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VLA POINTING ERRORS: PRELIMINARY SUMMARY AND CONCLUSIONS

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ABSTRACT

The observed deformations are found at least two times larger than desired, but just as large as to be theoretically expected. We expect errors $\Delta\phi \geq 23$ arcsec 1/3 of all time from high winds, and for sunny calm days we expect a daily maximum in the range $15 \leq \Delta\phi \leq 40$ arcsec with about 27 arcsec average, where the yoke may contribute more than the pedestal. The tilt-sensor readings confirm the importance of the yoke, and they agree well with the expected maxima and rms deformations. The astronomical pointing errors of 10 test runs show a maximum of 58 arcsec, once for one antenna out of 173 cases, with $\Delta\phi = 20$ arcsec rms errors. But the contributions from sun and wind could not yet be separated observationally.

The 10 pointing runs show a small and uncorrelated scatter (only 9 arcsec rms) about a larger systematic offset (17 arcsec rms) pointing away from sun and wind. This looks very promising: if the offset could be handled, the remaining residual error would be very small.

Thermal shielding is treated (1.0 to 1.5 inch foam seems best, for yoke and pedestal) and a possible wind-correction is mentioned. A detailed set of future measurements is suggested, which must be sufficiently specific, coordinated and numerous for planning improvements.

INTRODUCTION

A large amount of useful data is available about the VLA pointing errors: John Dreher did and evaluated 10 pointing runs (day minus night) to measure the actual size of the errors; Bill Horne had three tiltsensors mounted at various places in the structure and measured the deformations of yoke and pedestal during 83 days; temperature differences across the structure were measured by John Dreher on 45 days before, and 20 days after, the mounting of an experimental set of sun shields at one antenna; John Spargo collected the weather records; and 20 structural analyses regarding wind and thermal deformations were performed by Lee King.

In the present report we mainly try to combine, summarize and analyze the available data, adding a few estimates of our own. The goal is to understand the causes of the pointing errors in order to develop future improvements wherever possible. However, it turns out that we first need an additional set of measurements (which meanwhile are in preparation). They should be specific enough to distinguish between wind and sun, and more qualitative regarding both causes; the measurements should be coordinated to allow all different readings being taken simultaneously; and we need samples large enough to give statistically significant answers to our main questions. At least two methods of thermal shielding should be tried and compared.

Most of this report was presented at a meeting at the VLA site, on December 18, 1980. The results of our discussions are now included, as are the evaluations of some additional data I got meanwhile. Recently John Spargo sent me more than a year's weather records, but I have not yet managed to do the intended wind statistics.

I should apologize for having written up several things much more detailed than needed for the present purpose, for example the derivations and results of Table 1 (gain change) and Table . (sky fraction). These are things I always wanted to know but never dared to elaborate on.

I. DEMANDS

1. Astronomical Requirements

Astronomers would like to have the pointing error just as small as possible. But mostly they agree that a certain fraction $1/n$ of the half-power beamwidth β may be tolerated, with about $n \approx 10$, say:

$$\Delta\phi \leq \beta/n = \beta/10. \tag{1}$$

It is not the pointing error per se which matters for an interferometer like the VLA, but the resulting erratic changes of gain, phase, and cross polarization. A simple estimate shows that the phase error within the beam is negligible if the misalignment between optical axis and design axis is only a small number of beamwidths, which is well fulfilled. And since I was told that the change of cross polarization is always less demanding than the gain change, we shall regard only the latter.

Gain changes may be divided into three types. First, if the beam was centered on the source and then moves off by an error $\Delta\phi$, the resulting gain loss is only a quadratic effect and thus rather small. Second, when the whole beam area is mapped, we may consider a source at the edge of this field, say, at $\phi = \beta/2$ off axis; an error $\Delta\phi$ produces now a much larger linear gain change. Third, a strong source outside this field may cast a sidelobe into the field; this can be corrected for, but an error $\Delta\phi$ of the source location will cause a linear correction error which gives the wrong flux for a weak source to be measured.

