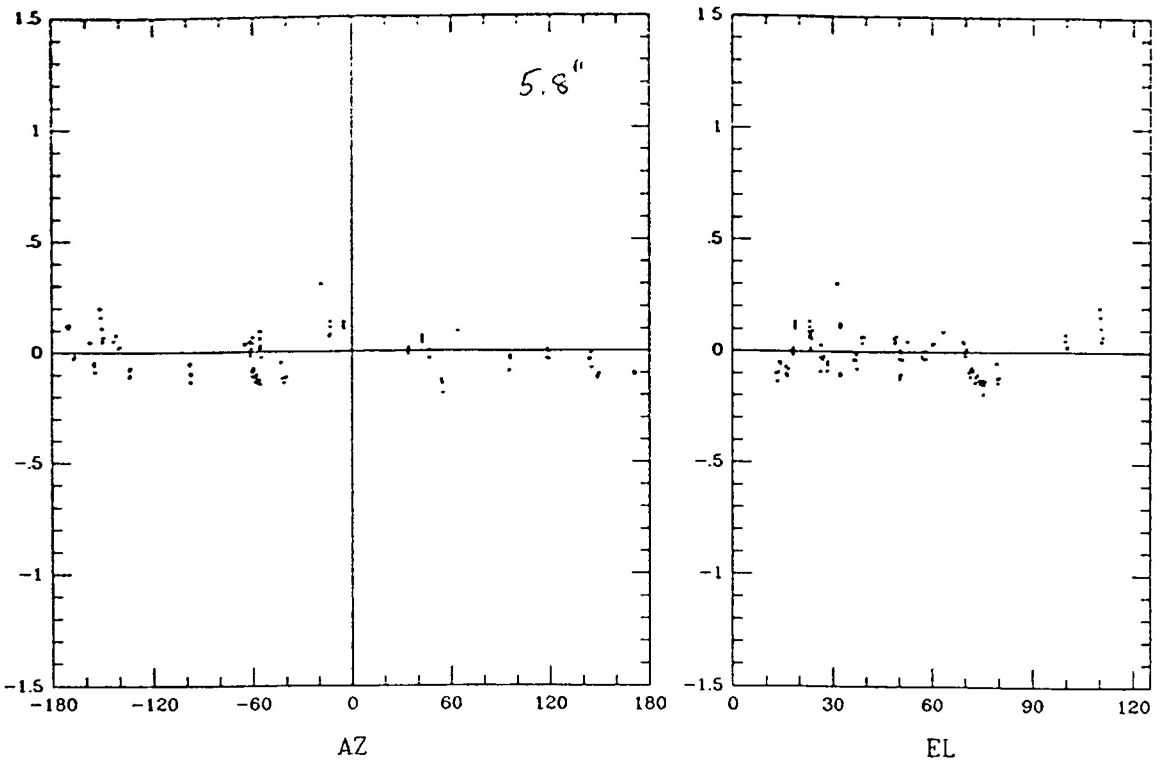
FIGURE 4

N90DEC05 - Antenna 03 - Elevation postfit 6 terms



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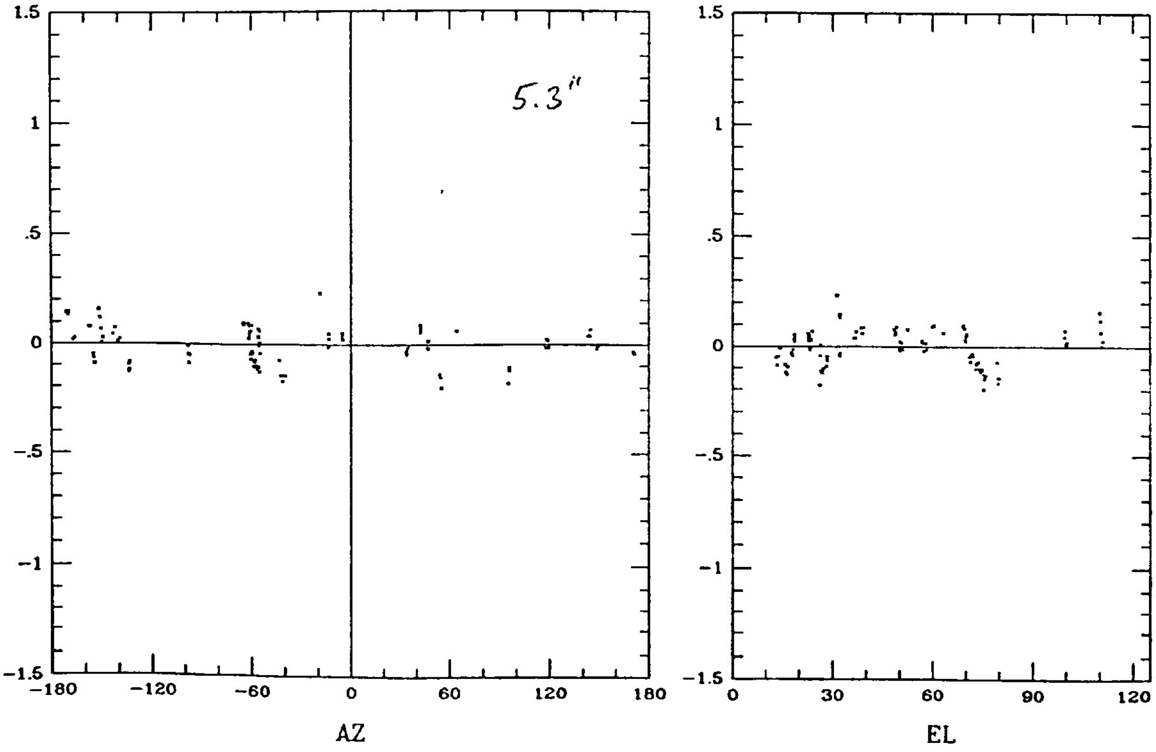

