NATIONAL RADIO ASTRONOMY OBSERVATORY
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VERY LARGE ARRAY PROGRAM

VLA TEST MEMORANDUM No. 135

ANALYSIS OF TEST RESULTS WITH SHIELDED AND UNSHIELDED ANTENNA

Sebastian von Hoerner

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ABSTRACT

Antenna 22 was shielded with thermal insulation, antenna 6 stayed unshielded. Both were equipped by D. Weber with thermistors and tiltmeters. Measurements were organized and recorded by B. Newell. This memo analyzes the following test results, up to Feb. 3, 1982: heat application to two pedestal members, and resulting tilts; azimuth rotation tests, with Fourier analysis of tilt as function of azimuth; antennas parked stationary, with thermal tilt change in sunshine versus night; stability of tiltmeters, and their possible use for on-line correction of pointing errors.

The conclusions are: the pedestal I-beams do not need thermal insulation; the tubes need it, and the present insulation seems adequate. The yoke insulation needs improvement by removing the front-back difference caused by the platform. The non-planar azimuth warp agrees with a worst-case analysis by Lee King, the hysteresis is more severe and still unsolved, and both together yield pointing errors of 20 arcsec max and 6 arcsec rms. The tiltmeter stability seems adequate; their use would correct many but not all types of errors, but may add some errors of their own; for a final decision, we would need some more data.

I. HEAT APPLICATION TO TWO PEDESTAL MEMBERS

Two tests were performed where a pedestal member was heated artificially in a controlled way by about 10° C, with heat pads of 1 kw total attached, and wrapped in insulation, recording the resulting yoke tilt. We wanted to know, first, whether the yoke tilt (pointing error) agreed with the theoretical thermal analysis; second, whether the horizontal I-beams would also need shielding (both to be described in this section); and third, whether the non-planar warp of the yoke depends on thermal deformations (to be described in Section II).

1. Southeast Tube of Antenna 6

This test was done in the early morning of Oct. 20, 1981. The heat was turned on at 0300 MDT (Mountain Daylight Time), and the heat was turned off and all insulation removed at 0530 MDT. Tilts were measured in two different ways: with the antenna stationary "parked" at true azimuth AZ = 146°, where the yoke is perpendicular to the heated tube, see Fig. 1a, such that the resulting tilt is measured as an x-tilt, with zero y-tilt. Second, an azimuth rotation test was performed before, during, and after heating, where planar tilt and non-planar warp is obtained by a Fourier analysis of the tiltmeter records.

From the thermal analysis of Lee King (VLA Memo 129, January 1981), we use Table 4, Case A, which predicted 11 arcsec tilt from ΔT = 5° C when heating an outer single pedestal tube, or

$$\Delta\phi/\Delta T = 2.2 \text{ arcsec/°C}. \tag{1}$$

Table 1. Tilt readings SX1 on yoke top, and temperature difference ΔT between SE and NE tubes, with antenna parked at AZ = 146°.

MDT	heat turned	ΔT °C	SX1 arcsec
0300	on	0.9	0
0430		6.7	12
0530	off	9.1	26
0630		7.6	22

Table 1 shows the results of the stationary parked antenna. A linear regression analysis of these data gave a correlation coefficient of 0.96, a slope and its mean error of

$$\Delta\phi/\Delta T = (3.1 \pm 0.7) \text{ arcsec/°C} \quad (2)$$

and an rms deviation from this line of ± 4.1 arcsec.

The results of the four azimuth rotations are given in Table 2; ΔT is the measured temperature difference between the SE tube and the average of the

Table 2. Temperature difference ΔT, and resulting planar tilt of yoke top with amplitude A_1 and phase α_1 from 360° azimuth rotation. Pointing deviation $\Delta\phi$ from Figure 2.

Fig. 2 Case	MDT			ΔT (°C) range		ΔT (°C) average	A_1 arcsec	α_1 degree	$\Delta\phi$ arcsec
a	0200 to 0300		before	0.1 to 0.8		0.4	28.7	-19.0	0
b	0430	0530	heated	6.6	9.1	7.8	17.5	- 3.5	12.8
c	0630	0730	cooling	7.6	5.6	6.6	21.9	- 9.0	8.2
d	0730	0830	Sun up	5.6	4.4	5.0	23.7	- 4.5	7.1

NE and W tubes; A_1 and α_1 are amplitude and phase of the first Fourier term (Planar tilt) of the yoke top. These are also plotted in Fig. 2, but rotated by 180° in order to show the pole of the rotation plane (α_1 is the phase of the cosine, meaning the azimuth at which the plane is highest).

Fig. 2 confirms that the change of tilt is indeed parallel to the direction of the heated SE tube and in the right direction, from (a) to (b) to (c). Also, the beginning of sunshine out of the east tilts the plane somewhat to the west, to (d). The projection $\Delta\phi$ of the tilt change on the tube direction is entered in the last column of Table 2. A linear regression analysis of $\Delta\phi$ versus ΔT yields a correlation coefficient of 0.98, a slope of

$$\Delta\phi/\Delta \quad = \quad (1.6 \pm 0.3) \text{ arcsec/°C} \qquad (3)$$

and an rms deviation from the straight line of ± 1.4 arcsec.

Comparing the theoretical expectation (1), the directly measured tilt (2) when parked at 146° azimuth, and the tilt (3) of the azimuth rotation plane, we find that the parked tilt is 41% larger than expected, and the rotation tilt is 27% smaller than expected. Since we do not know how good our theoretical model is, and how well we have measured the average temperature of the tubes in question, we may consider each measured deviation from the model sufficiently small. However, the disagreement between the two measured tilts, (2) and (3), is almost a factor of two; regarding the combined mean error this deviation is 1.9 sigma which looks significant.

For a more direct comparison, we could try to read the rotation curve at 146° azimuth, but unfortunately this is just the azimuth where antenna #6 has the large hysteresis, up to 19 arcsec (to be discussed in Section II, 3). Since the antenna was rotated in between the readings at 146° azimuth, the hysteresis seems to be the best explanation of the large value (2). In any case, the tilt (3) of the rotation plane should be the more accurate one of the two, and we regard the agreement within 27% as satisfactory, explaining the difference by the heat loss through conduction into the heavy joints which reduces the average tube temperature.

2. East I-beam

One of the horizontal I-beams at the pedestal base was supplied with the same heat pads and insulation. On October 21, the heat was turned on at 0252 MDT, and at 0600 it was turned off and the insulation removed. The antenna was parked at true azimuth 86°, see Fig. 1, b, without azimuth rotation. From an analysis of Lee King of December 1980, the expected tilt is (front down, negative sign):

$$\Delta\phi/\Delta T = -0.9 \text{ arcsec/°C.} \quad (4)$$

At 0600 the temperature difference between this beam and an unheated reference beam was $\Delta T = 10$ °C, and we should expect a tilt of $\Delta\phi = -9$ arcsec. But the measured tilt change between 0230 and 0600 was a factor of three smaller than expected:

$$\Delta\phi = -(3.1 \pm 0.8) \text{ arcsec.} \quad (5)$$

To some extent, this may be explained by the heat conduction from the I-beam through three heavy joints into the five rising tubes and two neighboring I-beams. First, this cools down the middle and the ends of the heated I-beam, especially amplified by rain and heavy winds during the last part of the test; the average temperature thus will be less than the 10° C measured, maybe about $\Delta T = 7$°C, say, or $\Delta\phi = -6.3$ arcsec expected. Second, this conduction makes the rising tubes a bit warmer, by 0.4° C from the available measurements, which gives a positive $\Delta\phi = 0.9$ arcsec from (1). In total, the reduced expected tilt is now

$$\Delta\phi = -5.4 \text{ arcsec} \tag{6}$$

which is in a better, though still somewhat poor, agreement with the observed value of (5).