We assume a Gaussian beam shape

$$G(\phi) = e^{-\frac{1}{2}(\phi/\sigma)^2}. \tag{2}$$

Standard deviation σ and half-power beamwidth β then are connected by

$$\beta = \sigma \sqrt{8 \ln 2} \tag{3}$$

which means that (2) can be written as

$$G(\phi) = 16^{-(\phi/\beta)^2} . \tag{4}$$

With $\mu = \phi/\beta$ and $\nu = \Delta\phi/\beta = 1/n$, the gain change ΔG resulting from a pointing error $\Delta\phi$ then is

$$\Delta G = G(\phi) - G(\phi+\Delta\phi) = 16^{-\mu^2} - 16^{-(\mu+\nu)^2} \tag{5}$$

and the relative gain change shall be defined as

$$\Delta g = \frac{G(\phi) - G(\phi+\Delta\phi)}{G(\phi)} = 1 - 16^{-\nu(\nu+2\mu)} . \tag{6}$$

For the first type of the centered beam, we have $\mu = 0$ and apply equation (6), with the resulting Δg shown in Table 1. We see that $n = 10$ seems a reasonable demand, keeping the flux error below 3%. At the shortest VLA wavelength, $\lambda = 1.35$ cm, this would require

$$\Delta\phi \leq 12 \text{ arcsec} \tag{7}$$

while $\Delta\phi = 15$ arcsec yields 4.2% flux error which may be tolerable, too.

For the second type of a source (or part of an extended one) at $\beta/2$, we have $\mu = 1/2$ for equation (6). Table 1 shows that a flux error below 3% would require $n \geq 100$ which can be met only for the largest VLA wavelength, $\lambda = 20$ cm. For short wavelengths the flux error at the field edge will just be very large, no matter what, and there is nothing we can do about it (except to warn new observers).

For the third type, we consider sources at $\phi = \beta$ and $\phi = 1.5\ \beta$, and use equation (5); the resulting ΔG is shown in Table 1. But for application and interpretation one would have to know many details: source strength and location, UV-coverage and sidelobe level, dynamic range, and a better approximation than (2) for the actual tail of the beam.

Table 1. Relative gain change Δg within the beam β, and gain change ΔG outside, as functions of the pointing error, with $\Delta\phi = \beta/n$; see (5) and (6). For the beamwidth β of the VLA, the resulting pointing error $\Delta\phi$ for given n is shown for three wavelengths λ.

n	Δg [% of $G(\phi)$]		ΔG [% of G(o)]		$\Delta\phi$[arc sec], VLA		
	center, μ=0	edge, μ=½	μ=1.0	μ=1.5	λ=1.35 cm	6 cm	20 cm
6	7.41	41.7	3.95	0.15	20.0		
8	4.24	32.3	3.26	.13	15.0		
10	2.73	26.3	2.76	.11	12.0		
15	1.22	17.9	1.98	.08	8.0	35.5	
20	.69	13.6	1.55	.07	6.0	26.6	
40	.17	6.86	.82	.04		13.3	44.4
60	.08	4.59	.56	.03		8.9	29.6
100	.03	2.76	.34	.02		5.3	17.8
150	.01	1.84	.23	.01			11.8
200	.01	1.38	.17	.01			8.9

In summary, the astronomical demands are not so well-suited for deriving a well defined specification for the pointing error: the first type is a bit lenient, the second type much too demanding, and the third type depends too much on detail. Thus, it comes back to wanting the pointing error just as small as possible, and then to live with what one can get.