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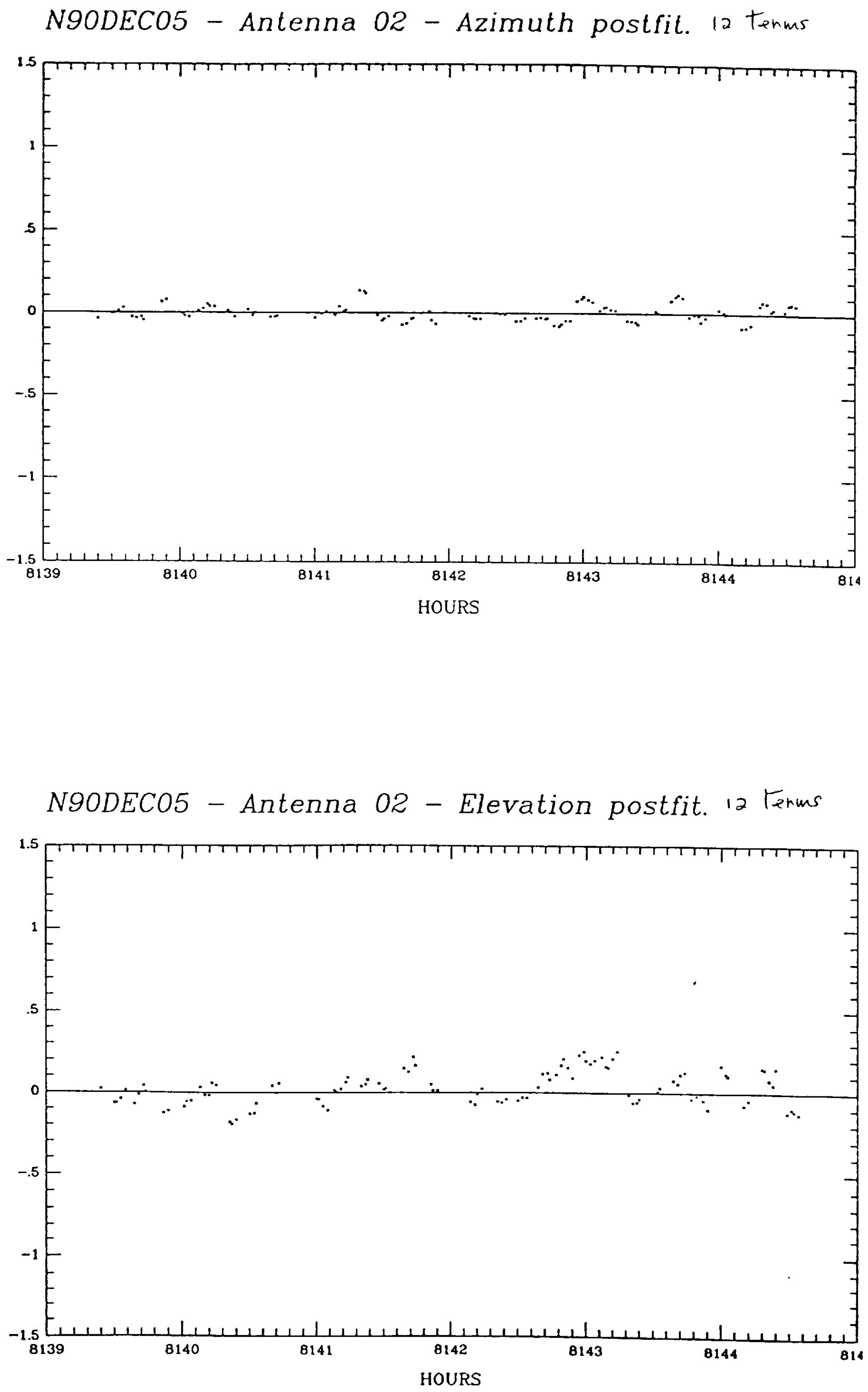
N90DEC05 - Antenna 02 - Azimuth postfit. 12 terms
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.5
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-.5
-1
-1.5
8139
8140
8141
8142
8143
8144
814
HOURS
N90DEC05 - Antenna 02 - Elevation postfit. 12 terms
1.5
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-.5
-1
-1.5
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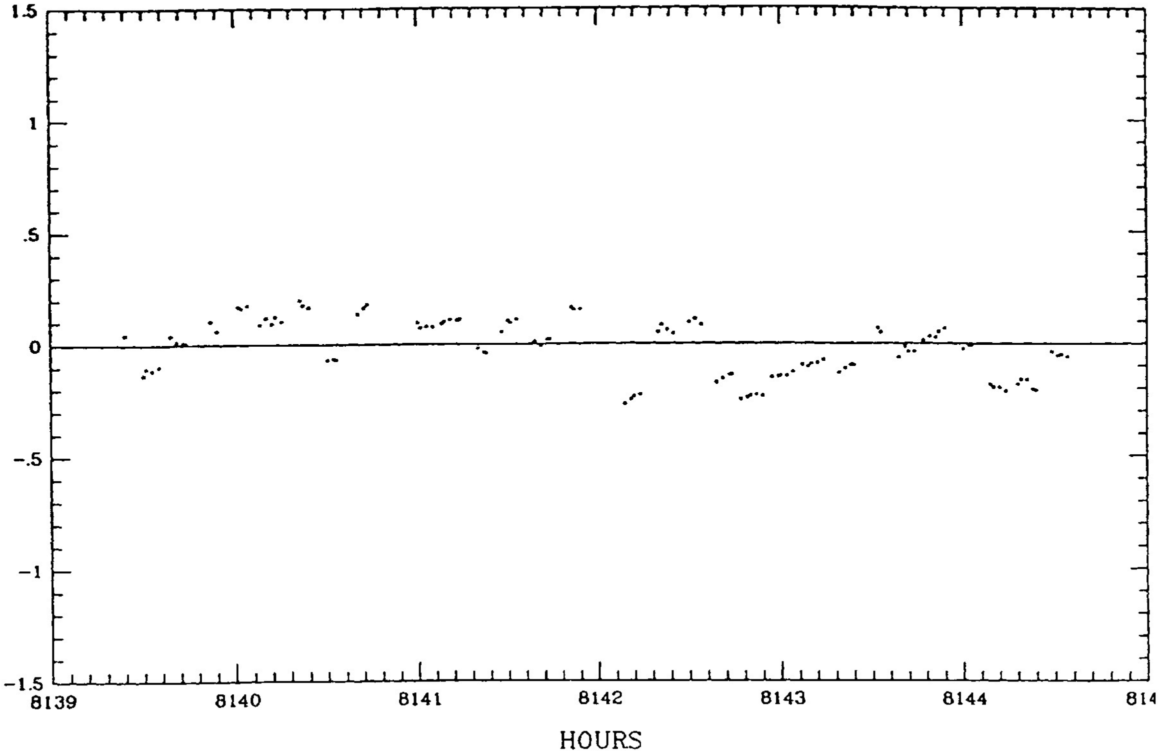
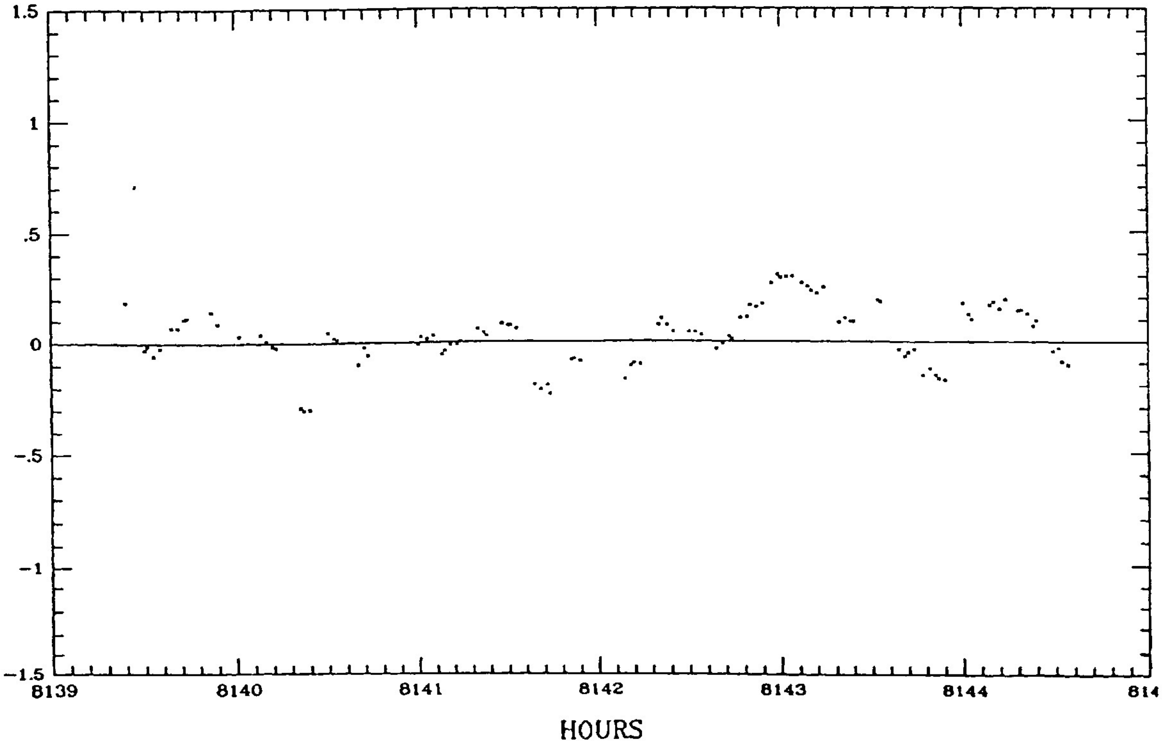
8140
8141
8142
8143
8144
814
HOURS