From this test we may conclude that a thermal insulation of the three I-beams is not needed. The measured effect is smaller than originally expected and becomes negligible. Furthermore, the heat conduction from the unshielded I-beams into the shielded tubes will always have some counter-acting effect, especially for longer durations. This is a fortunate result, because the I-beams are used for walking, and their insulation would cause problems.

II. AZIMUTH ROTATION TEST

1. Data Analysis

The antenna is moved step-by-step clockwise through 360° in azimuth, and then returned counter-clockwise. On each step, x and y tiltmeters are recorded at the top and the bottom of the yoke, x1 and y1 at top, and x2 and y2 at bottom. Differences between top and bottom mean internal deformations of the yoke. From April 28 through May 19, 1981, N = 8 steps of 45° were taken; thereafter, always N = 16 steps of 22.5°.

For each tiltmeter, the readings are investigated for hysteresis (difference between clockwise and return readings) and averaged. Then a Fourier analysis is applied, for obtaining the coefficients of

$$\text{tiltreading } \phi(\alpha) = A_o + \sum_{k=1}^{N/2} \left\{ a_k \cos(k\alpha) + b_k \sin(k\alpha) \right\} \tag{7}$$

$$= A_o + \sum_{k=1}^{N/2} A_k \cos(k[\alpha - \alpha_k]) \tag{8}$$

where $A_k = \sqrt{a_k^2 + b_k^2}$ = amplitude (9)

α_k = (1/k) arctan(b_k/a_k) = phase angle = azimuth of maximum. (10)

The angles have an ambiguity for $k \geq 2$, with $\alpha_2 \pm 180°$, $\alpha_3 \pm 120°$, ± 240; and in general with

$$\alpha_k \pm (m/k)\ 360°, \quad m = 1, 2 \ldots (k - 1). \tag{11}$$

A_o is just the zero reading of the tiltmeter, depending on its mounting. The first term, with A_1 and α_1, describes a tilt or axial misalignment of the azimuth rotation plane, which normally is taken care of by the on-line pointing program after having been measured astronomically. But all higher terms describe deviations from this plane, meaning non-planar distortions or warps of the azimuth drive, which normally are considered absent or negligible.

Let the azimuth plane be tilted such that its highest point is at azimuth α. Then we see from Fig. 1a that the x-readings will have their maximum directly at azimuth α, whereas the y-readings have their maximum when the antenna points at azimuth α -90°. Thus, 90° have been added to all α_k for all y-readings, to make tilts comparable.

Some confusion was caused by the orientations or signs of the tiltmeters, originally mounted random-wise and occasionally changed in the computer as it seems. On October 25, several meters were remounted, and all were calibrated by turning a mounting screw and reading the change in the computer output. The result showd that now all signs should be positive (as defined in Fig. 1a) except Sy2 of both antennas; but inspection of recent tests showed that Bx2 of antenna #22 is still negative, too. A final decision was now done by demanding that all four α_1 of an antenna in one rotation test must have the <u>same</u> sign, and that this sign should agree with strong thermal deformations. All "raw" readings were then multiplied by their proper signs; they are shown for both antennas and all days in Tables 3 and 4. Furthermore, our azimuth α means always "true azimuth" defined by North = 0°, East = 90° (as opposed to "antenna azimuth" defined by arm directions).

2. Non-Planar Warp of Azimuth Rotation

These unexpected distortions are rather large, as mentioned in Memo 129 for antenna #6. They are again found in all rotation tests, and for the shielded antenna #22 as well and not smaller. Table 3 gives all observed data for the yoke bottom where distortions are largest. The smaller yoke top warps are given in Table 5. If $A_k < 2$ arcsec, the phase angles α_k are not reliable and were omitted. All higher terms, with $k \geq 4$, are small and spurious with amplitudes of 1 arcsec average and 3 arcsec maximum (except for a few cases with very large hysteresis). The following can be derived from Tables 3 and 5.

First, the differences between x and y readings, and especially those between yoke top and bottom, demonstrate clearly that the yoke is not just tilted but is internally deformed. A structural analysis for dead loads (Lee King, 11/06/81) showed that for the worst imaginable case, if the yoke is supported at only three equidistant points of its azimuth bearing, the angular deformations between these points range indeed between 10 and 19 arcsec. This is just the size observed, which may indicate some physical explanation, although this support model seems not very realistic.

Second, the warp stays very constant. We do not observe any thermal effects, not even when one of the three tubes supporting the azimuth ring was heated (Oct. 20) which gave a tilt of 13 arcsec (Table 2). Thermal effects from sunshine might have been expected, regarding the time of day, on

Table 3. Warp of yoke bottom during azimuth rotation, second and third Fourier terms of tilt readings. A_k = tilt amplitude (arcsec), α_k = azimuth phase (degree), see equation (8).

day	average MST	sign x2	sign y2	A_2(x2)	α_2	A_2(y2)	α_2	A_3(x2)	α_3	A_3(y2)	α_3
Antenna #6:											
1981- 4-28	1330	+	+	14.8	- 2	12.2	+33	14.5	+29	8.6	-34
5- 9	0530	+	+	18.8	- 4	15.8	+46	15.8	+28	10.3	-30
5-11	1730	+	+	10.4	+10	13.0	+52	12.1	+33	10.4	-33
5-12	0645	+	+	18.4	- 1	14.5	+47	16.2	+30	9.0	-29
5-15	0445	+	+	17.6	- 3	12.9	+45	15.2	+30	8.0	-31
5-19	0030	+	+	12.8	- 2	12.7	+44	11.4	+31	7.9	-30
(8-18)	Antenna moved, same arm and orientation.										
9-29	2300	+	+	14.6	-34	13.7	+15	12.7	+29	8.5	-31
(10-20) before	0130	-	+	14.7	-31	8.8	+12	13.1	+31	5.6	-31
heated	0400	-	+	14.8	-31	9.0	+12	13.5	+31	4.8	-34
cooling	0600	-	+	14.7	-32	8.3	+ 8	13.6	+30	5.0	-33
Sun	0700	-	+	17.9	-35	7.9	+14	15.5	+28	5.4	-31
(10-25)	Tiltmeters calibrated.										
11-13	0645	+	-	13.9	-35	13.3	+16	12.1	+28	8.6	-32
11-14	0615	+	-	13.6	-34	13.2	+16	11.5	+29	8.2	-31
12-23	1600	+	-	11.2	-35	13.7	+15	9.4	+31	7.8	-30
1982- 2- 3	0400	+	-	11.0	-35	13.2	+16	9.6	+30	7.8	-31
	n = 15;	rms =		14.5		11.5		13.2		7.9	
Antenna #22:	(probably gain error in first line, factor 2)										
1981- 8-23	0030	-	-	(3.0)	+66	(7.0)	+24	(43.4)	+29	(37.4)	-29
9-29	2300	-	-	2.0	+58	3.6	+23	21.3	+29	18.2	-29
(10-13)	Antenna moved, same arm and orientation.										
10-20	0130	-	-	2.0	-21	2.4	+12	20.7	+29	18.6	-29
(10-25)	Tiltmeters calibrated.										
11-13	0645	-	-	1.2		2.2	+ 2	22.2	+28	20.6	-30
11-14	0615	-	-	1.0		1.7		21.3	+28	20.1	-30
12-23	1600	-	-	3.7	-28	3.6	+12	18.9	+29	18.3	-29
1982- 2- 3	0400	-	-	1.7		2.1	-1	20.5	+29	19.3	-30
	n = 6;	rms =		2.1		2.7		20.8		19.2	

four occasions: on 4-28, 5-11 and 12-23 for antenna #6, and on 12-23 for antenna #22, but no significant change occurred. Also, shielding did not help.