2. Design Specifications

In the original design specifications, the following operational conditions were selected for precision operation:

$$\Delta T = 5°F = \text{maximum temperature difference between any structural parts} \tag{8}$$

$$v = 18 \text{ mph} = \text{maximum wind velocity (including gusts) at 40 ft above ground, for any azimuth and elevation.} \tag{9}$$

The pointing error under these conditions was then specified as

$$\Delta\phi \leq 15 \text{ arcsec} \tag{10}$$

where $\Delta\phi$ was further defined as the RSS (root of sum of squares) of all the RMS values (root of mean of squares) of the single contributions, if they can be determined; in other cases, such as the wind deformations, one may

replace "RMS" by "1/2 of worst case". (11)

Measurements done more recently have shown that the internal error (whole servo loop) is negligibly small, at most 4 arcsec in low winds; for highest winds it may go up to about 8 arcsec (fast gusts, time-lag of servo response), which again may be neglected as compared to the largest wind deformations of the structure. Thus, it is sufficient to consider only thermal and wind-induced contributions to the pointing error. Regarding structural stability and safety, the antennas must be in stow position for winds (plus gusts) above 50-60 mph.

We shall now discuss several items of these specifications. First, we know from many previous NRAO experiments that, instead of 5°F, the difference between sunshine and shadow for white-painted members is up to

$$\Delta T = 5°C \tag{12}$$

at noon for 95% of all clear calm days. The distribution of ΔT is such that the median is already close to this value, because most clear days are almost equal. Also, precision observations at shortest wavelength, where small $\Delta\phi$

matter most, will mostly be confined to clear skies. Thus, (12) should be used for specifying demands and for estimating expectations.

Second, there is a discrepancy of exactly a factor of two between "for any azimuth and elevation" in (9), and "1/2 of worst case" in (11). Actually, neither the worst case, nor half of it, nor the RMS is really satisfactory. If possible, one should find the distribution function of $\Delta\phi$ and then specify a certain percentage level. This was done for (12) in previous experiments. To do it for the wind, too, would need at least a year's worth of data at the VLA site (which meanwhile I have gotten); and the angle of attack will be treated in the following section.

Third, single contributions add up quadratically (RSS) only if they are uncorrelated. But in one-sided sunshine, both pedestal and yoke bend in the same direction, away from the sun, and their contributions just add up directly. This is similar for the wind, where all single parts bend away from the wind.

Fourth, the worst cases of wind and temperature need not be combined, because strong winds will smooth out large temperature differences, keeping everything close to ambient air temperature.

II. EXPECTATIONS

1. Wind Deformations

Regarding the wind velocity, we would suggest to use the third quartile of the distribution (75% level). In lieu of sufficient data, the few we have seem to indicate that the choice of

$$v = 18 \text{ mph} = 8.0 \text{ m/sec} \tag{13}$$

which had been used for the structural analysis and the specifications, may be a reasonable number, which shall be used in the following. (Strong winds come mostly from SW, and the calmest period is July-August.)

Lee King has used some wind tunnel data about resulting torques and forces on parabolic dishes under various angles of attack, and he has performed a structural analysis for some angles, see Table 2. Here, γ is the angle between the wind and the optical axis. The worst case is the elevation error for horizon pointing and face-on wind. In general, almost 1/2 of the total error is contributed by the pedestal and 1/2 by the yoke, while backup structure and bearings give only smaller contributions.

Table 2. Calculated pointing errors from 18 mph wind, for several pointings. The angle between wind and optical axis is γ. Analysis of Lee King.

Telescope elevation, E [degrees]	Wind azimuth, α (zero is face-on) [degrees]	Pointing error, $\Delta\phi$ [arcsec] in elev.	Pointing error, $\Delta\phi$ [arcsec] in azim.	γ [degrees]
0	0	27.5		0
90	0	4.0		90
120	0	18.2		60
90	90		7.0	90
0	120		8.8	60
0	90		14.9	90

Table 2 shows that the wind can yield much larger pointing errors than demanded in (7) or (10). But how frequently will they be how large? First, regarding the velocity, we have assumed that 18 mph is the third quartile, where 1/4 of all time the wind is higher and thus $\Delta\phi$ larger than that of Table 2. For other velocities, we would have to know the detailed distribution function f(v), then using $\Delta\phi \sim v^2$.