FIGURE 6



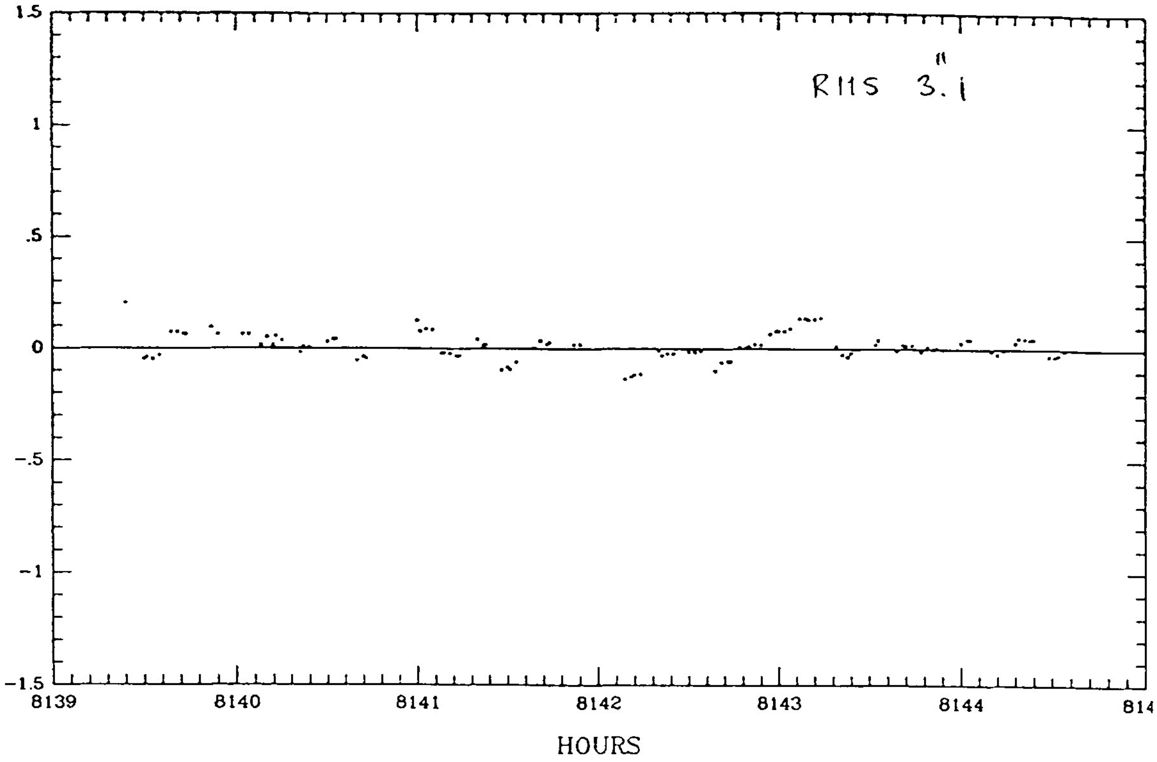
N90DEC05 – Antenna 01 – Azimuth postfit. 12 terms