Third, I will mention some obvious regularities without knowing what they might mean. (a) The difference in α_2 between x and y is always about 45° (average = 44.5$\pm$1.3), in α_3 about 60° (average = 60.3$\pm$0.5). (b) The phase angles α_3 are practically the same for both antennas, while the α_2 are different. (c) When the antennas were moved along their arm, none of the warp amplitudes changed significantly; phase angles α_3 changed not at all, while angles α_2 did change. (d) The preferred angles of α_3, -30° and +30°, are close to (though not identical with) the corner points of the supporting hexagonal plate structure, -34° and +26°.

3. Plane of Yoke Top Rotation

What matters for the pointing error is the yoke top: the plane of its rotation, Table 4, and the deviations from this plane, Table 5. Table 4 shows that the rotation plane (A_1 and α_1) stays mostly quite stable over several months, as long as the antenna stays in the same location. To show this in detail, and to check for thermal effects, we plot in Fig. 3 all cases listed in the last column of Table 4, taking x-y averages, and rotating again by 180° to give the direction of the pole or axis of the plane (as we did for Fig. 2).

Of the 18 cases plotted, there is one extremely large deviation of 32 arcsec, case I,3, in a direction which cannot be explained by sunshine nor by the exceptionally strong wind of 22 mph average from SSW.

All other 17 cases are well behaved: the four larger deviations occurred only when the sun was up, and they pointed always in the right direction: away from the sun. The remainder of each group, at night, scatter only very little.

Table 4. Tilt angle of yoke top plane during azimuth rotation, first Fourier terms of tilt readings. A_1 = tilt amplitude (arcsec), α_1 = azimuth phase (degree), A_o = zero reading of tilt meter.

day	average MST	sign x1	sign y1	A_o(x1)	A_o(y1)	A_1(x1)	α_1	A_1(y1)	α_1	Fig. 3	
Antenna #6:											
1981- 4-28	1330	-	-	+20.4	-71.4	29.7	-56	41.2	+60	1	
5- 9	0530	-	-	+19.4	-46.0	34.7	+30	43.2	+42	2	
5-11	1730	-	-	+22.0	-39.6	66.5	+40	76.4	+38	3	
5-12	0645	-	-	+19.0	-32.8	31.7	+34	46.2	+43	4	I
5-15	0415	-	-	+22.5	-34.0	33.2	+42	44.4	+49	5	
5-19	0030	-	-	+22.3	-29.0	38.8	+44	46.3	+49	6	
(8-18)	Antenna moved										
9-29	2300	+	+	-31.0	+30.6	28.6	- 3	38.9	-21	1	
10-20	0130	+	+	+18.5	+50.0	24.6	-17	32.7	-21	2	
10-20	0700	+	+	+20.2	+45.6	19.2	+ 6	28.2	-15	3	
(10-25)	Tiltmeters calibrated										II
11-13	0645	+	+	+13.5	+43.2	21.2	-13	30.2	-23	4	
11-14	0615	+	+	+14.4	+44.4	24.1	-11	32.0	-21	5	
12-23	1600	+	+	+19.6	+40.8	25.6	-35	32.8	-41	6	
1982- 2- 3	0400	+	+	+19.9	+44.4	26.6	-12	32.8	-20	7	
Antenna #22: (probably gain error in first line, factor two)											
1981- 8-23	0300	-	-	(-93.2)	(-125.0)	(29.5)	+187	(29.4)	+177		
9-29	2300	-	-	- 4.6	-64.6	12.9	+175	13.4	+158		
(10-13)	Antenna moved										
10-20	0130	-	+	- 4.8	- 4.3	54.7	+185	52.3	+188	1	
(10-25)	Tiltmeters calibrated										
11-13	0645	+	+	-44.8	-83.7	54.5	+185	55.0	+188	2	III
11-14	0615	+	+	-45.3	-81.8	54.4	+183	53.5	+187	3	
12-23	1600	+	+	-58.5	-78.8	58.2	+185	52.1	+193	4	
1982- 2- 3	0400	+	+	-52.8	-75.4	51.9	+181	50.4	+186	5	

Table 5. Deviation from planar azimuth rotation at yoke top, second and third Fourier term. Time and sign as in Table 3. Hyst = hysteresis (arcsec, ptp), maximum of x and y. Dev = deviation from plane (arcsec).

Day	A_2(x1)	α_2	A_2(y1)	α_2	A_3(x1)	α_3	A_3(y1)	α_3	Hyst	Dev rms	Dev max
Antenna #6:											
1981- 4-28	6.4	- 7	.6		5.9	+29	.4		8	6.6	14.4
5- 9	6.0	- 6	3.1	-140	4.8	+31	2.7	-17	5	6.6	14.6
5-11	1.5		1.9		5.9	+43	2.0	-15	11	5.6	9.7
5-12	9.1	+ 1	1.8		8.4	+30	2.6	-20	12	9.5	20.5
5-15	5.9	0	.2		5.8	+32	1.8		7	6.2	13.5
5-19	1.8		.9		2.4	+42	2.1	- 1	12	2.6	4.4
(8-18)	Antenna moved										
9-29	3.5	-34	.7		3.5	+32	1.8		12	4.2	8.5
10-20	3.8	-27	1.0		4.0	+38	1.4		17	4.3	9.4
10-20	6.0	-35	1.3		5.0	+25	2.0	- 8	17	6.6	15.0
(10-25)	Tiltmeters calibrated										
11-13	4.3	-37	.9		4.4	+30	1.4		19	4.7	11.3
11-14	3.9	-32	1.0		3.8	+30	1.6		17	4.5	9.0
12-23	2.3	-31	.4		2.8	+38	1.9		13	3.0	5.1
1982- 2- 3	2.2	-30	.6		2.7	+36	1.5		5	2.8	5.5
n = 13; rms =	4.9		1.3		4.8		1.9		13	5.5	11.7
Antenna #22: (probably gain error in first line, factor two)											
1981- 8-23	(4.1)	- 2	(5.2)	- 65	(7.1)	+36	(11.4)	+ 3	(13)	(9.4)	(19.8)
9-29	2.0	- 8	2.2	- 58	3.4	+36	5.0	+ 3	16	4.2	8.8
(10-13)	Antenna moved										
10-20	1.9		2.4	- 75	3.7	+37	5.3	+ 2	7	4.5	9.9
(10-25)	Tiltmeters calibrated										
11-13	1.0		.9		5.2	+35	3.8	-6	7	3.5	5.8
11-14	1.5		.8		4.1	+36	4.1	-1	11	3.2	6.4
12-23	2.8	-19	2.6	+10	3.8	+38	4.8	-2	26	4.1	14.1
1982- 2- 3	1.7		1.6		4.6	+37	4.3	-4	14	3.5	7.5
n = 6; rms =	1.9		1.9		4.2		4.6		15	3.9	9.2

All data are summarized in Table 6. It seems that the shielded antenna #22 is considerably better than #6; but this nice result calls for confirmation from more data.

Table 6. Stability and thermal deviation of azimuth rotation axis, at yoke top.