Second, regarding the two angles of attack, azimuth and elevation, Table 2 shows that $\Delta\phi$ actually depends on two parameters. But for a rough simplification, we shall consider only one parameter, γ, using for 18 mph:

$$\Delta\phi = (8 + 20\,|\cos\gamma|) \text{ arcsec.} \tag{14}$$

Our next question then is: for which fraction Q of the "useful" sky (above elevation E) is the angle between wind and telescope axis smaller than a given value γ, and thus the pointing error larger than $\Delta\phi$ of (14)? If the observations are equally distributed over the sky above elevation E, then $Q(\gamma,E)$ is also the fraction of all time where the wind angle is smaller than γ. Omitting a rather lengthy derivation, we find

$$Q(\gamma,E) = \frac{2}{\pi\,(1-\sin E)} \int_E^{\gamma} \sin\gamma' \, \arccos\left(\frac{\sin E}{\sin\gamma'}\right) d\gamma'. \tag{15}$$

Table 3. Pointing error and sky fraction, for 18 mph wind. Considering only the part of the sky above elevation E, the fraction $Q(\gamma,E)$ of this part will have pointing errors larger than $\Delta\phi$.

γ [degrees]	$\Delta\phi$ [arcsec]	Q: E = 15°	E = 20°	E = 25°
15	26.9	0	-	-
20	26.4	.0114	0	-
25	25.8	.0350	.0141	0
30	24.9	.0688	.0428	.0173
35	24.1	.1118	.0827	.0515
40	23.0	.1634	.1327	.0985
45	21.9	.2230	.1920	.1567
50	20.6	.2900	.2597	.2248

Table 3 was derived numerically from equation (15). The result is not very helpful: reasonable percentage levels of Q will give errors $\Delta\phi$ already close to the maximum. If we admit that precision measurements at the very shortest wavelength will only seldom be tried below E = 25°, and if we ask for the 90% level (Q = 0.10), Table 3 yields $\Delta\phi$ = 23 arcsec. Combined with the 75% level for the velocity, we expect:

$\Delta\phi \leq 23$ arcsec for the wind-induced pointing error, for about 2/3 of all time. (16)

This is considerably larger than the demands of (7) or (10). However, a weak link in the derivation is the use of wind tunnel data of a different antenna. This means we need a good sample of actually measured pointing errors or tilts during nights at various wind speeds.

2. Thermal Deformations

The temperature itself should not matter because of the structural symmetry, and only temperature differences ΔT between members at opposing locations may give pointing errors. We will use ΔT = 5°C in the following, as defined after (12).

Lee King has performed a structural analysis for the thermal bending of the pedestal, for 10 different cases where one or the other or several structural tubes are warmer than the others. The cases which I think could actually occur (sun and shadow) are given in Table 4, where $\Delta\phi$ is the average tilt of the azimuth bearing (a sometimes superimposed warp of up to 4 arcsec has been subtracted). The member numbers are explained in Fig. 1.

Table 4. Thermal tilt $\Delta\phi$ of azimuth bearing on top of pedestal, from L. King's analysis. All pedestal members have equal temperature, except the listed ones which are warmer by ΔT = 5°C.

Case	$\Delta\phi$ [arcsec]	member #, Fig. 1	warmer part of pedestal
A	11	16	one outer corner
F	22	17, 19, 23	one whole corner
G	9	16, 17, 19, 31, 25	one whole side

It is difficult to judge how frequently occurring and how realistic these cases are. Also, I do not understand the large difference between F and G. Nevertheless, we will tentatively regard $\Delta\Phi = 18$ arcsec as a tilt of the pedestal tube structure which does occur but is seldom passed. (Sorry, no percentage level available.) We count the tube structure as the first thermal item.