N90DEC05 – Antenna 01 – Elevation postfit. 12 terms

FIGURE 7

N90DEC05 - Antenna 03 - Azimuth postfit. 12 terms



N90DEC05 - Antenna 03 - Elevation postfit. 12 terms

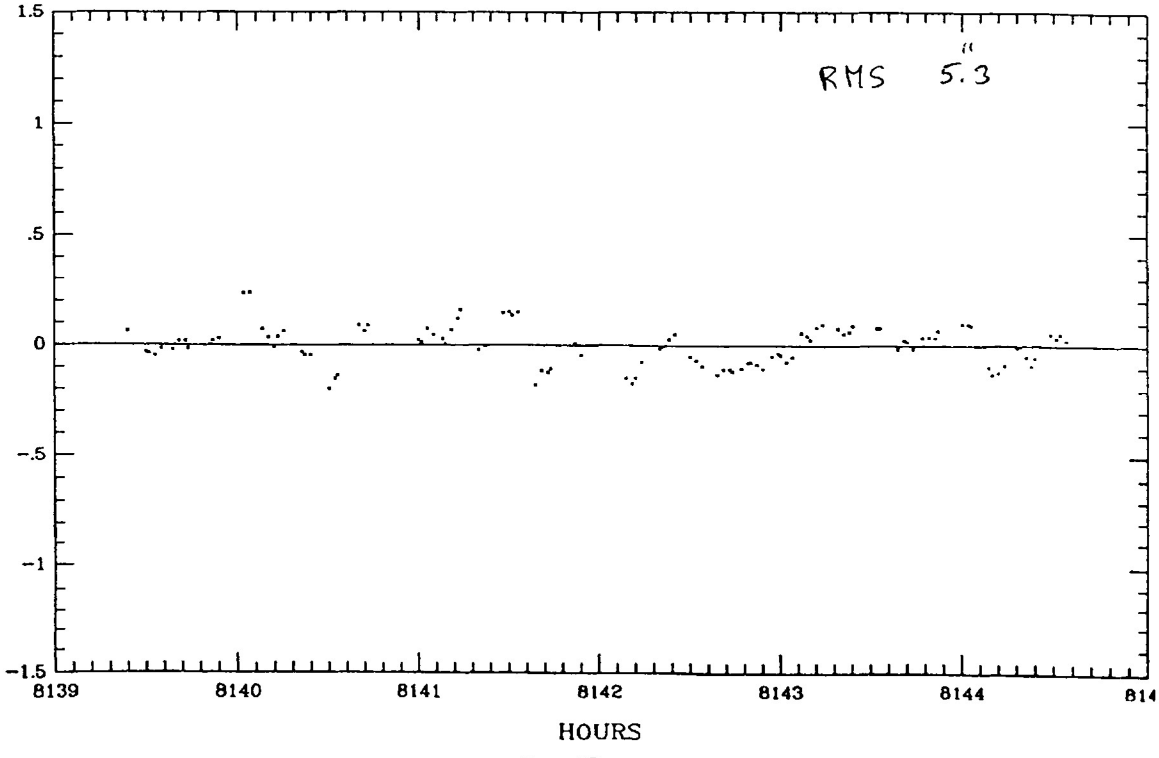
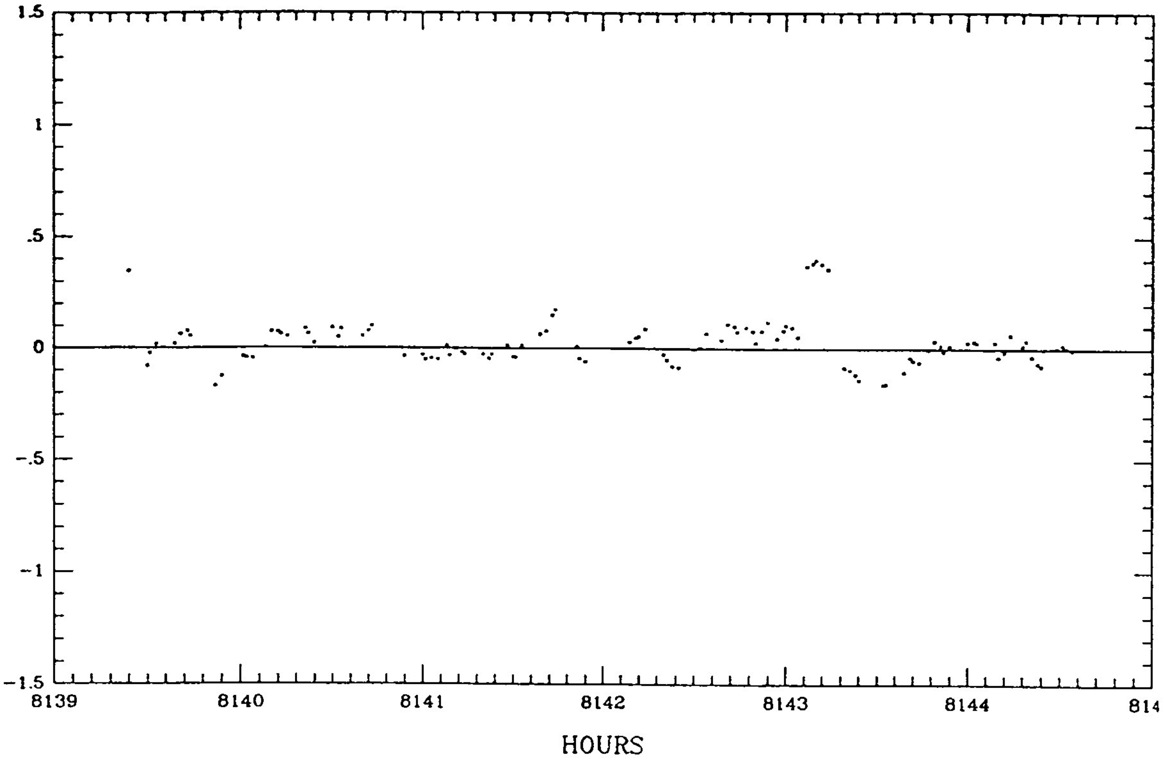