Antenna	Group Fig. 3	scatter at night n	ptp arcsec	rms arcsec	larger deviations Case Fig. 3	MST	deviation arcsec
#6	I	4	7.5	2.8	1	1330	12.0
	II	5	8.2	2.9	3	0710	8.6
					6	1600	10.6
#22	III	4	4.3	1.4	4	1600	4.9

I would like to emphasize that, so far, the only reliable method to measure the thermal and long-time deformations of the pedestal is to obtain A_1 and α_1 of the yoke top (x-y average) from the azimuth rotation tests, Tables 4 and 6 and Fig. 3. All other measurements are more or less hampered by zero-drifts of tiltmeters, by the strong non-planar warp of the yoke bottom, by hysteresis, and by deformations of the yoke. During a full azimuth rotation, and asking for the best-fit plane, all of these effects are cancelled (or greatly reduced) by the 360° average. Thus, the results of Fig. 3 and Table 6 may be regarded with some confidence: a high stability at night; and, for the unshielded antenna, thermal deformations of 12 arcsec in sunshine (as to be expected from Tables 4 and 5 of Memo 129), but only 5 arcsec when shielded which, however, needs confirmation by more data. If confirmed, it would mean that the presently used pedestal insulation is sufficient and recommendable.

4. Deviation from Plane at Yoke Top

There are two types of deviations, both contributing to the pointing error: hysteresis between clockwise and return rotation, and non-planar warp as described by second and third Fourier terms. Both types are given in Table 5.

The rather large hysteresis , of 14 arcsec average and up to 26, remains a puzzle. It mostly occurs for the same antenna at the same azimuth on different days, the same for x and y (no 90° added) and about the same for yoke top and bottom. Frequently it occurs just on one azimuth step, or on one neighbor, too. We checked on Oct. 21 for local friction or notches of the bearings by measuring the current of the azimuth drive motors during slow constant rotation, but nothing at all happened at the azimuth of the large hysteresis.

The last two columns of Table 5 give the sum of the two types of deviations, the actual measured tilt ϕ minus the best-fit plane:

$$\mathrm{Dev}(\alpha) \quad = \quad \phi(\alpha) - [A_o + A_1 \cos(\alpha - \alpha_1)]. \tag{12}$$

We see that the rms deviations look tolerable. But the single large deviations, up to 20 arcsec, are still a problem.

In general, large deviations are caused more by the occasional and variable hysteresis than by the stable repeatable warp. Since we do not know the cause of the hysteresis, we do not know how to prevent it. And the only way to correct for it would be to use tiltmeters on all yoke tops for on-line corrections. This will be discussed in Section V .

III. ANTENNAS PARKED STATIONARY MANY HOURS

1. Test Procedure

Occasionally the two antennas were parked at the same given pointing and left unmoved, for longer durations between 12 and 27 hours, while readings of temperatures and tilts were taken. The azimuth was mostly due North or South, and the elevation 20° North of the zenith, in order to have the yoke exposed to sunshine. The main purpose is to see how effective the thermal insulation of antenna 22 is, as compared to the unshielded antenna 6.

Most important are the thermal tilt changes at the yoke top (x1, y1) which are the pointing errors. We would also like to obtain their breakdown into pedestal deformation (x2, y2) and yoke deformation (x1-x2, y1-y2), but unfortunately, the readings at the yoke bottom (x2, y2) are not just the pedestal deformation but they include also the large warp of the yoke bottom.

Temperature readings of the pedestal were taken at the middle of the three main tubes, which is straightforward except that some thermal influence from the heavy joints will not be measured in the middle of the shielded tubes but will still give some deformations. Temperature differences between middle and bottom of the SE tube were measured and are typically 3.0° C for antenna 22 in sunshine, and 1.5° C for antenna 6. Temperature readings at the yoke are more of a problem because of the uneven input of heat flow, mainly from the platform at the back; and since we do not know which point represents best the average temperature, we have changed the location of the thermistors a few times. Also, there seems to be a thermal time lag between a temperature rise at the measuring point and a following rise of the average, resulting in delayed tilt.

2. Results

Because of these problems, we have not evaluated temperatures and tilts as a function of time for a correlation analysis, but have only noted the peak-to-peak variations of both. The results are shown in Table 7. The breakdown between pedestal and yoke does indeed not look useful. But the more reliable readings at yoke top give an average of the peak errors of 20 arcsec for antenna 6, and only 12 arcsec for antenna 22, thus the shielding gives an improvement of a factor two.

Table 7. Peak-to-peak variations of temperature differences and of tilts, with antennas parked unmoved.

Date(MST) Start-End	duration hours	Azim. Elev.	clear	calm	Ant. #	ptp ΔT(°C) tubes	ptp ΔT(°C) yoke	ptp tiltmeter (arcsec) pointing x1	pointing y1	pedestal x2	pedestal y2	yoke x1-x2	yoke y1-y2
Oct. 20 (13)		E 86			6	5.6	4.2	29	14	24	12	10	7
-Oct. 21 (01)	12	90	y	y	22	1.6	1.1	24	6	10	4	14	4
Oct. 27 (21)		S=180			6	.9	1.5	8	18	3	4	6	15
-Oct. 28 (09)	12	110	y	y	22	.6	.5	2	15	12	2	10	14
Oct. 28 (14)		S=180			6	2.1	3.7	29	7	7	3	25	8
-Oct. 29 (04)	14	110	y	y	22	.2	.6	11	9	14	2	5	7
Nov. 3 (16)		N=0			6	4.1	2.2	18	24	13	18	16	16
-Nov. 4 (10)	18	70	y	y	22	.7	3.3	11	10	17	15	18	14
Nov. 9 (13)		N=0			6	4.7	1.4	30	27	16	21	24	19
-Nov. 10 (17)	27	70	y	y	22	.9	3.0	15	21	14	12	15	20
n = 10;		average =			6			20.4±2.8					
					22			12.4±2.1					

Bob Newell pointed out that we should investigate the distribution of the errors, to find out how frequently the errors are larger than the specified limit of 15 arcsec. This is shown in Fig. 4 for the peak error in sunshine at the yoke top, in x and in y, for all tests with parked antennas. We see that seven of the ten cases are too large for antenna 6, but only two for antenna 22, which is a nice improvement.

3. Suggested Shielding

The results also show that the larger thermal deformations of the shielded antenna occur when the back is exposed to sunshine. Thus we suggest to shield the platform, too, in some inexpensive way, for example by a sheet of plywood (with some foam underneath, maybe).

This would shield the platform against sunshine, but would still leave a one-sided heat flow from the ambient air going to the yoke back, missing at the front. This would be difficult to avoid, but more easy to counterbalance. We suggest to lift the lower part of the shielding at the yoke front by an angle of about 30° or less, such that also the front is shielded against sunshine but open to ambient air. See Fig. 5. Our task is to make the front and back of the yoke thermally equal. Since we cannot make them equally good, let us make them equally bad. This is similar to the demand for an equal-softness structure to counteract gravitational deformations.

IV. TILTMETER ZERO CHANGES

If tiltmeters were to be used for on-line pointing corrections, it would be very important that they do not change with time, regarding their zero offset and gain. Both may have any value, as long as they stay constant. Constant gains are indicated by the very small scatter at night in Fig. 3 and Table 6, and also by the constant warp amplitudes, A_2 and A_3, in Table 3; but we would need a direct tilt calibration once in a while, to check the gain more accurately and independent from any possible warp changes. In the following, we investigate the constancy of the zero offsets.

1. Azimuth Rotation Tests

The fourier analysis yields A_o, the zero offset of a tiltmeter. This offset depends only on the original mounting of the tiltmeter with respect to gravity, and it should stay constant in time except for antenna relocations and tiltmeter calibrations. Table 4 gives A_o(x1) and A_o(y1) at the yoke top where it matters for pointing. There are three groups for antenna 6, and one for 22, where constant values are expected within each group because nothing was altered. Regarding the group names in the last column of Table 4, we add now letters a and b to incidate first and second parts when a calibration was done in between.