Second, above the tubes is a flat cylinder of pedestal plates of height $h = 46$ inch and diameter $d = 142$ inch. If exposed to sunshine, it will contribute

$$\Delta\phi = C_{th}\ \Delta T\ h/d = 4 \text{ arcsec.} \tag{17}$$

Third, the yoke is rather high and slender, thus yielding a large tilt at its top if exposed from the front or back. (Note: sunshine will produce a front-back difference, not a gradient, where the latter would yield only half the tilt of the former.) For our estimate, we represent the yoke, seen sideways, by the triangle of Fig. 2. This model yields in general

$$\Delta\phi = \frac{1}{2} C_{th}\ \Delta T\ \left(\frac{2h}{b} + \frac{b}{2h}\right) \tag{18}$$

and for the yoke dimensions, steel and 5°C, we have $\Delta\phi = 25$ arcsec.

Fourth comes the backup structure of the dish for which we have no good estimate. A rough guess using its dimensions and possible exposures gave about $\Delta\phi = 8$ arcsec maximum. Finally there are the Cassegrain support legs for which we use Fig. 2 again, yielding 19 arcsec tilt if the sun shines exactly along the direction of one leg, not heating it at all, or if one leg is exactly in the shadow of another leg. This will happen only very seldom and will then be of very short duration; after some tries with various illuminations, we consider about $\Delta\phi = 5$ arcsec as a realistic value for the leg contribution.

Table 5. Expected thermal pointing errors $\Delta\phi$ [arcsec].

Item	S single max. value	H (high sun)	L (low sun)
tubes	18	+ 18	+ 9
plates	4	0	+ 4
yoke	25	0	+25
backup	8	$\pm$ 8	$\pm$ 8
legs	5	- 5	- 5
total $\Delta\phi$	RSS = 32	equ.(19) = 15	equ.(20) = 34

How to combine these five items? Table 5 lists their single maximum values $\Delta\phi$ described so far. Just adding them up quadratically would give RSS = 32 arcsec; however, they are not uncorrelated. Regarding their sign, we know that tubes, plates and yoke bend always in the same direction, away from the sun; the backup may go either way, depending on illumination details; but the support legs, bending also away from the sun, will yield a beam tilt always in the opposite direction; these signs are entered in columns H and L. And regarding the size, we cannot have all maximum values simultaneously. For example, H describes the case where $\Delta\phi$ of the tubes is maximum, case F of Table 4, which probably implies that plates and yoke are shadowed. This holds for certain sun-dish orientations and will occur mostly when the sun is higher up, see Fig. 3. The total error then is

$$\Delta\phi = \sqrt{(18 - 5)^2 + 8^2} = 15 \text{ arcsec.} \tag{19}$$

The other extreme is case L where we have the maximum of plates and yoke, but then only about 1/2 the maximum of the tubes. This will mostly occur when the sun is lower, see Fig. 3. The total then is

$$\Delta\phi = \sqrt{(9 + 4 + 25 - 5)^2 + 8^2} = 34 \text{ arcsec.} \tag{20}$$

This subtraction of the leg contribution will be mostly alright but not always. If the dish points close to the sun or about 90° away from it, all four legs will have the same temperature. Omitting the "-5" in equations (19) and (20) then yields

$$\Delta\phi = \begin{cases} 20 \text{ arcsec, case H,} \\ 39 \text{ arcsec, case L.} \end{cases} \tag{21}$$

Finally, we ask for the thermal time constant τ of the main structural parts. Suppose one member is in sunshine and is ΔT_o warmer than another one in shadow, and at $t = 0$ the first one is shadowed, too; then thereafter

$$\Delta T(t) = \Delta T_o \, e^{-t/\tau} . \tag{22}$$

In an older investigation ("Thermal Deformations of Telescopes", LFST-Report 17, of Jan. 3, 1967) I found for tubes and other hollow members, for steel and white paint,

$$\tau = 1.73 \text{ hours per inch of wall thickness} \tag{23}$$

and 1/2 that value for open shapes. The main members of the VLA antennas are listed in Table 6. We see that τ is about 2 hours, which means that the "thermally quiet" part of the night may begin about $2\tau = 4$ hours after sunset, which is quite a delay.