FIGURE 8

N90DEC05 – Antenna 05 – Azimuth postfit. 12 Terms



N90DEC05 – Antenna 05 – Elevation postfit. 12 Terms

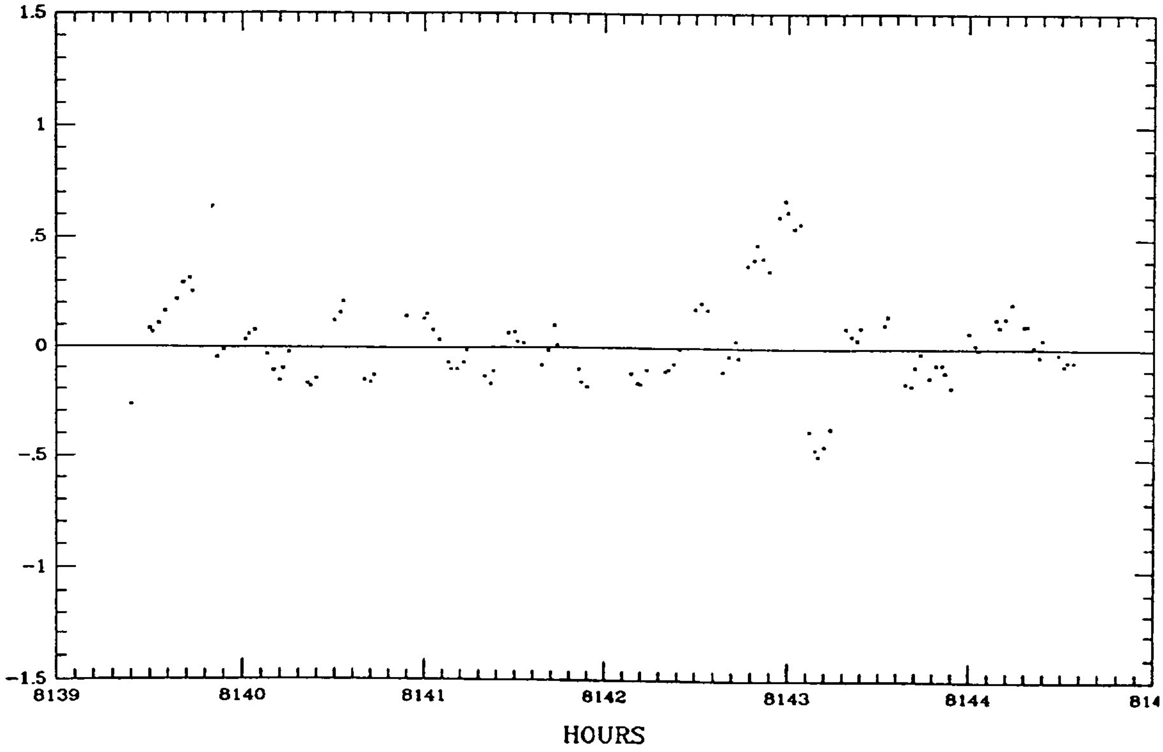
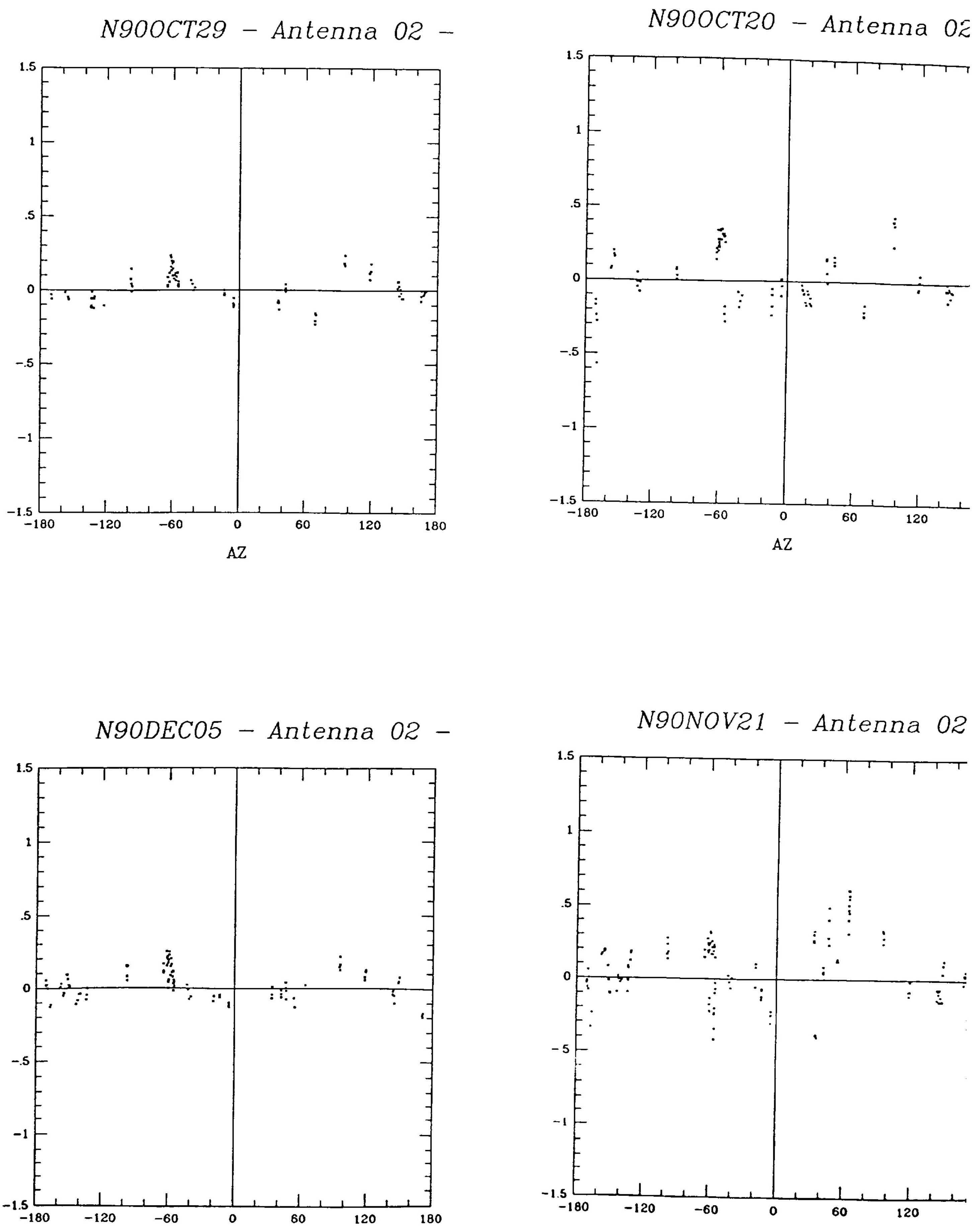