First, we see from Table 4 occasionally very drastic changes, where a value A_o falls completely out of its group, i.e. on Sept. 29 both A_o(x1) and A_o(y1) in group IIa, and A_o(y1) on April 4 in group I. We have no explanation, it may have happened in the mounting or in the computer. Both dates are fairly early in the game; no drastic changes occurred after the calibration was done on Oct. 25, and more care was applied to the data handling thereafter.

Second, after elimination of the three drastic cases, we investigate the remaining changes in the groups. This is summarized in Table 8. Although we could tolerate the standard deviations of 2 to 7 arcsec with 4.4 arcsec rms, we still are worried about the large peak-to-peak differences up to 17 arcsec with 10.0 arcsec rms. And especially so since in all cases of large differences we seem to see in Table 4 not just a random scatter, but a gradual drift during the times of 1 to 3 months covered by a group. We would like to get some more rotation tests, in order to see whether this apparent drift was just a chance result, or whether it continues in a regular fashion.

Table 8. Changes of tiltmeter A_o, from azimuth rotations of Table 4, within groups where nothing was altered. Shown are peak-to-peak variations, underlined in cases of apparent drifts; and the standard deviations from the average (n-1 weighted). Both in arcseconds.

antenna	Group (Table 4)	A_o(x1) ptp	A_o(x1) st. dev.	A_o(y1) ptp	A_o(y1) st. dev.
#6	I	3.5	1.5	<u>17.0</u>	6.6
	II b	6.4	3.4	3.6	1.7
#22	III b	<u>13.7</u>	6.6	<u>8.3</u>	3.6
n = 6;		rms (st. dev.) = 4.4 arcsec; rms (ptp) = 10.0 arcsec			

2. Change During 24 Hours

In some cases of parked antennas we have readings at night 24 hours apart, many hours after sunset, where we should expect the same readings of the tiltmeters. Table 9 gives the rms values of these zero drifts, for all four tiltmeters on both antennas.

Table 9. Zero drifts of night readings within 24 hours. Shown is the rms (arcsec) of the four differences on Oct. 28, and the three on Nov. 9.

day and time	antenna	x1	y1	x2	y2
Oct. 28 MST = 22, 24, 02, 04	#6	1.8	2.4	3.4	2.3
	#22	3.0	2.7	4.2	.8
Nov. 9 MST = 06, 07, 08	#6	1.7	5.2	1.6	1.2
	#22	2.2	7.0	7.1	1.2
	n = 16;	rms = 3.5 arcsec			

Occasionally we see unpleasant drifts of up to 7 arcsec, but in the average they are small enough. If the larger ones are not zero drifts but actual <u>tilt</u> differences, they would then be caused by yoke deformations since the detailed data show not much correlation between the differences at top and at bottom of the yoke.

3. Pointing North or South before Sunrise

Another way of checking the zero stability is to collect all cases where the antennas were pointed at the same azimuth, early at morning before sunrise, when we should expect the same tilt readings for the same azimuth. We choose North and South azimuth, for parked antennas as well as from azimuth rotation tests, after the calibration of Oct. 25.

Values for parked antennas are direct measurements, N or S. But for the azimuth rotation we must interpolate, between the azimuth steps 352.5° and 14.0° for N = 0°, and between 172.5° and 195.0° for S = 180°. For larger tilt steps, up to 30 arcsec difference, this introduces some uncertainty, maybe up to 6 arcsec but not much more, and about the same amount on different days for the same tiltmeter.

The results are shown in Table 10. We see no significant difference between the two antennas, nor between yoke top and bottom. The standard deviations from the average are tolerable, with 5.0 arcsec rms for all data. But the peak-to-peak variations are occasionally very large, up to 23 arcsec in two cases (both on Feb. 3 at 0400 MST), but with only 13.5 arcsec rms for all data. This is very similar to the results regarding the A_o terms of the azimuth rotations. Comparing both methods, we have

	stand. dev.		peak-to-peak			
	max	rms	max	rms		
Fourier A_o of az. rot.	6.6	4.4	17	10.0	changes of tiltmeter zeroes (arcsec)	(13)
N or S night readings	8.9	5.0	23	13.5		(14)

Table 10: All tiltmeter readings after calibration (Oct. 25) when pointing North or South, before sunrise (no sign correction). In each group, we give the peak-to-peak variation, and the standard deviation from the average (n-1 weighted).

Day	MST	Test	ant. #6 (arcsec) x2	x1	y2	y1	ant. #22 (arcsec) x2	x1	y2	y1
North										
11- 4	0400	parked	+14	+38	+25	+30	-23	-94	+ 4	- 96
11-10	0400		+20	+41	+24	+28	-26	-96	- 2	-100
11-13	0645	azim. rotat.	+18	+33	+25	+29	-30	-99	0	-94
11-14	0615		+17	+39	+26	+33	-33	-99	- 4	-89
2- 3	0400		+ 2	+45	+26	+34	-36	-105	+10	-83
n = 5;		ptp	18	12	2	6	13	11	14	17
		st. dev.	7.1	4.4	0.8	2.6	5.2	4.2	5.5	6.6
South										
10-28	0400	parked	-24	-17	+ 7	+61	-135	+25	+21	-72
10-29	0400		-27	-20	+10	+62	-136	+20	+22	-72
11-13	0645	azim. rotat.	-14	- 9	+11	+53	-133	+11	+15	-76
11-14	0615		-20	- 9	+11	+55	-137	+11	+16	-77
2-03	0400		-37	- 6	+11	+56	-136	+ 2	+30	-73
n = 5;		ptp	23	14	4	9	4	23	15	5
		st. dev.	8.6	6.0	1.7	3.9	1.5	8.9	6.0	2.3
all 16 groups		rms(ptp) = 13.5								
		rms(st. dev.) = 5.0								

V. POINTING CORRECTIONS FROM TILTMETERS

The last section showed that the tiltmeter stability may (just) be good enough for on-line pointing corrections. Therefore, we discuss this possibility in more detail.

1. How Many Tiltmeters?

We need tilt readings only on top of the yoke (not its bottom). In general, one would need 4 meters per antenna: x and y readings on both yoke arms, in order to see the difference between x-tilt and centrifugal force when rotating, and between y-tilt and accelerated rotation. This would be needed when scanning over a source, which the VLA seldom does.

When tracking a source, the angular speed is $\Omega = (2\pi/24 \text{ hours})/\cos E$, and the centrifugal acceleration is $R\Omega^2$, to be compared with the gravitational one of 981 cm/sec^2. This gives a deviation of the tilt from the horizontal of

$$\Delta\phi \quad = \quad (5 \times 10^{-4} \text{ arcsec}) \ / \ (\cos E)^2 \tag{15}$$

which is negligible except for a small zone of avoidance of 1 degree near zenith. This means we need only 2 tiltmeters/antenna, close to the elevation encoder, under the following conditions:

1. During observations, track only (no scan);
2. For pointing calibration, track source on both sides of its maximum;
3. During slew, or all cases except tracking, turn off tiltmeters.

2. What will be Corrected?

The following pointing errors can be properly corrected:

a) x and y of pedestal } thermal deformations, average wind, azimuth warp and hysteresis;
b) x of yoke }

whereas the following will be misinterpreted:

c) y deformation of yoke (measuring yoke arm instead of elev. axis);

and still missing are the following:

d) wind-induced torque about azimuth axis (obtainable from motor current);

e) wind gusts (may also cause jitter and bias);

f) any deformation above the elevation axis.