Table 6. Thermal time constant τ of VLA mount.

main members	wall thickness (inch)	time constant (hours)
pedestal tubes (12")	1.5	2.6
pedestal tubes (8")	1.0	1.7
pedestal plates	1.5	2.6
yoke (front/back)	1.0	1.7

In summary, the thermal pointing errors to be expected during calm clear days range between 15 and 40 arcsec, depending on the details of shadowing, where the larger errors may occur more frequently during winter if the yoke is as important as our estimate indicates. As we found already for the wind, also the thermal errors are considerably larger than the desired limits. And they may last up to four hours after sunset.

III. MEASUREMENTS

1. Temperature Differences

The following data are from a letter of John Dreher, of Sept. 29, 1980. A device to measure differential temperatures was installed on the pedestal of antenna 17, reading the difference (East-West) first between two I-beams, later between two 12-inch tubes. A typical example is shown in Fig. 4, with notes about sky and wind.

The total I have is 45 days (before installation of sun shields). From these I select all those days ($n = 18$) with clear sky and wind $\leq$ 10 mph. I read the daily maximum of ΔT, mostly two hours before or after noon, regarding the quiet-night part as zero. The following result is in good agreement with our own earlier experiments of equation (12), and has again a very small scatter (standard deviation):

$$\begin{array}{lll} \underline{\text{daily max. } \Delta T}: & \text{rms}(\Delta T) & = 4.99°\text{C} \\ & \text{stand. dev.} & = 0.46 \\ & \text{average} & = 4.97 \\ & 90\% \text{ level} & = 5.42 \end{array} \tag{23}$$

Regarding the sky, we have in the average, with wind $\leq$ 10 mph:

$$\begin{array}{llll} \Delta T = & 5.0 & \pm\, 0.3°\text{C}, & \text{clear sky,} \\ & 3.3 & .5 & \text{partly cloudy,} \\ & 1.3 & .2 & \text{overcast.} \end{array} \tag{24}$$

And regarding the wind, we find a smoothing effect, though not as much as I would have expected, where

$$\Delta T = 2.8 \pm 0.5°\text{C, clear, 20 mph.} \tag{25}$$

2. Tiltsensors

Bill Horne has mounted and monitored three tiltsensors, first on antenna 3, later on antenna 17. I have readings for a total of 83 days, November 1978 to December 1980. Unfortunately, for almost all of these days there are no weather records available (I got all records of 1980 from J. Spargo), but high winds are noted on the tilt readings, see Fig. 5. When three sensors were mounted on the azimuth bearing house below the bearing, it was found that their readings could not be fitted by a simple tilt; there must also be a strong warp (at least about 20 arcsec) of the platform on the pedestal top. A warp was also predicted by Lee King's structural analysis, but of only 4 arcsec. Maybe the observed warp is of a more local nature. Thereafter, for all measurements of 1980, the tilt of the pedestal top was always measured inside the bottom of the yoke.

The readings seem to show the wind deformations, but it is difficult to distinguish between wind and sun (Fig. 5), because strong winds occur mostly from SW early after noon, and we have no records regarding cloudiness. The strongest winds occurred May 7-9, 1979, with 50-75 mph, and with apparently correlated tilts up to 40 arcsec at yoke top, and 31 arcsec at yoke bottom, in stow position. If we fit $\Delta\phi \sim v^2$ to five such events, we extrapolate $\Delta\phi$ = 3.5 arcsec for v = 18 mph, to be compared with the predictions of Table 2. There we have a choice between 4.0 arcsec and 7.0 arcsec for stow position (E = 90°), depending on the wind azimuth which we do not know for the measurements. Thus, there may be agreement (and maybe not). At least, there is no contradiction.