FIGURE 9


N90OCT29 - Antenna 02 -

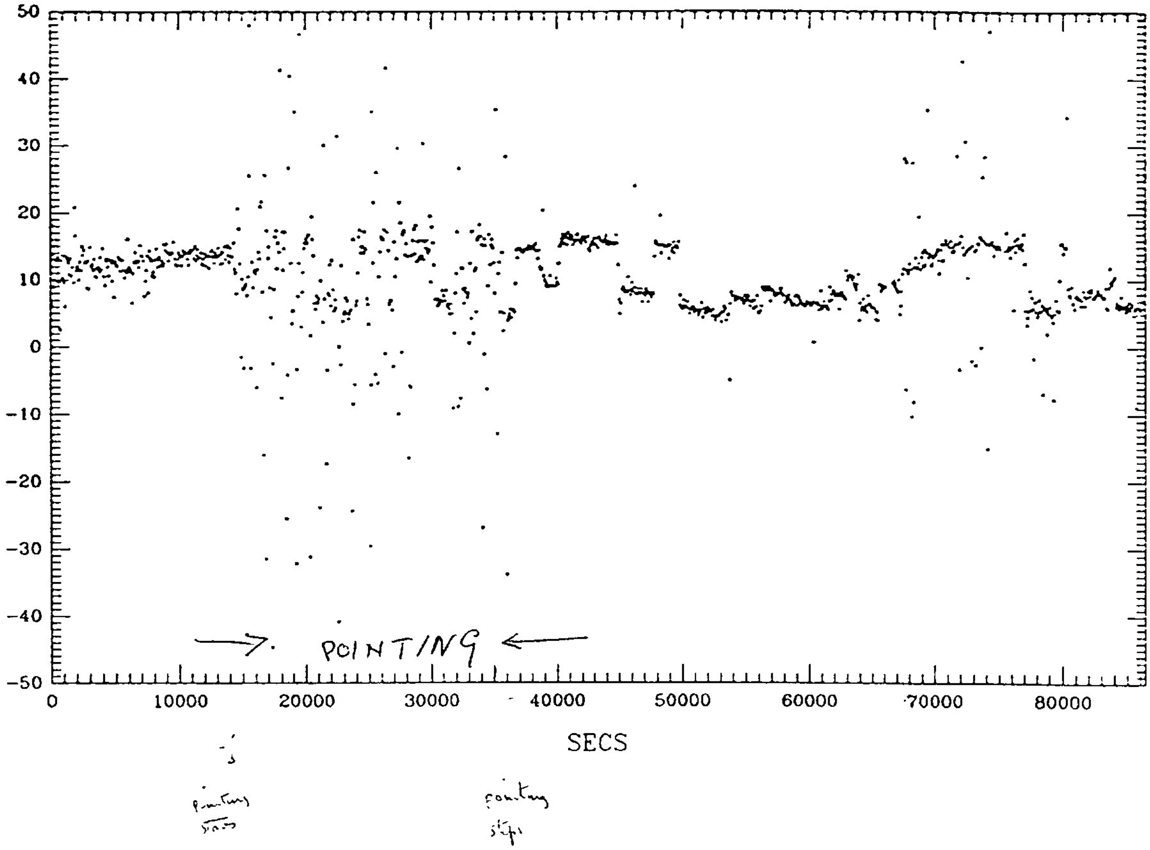
N90OCT20 - Antenna 02

N90DEC05 - Antenna 02 -

N90NOV21 - Antenna 02