3. Experience at 300-ft

A tiltmeter (Talyvel) was installed April 1981 at the 300-ft, close to its elevation encoder, and is now constantly used for correcting the elevation pointing. Dave Heeschen observed over 200 sources daily for 25 consecutive days at λ = 9 cm (May-June 1979), and again after installment (Nov.-Dec. 1981) with identical procedure. His results are described in a Note including two graphs. Without the tiltmeter, he found much larger pointing errors during daytime than at night, while the tiltmeter reduced the large day errors but added some of its own at night.

I exclude two hours after sunrise and sunset, as transition times, and call Day and Night as follows:

	Duration (hours) May-June	Duration (hours) Nov.-Dec.	
Day = 2 hours after sunrise - sunset	12.5	7	(16)
Night = 2 hours after sunset - sunrise	7.5	13	

From Heeschen's two graphs I then obtain

tiltmeter	day	night	
without	11.4	5.0	arcsec pointing errors. (17)
with	7.5	6.6	

Chuck Bennett from MIT observed at λ = 6 cm over 200 sources during two months without tiltmeter, and again for two months with it. Its zero and gain seem stable. But a hysteresis of the structure was found, and was avoided by one-sided approach only. No division between day and night was done. He finds:

without tiltmeter	15	arcsec rms pointing error. (18)
with tiltmeter	8	

Riccardo Giovanelli (Note of Dec. 22, 1981) also made measurements with the tiltmeter. He finds both zero and gain stable during 1/2 year. The hysteresis was 20 - 25 arcsec and is still unexplained. I would like to add that a healthy structure can <u>not</u> have any hysteresis, and that many years ago a strong one was found at the 300-ft and could be tracked to a loose nut in the feed support structure. In general, a hysteresis can be caused by one-sided constraint, plastic deformation, coplanar joints, and friction. Bob Newell also mentioned play and friction in the cross-roller bearings of our azimuth drive.

Rick Fisher and others found pointing oscillations after stopping fast movements, decayed after about 15 seconds, to be explained by massive inertia [illegible] drive. (The drive chain of the 300-ft actually is held tight by a spring.)

Bob Newell mentioned that they have good experience at Owens Valley with tiltmeters for on-line pointing corrections. He will ask for details. Buck Peery tells me that the cost of two Talyvel levels plus one power and meter (what would be needed at each VLA telescope) is about $5000.00.

VI. DISCUSSIONS AND CONCLUSIONS

1. <u>Pedestal Insulation</u>

The two heat applications (Tables 1 and 2, Fig. 2) showed that Lee King's thermal analysis is fairly reliable regarding the main supporting tubes, and that the thermal effect of the horizontal basic I-beams is even smaller than estimated. We conclude:

Tube insulation is necessary,
I-beam insulation is [illegible]. (19)

The first Fourier term (A_1 and α_1) of the azimuth rotation gives a very reliable measurement of the pedestal tilt at various times. Table 6 and Fig. 3 show extremely good stability at night for both antennas. When the sun is up, we have pedestal tilt changes up to 12 arcsec, away from sun, for the unshielded antenna 6, but only 5 arcsec for the shielded antenna 22. This agrees with Table 7 but needs confirmation by more tests, and meanwhile we say tentatively:

Pedestal insulation seems adequate. (20)

2. Yoke Insulation

With both antennas stationary parked for many hours, we have peak-to-peak changes between night and sunshine, Table 7, at the yoke top (pointing errors) of 30 arcsec max and 20.4 arcsec average for antenna 6. We have 24 arcsec max and 12.4 arcsec average for antenna 22, where all larger values occurred when the yoke back was exposed to sunshine, Fig. 4. Unfortunately, no reliable breakdown between pedestal and yoke deformation is possible because of the warp of the yoke bottom. Still, after comparison with (20), and regarding the measured ΔT between yoke front and back, we may conclude:

Yoke insulation helps, but not yet enough. (21)

And for an improvement we would like to suggest (Fig. 5):

Shield platform, lift lower front part. (22)

3. Warp and Hysteresis

At the yoke bottom, the warp, $\sqrt{A_2^2 + A_3^2}$ from Table 3, is 20 arcsec for both antennas, in agreement with a worst-case analysis of Lee King. At the yoke top (pointing) we still have 7 arcsec for antenna 6 and 5 arcsec for antenna 22, which we may have to tolerate:

Not much to be done about 5 - 7 arcsec warp. (23)

The large variable hysteresis (Table 5) of 5 - 26 arcsec range, and 14 arcsec average, confined to a constant narrow azimuth range, is a severe problem, so far completely unsolved. Thus:

Keep thinking about hysteresis! (24)

4. Present Total Pointing Errors

We have the deviation from planar azimuth rotation, Table 5, consisting of warp and hysteresis, plus thermal deformations in sunshine, Table 7. (We still miss the wind deformation data.) In numbers:

		ant. 6	ant. 22	
	warp	7	5	
hysteresis	max	19	26	
	rms	13	15	
dev. plane	max	20	14	
	rms	6	4	(25)
	thermal	20	12	(26)
total	rms	21	13	(27)

The main contribution to the total error is still thermal for both antennas. Compared with the specified 15 arcsec, antenna 6 is worse, while antenna 22 just makes it. But the wind is missing, and thermal of #22 needs more data; however, yoke of #22 can be improved. What may hurt even more than the rms error is the occasionally very large hysteresis.

5. Insulation Versus Tiltmeter

As a general philosophy, avoiding mistakes is a lot better than correcting them. And trying both gets for us too expensive. This would speak in favor of thermal shielding.

However, some items cannot be avoided by shielding but can be corrected by tiltmeters; some items can neither; one can be shielded but not corrected. We summarize:

			avoidable (insulation)	correctable (tiltmeter)
thermal	pedestal, x,y		yes	yes
	yoke	x	yes	yes
		y	yes	no
warp and hysteresis x,y			no	yes
wind*)	average	x,y	no	yes
		z	no	no
	gusts		no	no

*) wind problems may be greatly reduced by scheduling (Memo 130).

Personally, I would hesitate to draw a final conclusion now. I would first like to recommend:

Get: (28)

a) improved yoke insulation, and test data;

b) wind deformation data;

c) reliable tiltmeter stability data;

d) Owens Valley tiltmeter experience.