The thermal deformations are also difficult to check because of the lack of weather records. They depend on the pointing, too. From the total of 83 days, we make a selection with the following criteria (and reasons):

1. Not before 1980 (warp of platform);
2. Daytime only (sun possible);
3. Max top tilt $\geq$ 15 arcsec (sun probable, pointing favorable);
4. No notes "windy" (thermal deformations only);
5. Same sensor orientation, yoke top and bottom (difference = yoke deformation).

This selection gives a sample of 17 days, supposedly sunny and calm. From the tilt records we read top and bottom tilts of the yoke, both at the time of top maximum (sometimes there is a well pronounced secondary maximum of opposite sign). All deformations go, as far as I can see, away from the sun, the sign depending on azimuth. These readings are shown in Fig. 6a.

The pedestal deformation is just the bottom tilt, and the yoke deformation is the difference top minus bottom. Both deformations are shown in Fig. 6b, neglecting the signs which are always the same for both deformations (away from sun). As compared to our predictions from Table 5, the observed results are summarized in Table 7 (and I would like to emphasize the fact that Table 5 was derived <u>before</u> I studied the observations). There is rather good agreement: the observed maximum thermal tilt at yoke top is 35 arcsec observed and 38 predicted, with an observed rms $(\Delta\phi)$ = 27 arcsec close to the maximum; the dominance of the yoke versus the pedestal is even more pronounced observed than it was predicted; the prediction that the maxima of yoke and pedestal do not occur simultaneously seems indicated in Fig. 6b, too, but not so well pronounced; the only lack of agreement is the predicted but not observed difference between summer and winter, Fig. 3, but then we do not have a large sample.

Table 7. Comparison of predicted thermal deformations [seconds of arc] with tiltsensor readings, for 17 clear calm days, daily maxima.

	predicted	measured		
	max	max	rms	average
top yoke tilt	38	35	27	25.9 ± 1.6
yoke deformation	25	26	16	15.2 ± 1.4
pedestal deformation	22	15	11	10.6 ± 1.0

Maybe it should be noted that the observed pedestal tilt is closer to case A and G than to case F in Table 4 of the structural analysis, where we found that the difference between F and G was difficult to understand; it seems now that case G is the more realistic one.

3. Astronomically Observed Pointing Errors

John Dreher made several pointing runs, and present ed a very useful method of evaluation. Each run consists of many observations of various sources all over the sky, one set at night, and a second set the following day. Separate solutions for the pointing parameters were then obtained for both sets. Using the night set as calibration, John calculated the day offset for zenith pointing, using the day-minus-night difference between both solutions. These offsets are then plotted on a polar graph. I got a total of ten such graphs, and for eight graphs I have data about wind and sky, either as noted on the graph or from John Spargo's weather records.

Fig. 7 gives a typical example; it is also typical regarding the sad fact that sun and wind both come from the same direction and are difficult to distinguish. As on Fig. 7, on most graphs there is some difference between the three arms of the "Y", resulting from different illumination angles on the pedestals; this difference is missing on two graphs and very pronounced on one. Another feature of Fig. 7 is fortunately also typical for the other graphs: a relatively small scatter about a sommon systematic offset which points away from sun and/or wind.