FIGURE 10

ANT6TN21.DAT X



ANT6TN21.DAT Y

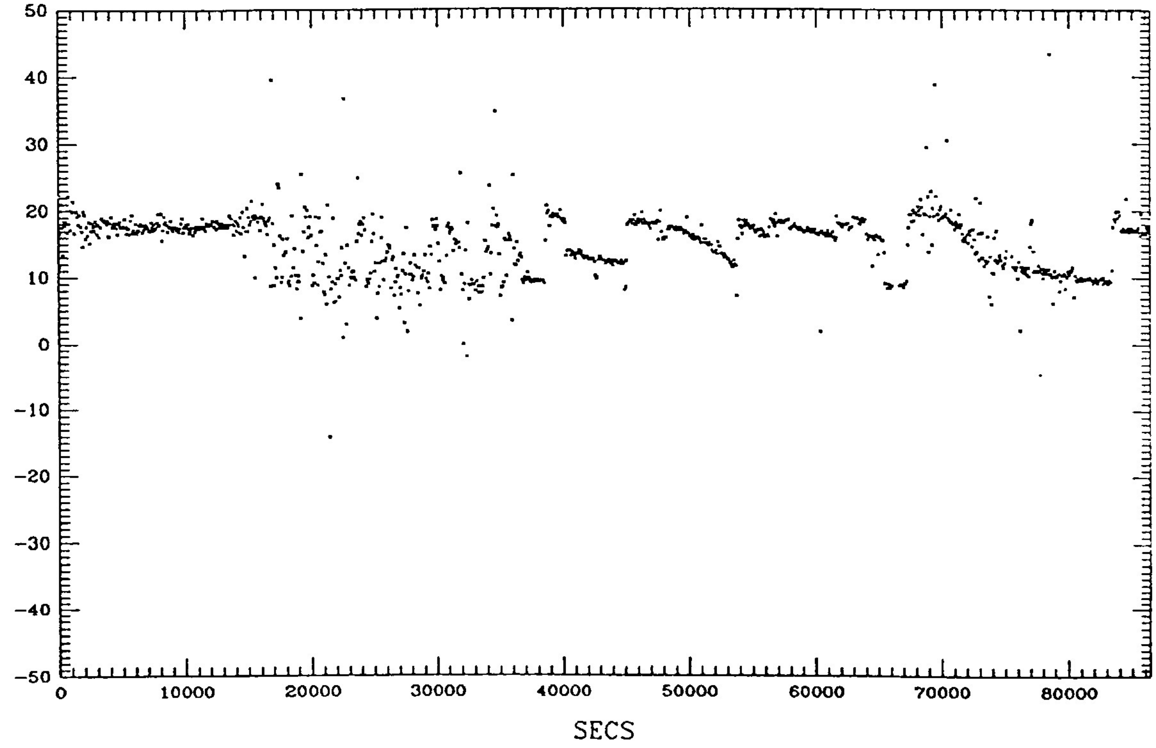
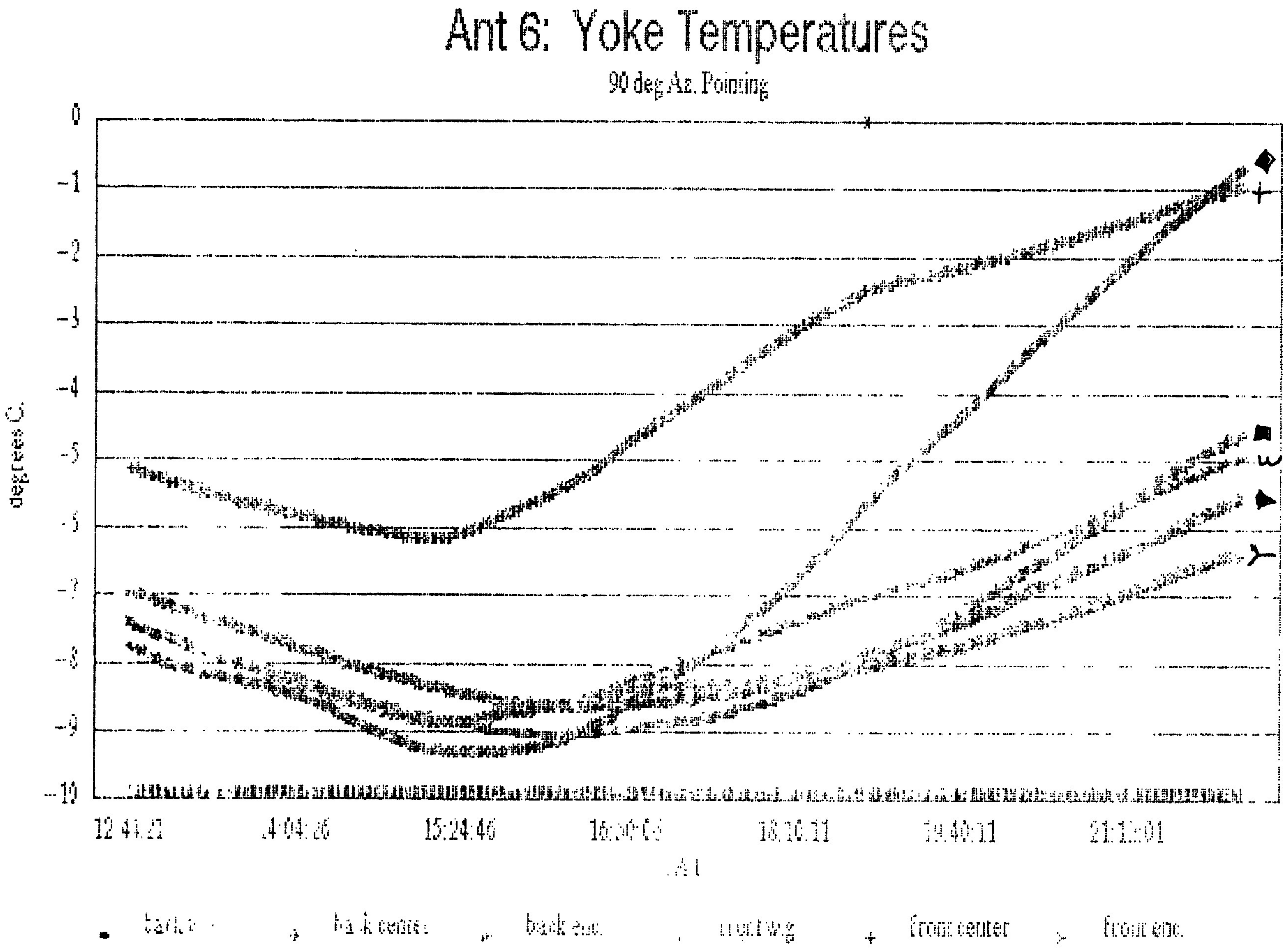