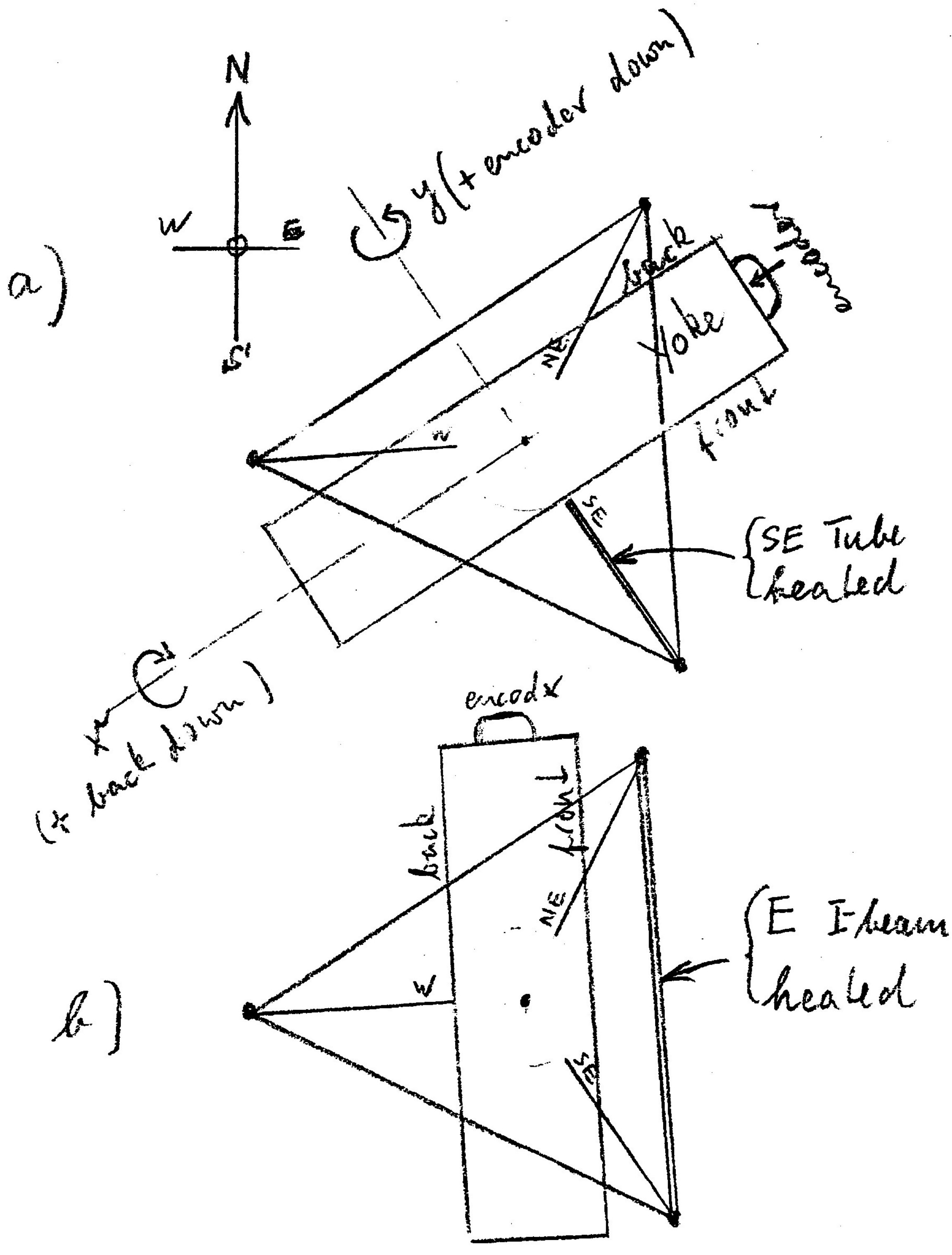

Fig. 1. Heating arrangement, antenna # 6.

(a) SE tube heated on Oct. 20, 1981. Pointing true azimuth 146°.

(b) E I-beam heated, Oct. 21. True azimuth 36°.

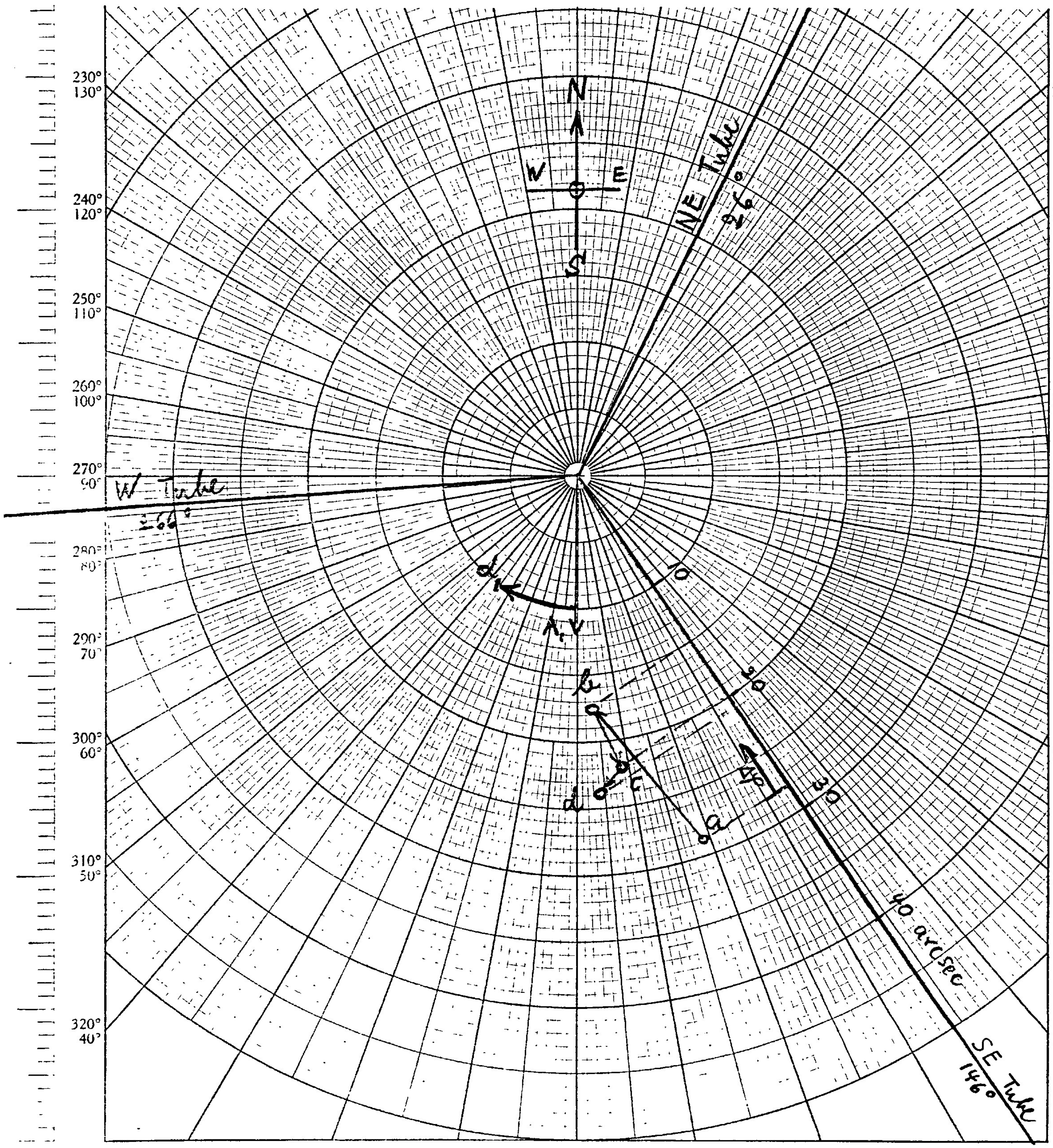

Fig. 2. Tilt of azimuth rotation plane during heating of SE tube of pedestal, on Oct 20, 1982. Shown is the pole of the plane with respect to the zenith; (a) before heating, (b) heated, (c) cooling, (d) cooling plus Sun from East.

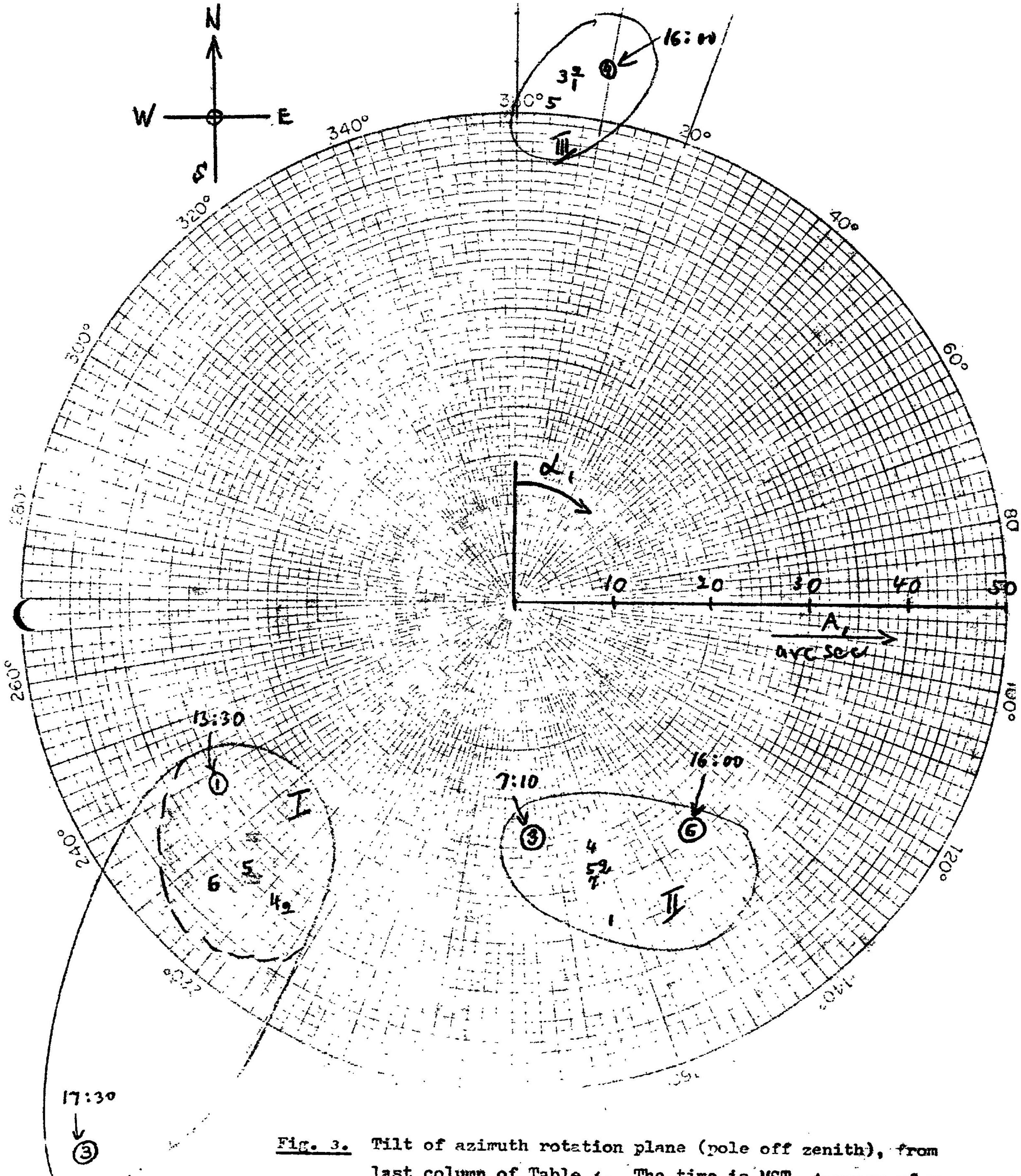

Fig. 3. Tilt of azimuth rotation plane (pole off zenith), from last column of Table 4. The time is MST. Average of x and y used for thermal bending; encircled cases with Sun up, all others at night.

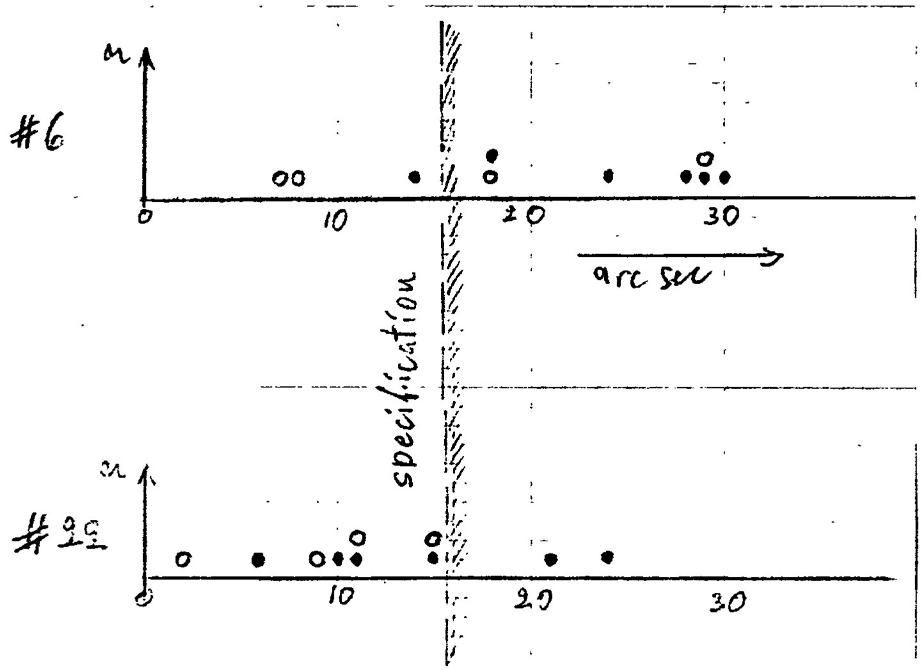

Fig. 4. Distribution of thermal tilt changes, sunshine versus night, at top of yoke. Antennas parked, stationary pointing.

• pointing N or E (platform in sunshine),

○ pointing S (platform in shadow).

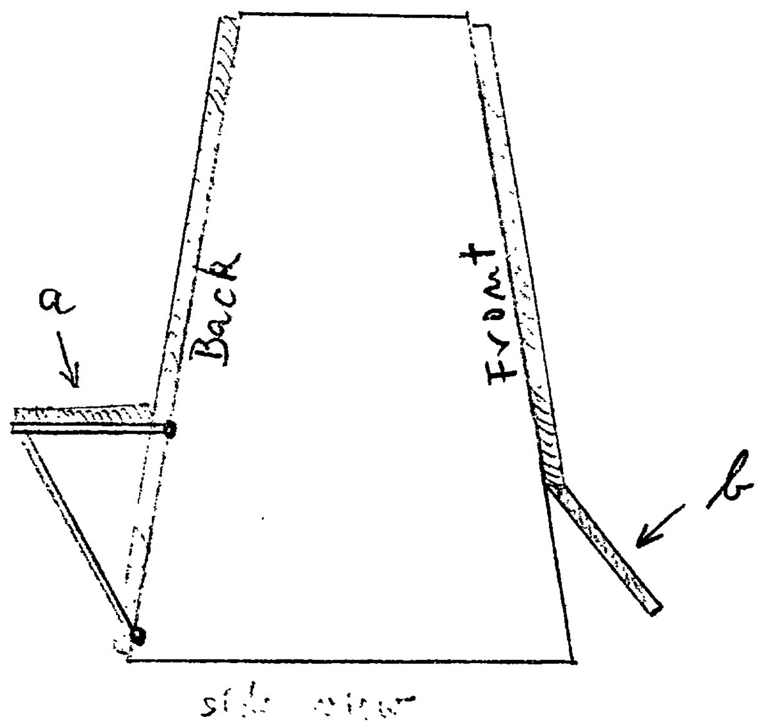

Fig. 5. Suggested changes for yoke insulation, in order to make the thermal behaviour more similar for front and back.

a. Plywood on platform, against sunshine;

b. Lift lower part by 30°, open to ambient air.