FIGURE 11



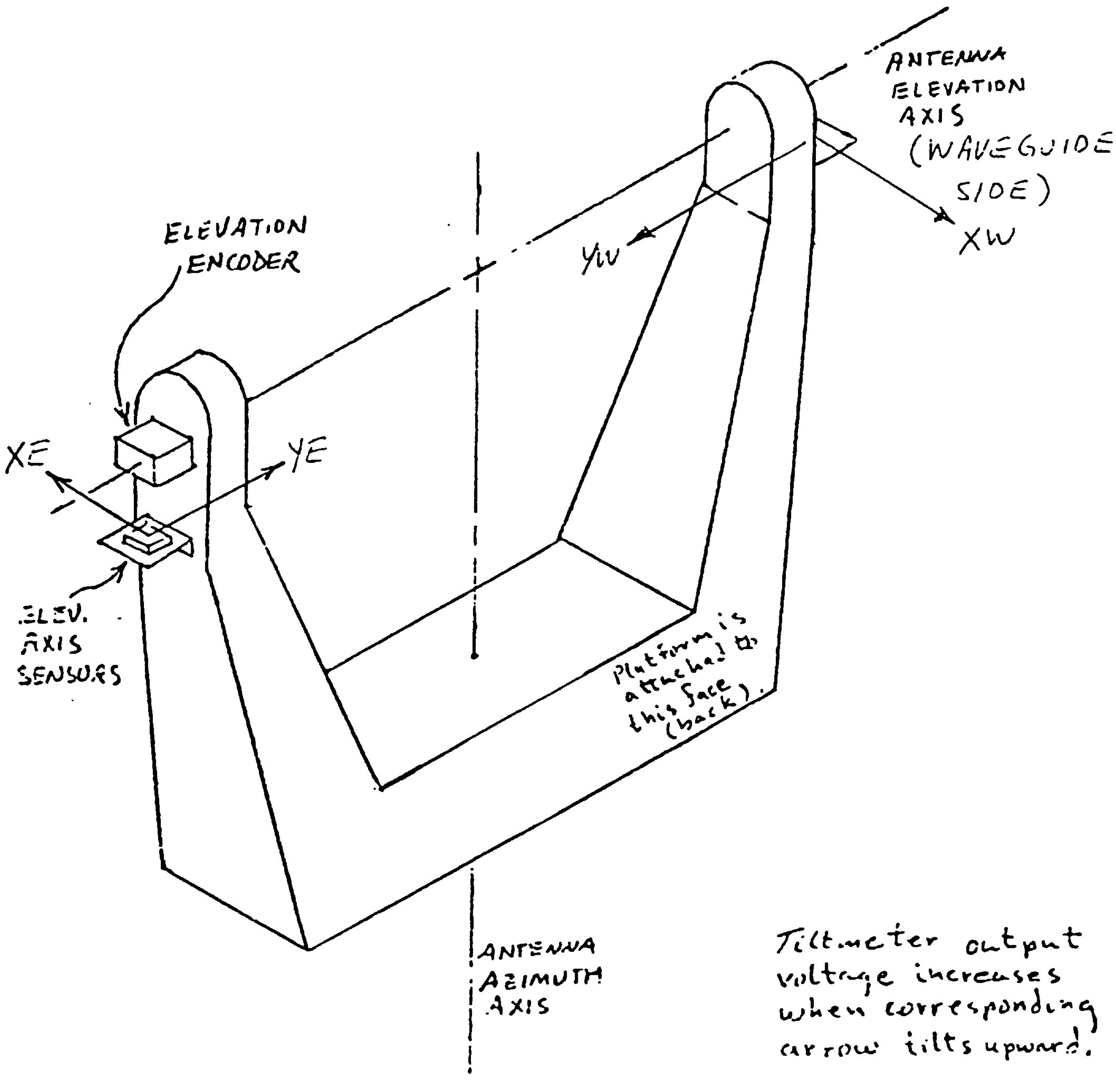
Ant 6: Yoke Temperatures

90 deg Az. Pointing

Data taken Jan 23, 1991
CCJ, Jan 24, 1991

FIGURE 12

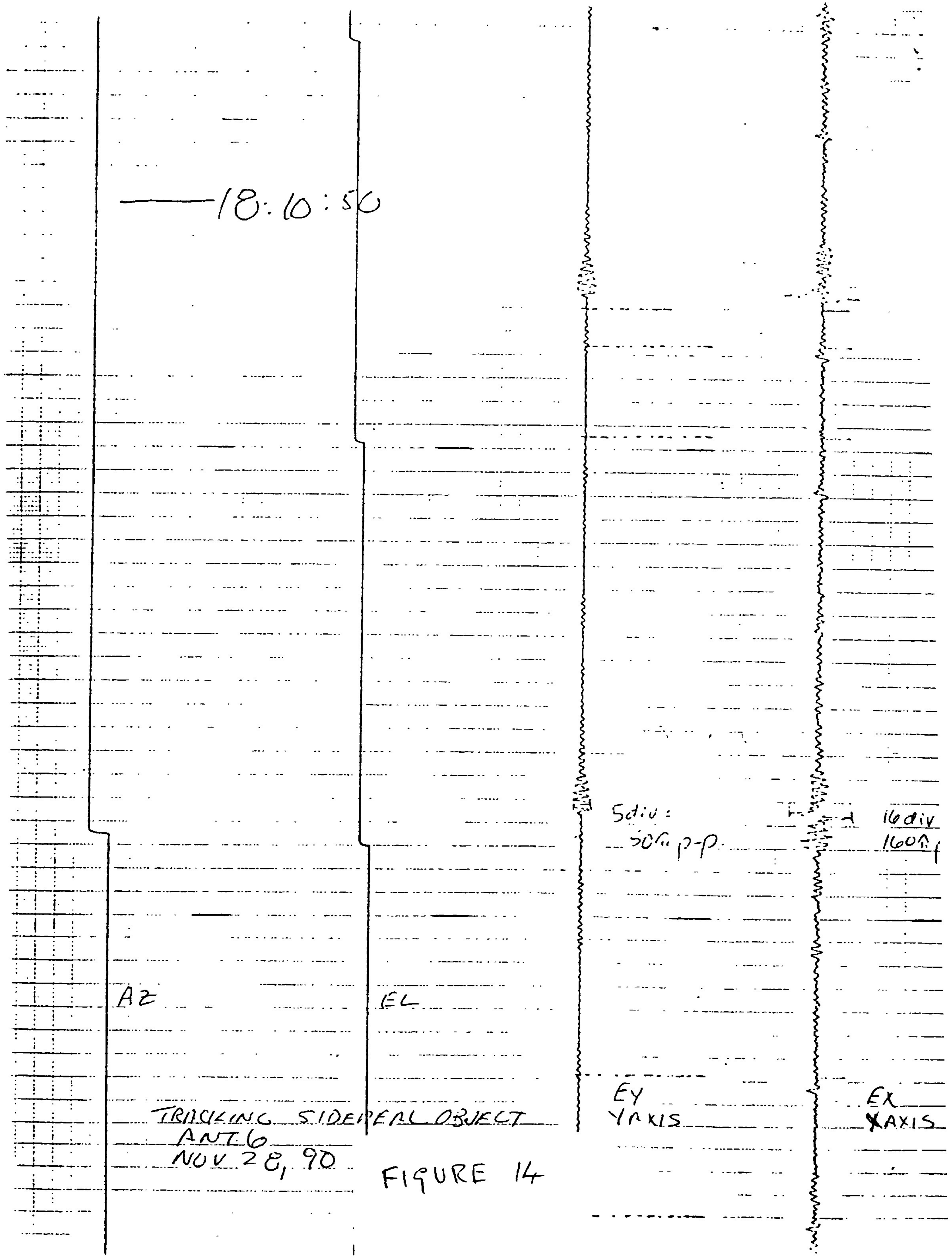
TILTMETER MOUNTING LOCATIONS
AND SENSING DIRECTIONS



Tiltmeter output voltage increases when corresponding arrow tilts upward.

FIGURE 13

Figure 13 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.



TRACKING SIDEREAL OBJECT
ANT 6
NOV 28, 90

FIGURE 14