All data are summarized in Table 8: the day, the number n of antennas used in a run, and the available information about sky clearness and wind. The next two columns give maximum and rms of the single pointing errors, or offsets from zero. The maximum of all errors is 58 arcsec, as occasionally claimed by an observer; the rms of all is 20 arcsec, to be more readily admitted by our staff, and about as large as to be expected under average weather conditions. Most promising for future improvements are the next two columns, showing in detail the feature just mentioned: the small scatter about a systematic offset. This means, if we could manage to prevent (or correct for) the systematic part of the pointing error, be it thermal or wind or otherwise, we then would be left with a surprisingly small residual error, even smaller than our demand (7) or (10), of only

$$\sigma = \text{rms error scatter} = 9 \text{ arcsec.} \tag{26}$$

This value thus sets our goal. However, to approach it, we need first a proper understanding of the systematic offset. The last two columns of Table 8 show the sun-angle for all cases of clear sky, and the wind-angle for all cases of higher winds of $\geq$ 15 mph.

These cases are plotted in Figs. 8a and 8b, showing that the systematic offset points away from sun and wind, as to be expected but difficult to distinguish because sun and wind came mostly from the same direction, see Fig. 7. Thus, in Figs. 8c and 8d we check for the expected correlations, which we find for the wind but not for the sun, making the wind the only important cause, in contradiction to the tiltsensor readings of Table 7 for calm days. Actually, however, it just shows that we need a much larger number of more specific data before we can try to understand the cause.

Table 8. Summary of astronomical pointing runs (see Fig. 7).

run No.	date	ant. used n	weather: sky 0 overc. 2 clear	weather: wind (mph) v	single-antenna offset (arcmin): max	single-antenna offset (arcmin): rms	2-dimens. median (arcsec): offset from zero $\Delta\phi$	2-dimens. median (arcsec): scatter from med. σ	angle (degrees) from median offset: to sun α	angle (degrees) from median offset: to wind β
1	1980-7-26/27	15	1	8	20	12	3	11		
2	7-18	16			11	9	4	7		
3	7-11	18	1	7	22	15	13	5		
4	6-23	18	2	17	25	15	12	8	+ 155	+ 125
5	5-30 pm	23	2	20	43	29	25	11	- 170	+ 160
6	5-30 am	24	2	15	25	17	13	9	+ 170	+ 85
7	4- 5	20	0.5	22	58	39	37	7		+ 175
8	1979-11-1	14	2	0	14	9	5	7	+ 170	
9	10-15	11	2	6	19	13	9	8	+ 175	
10	9-27	14			23	18	11	11		
	Total	= 173		rms =	29.2	19.7	16.6	8.6		
				average =	26.0±4.5	17.6±3.0	13.3±3.3	8.4±0.7		

Finally, Fig. 8e shows another pleasing result. Not only is the residual scatter small, it is also independent of the size of the offset, which means that even large offsets could be reduced to small residual errors.

4. Calm, Clear Nights

The performance of exposed telescopes is best during calm nights, and short-wave observations will mostly be limited to clear skies. It would thus be helpful for the observer if he could be informed about the quality and the average duration of good observing conditions. I do not have enough data for final answers, but I want to make a start.

As a first step, we try to answer the question: "What is the duration of the thermally quiet period of a clear calm night?" From the total of 45 nights where temperature differences ΔT have been measured in the unshielded pedestal structure, we select all those nights (n = 16) with clear sky and wind $\leq$ 15 mph. Then we measure the duration t of that part where $|\Delta T| \leq 1.0°C$, as shown in Fig. 4, which means that the thermal part of the pointing error should be $\Delta\phi \leq 5$ arcsec. The observed durations cover the range $8 \leq t \leq 16$ hours, with the resulting values:

Duration t of $\|\Delta T\| \leq 1°C$, clear calm nights, winter, Nov. 1979 to April 1980;	rms(t)	=	13.0 hours	
	stand. dev.	=	2.4	(27)
	average	=	12.8 ± 0.6	

The next step would be to do the same with the tiltsensor readings. I have not done this because of the lack of weather records; but the rather typical example of Fig. 5 seems to confirm (27) quite well. The final step would be to analyze many pointing runs at clear calm nights which sounds rather impractica. Thus, if not changed by future data, we may consider about t = 12 hours as our result for winter and somewhat less for summer; which is better than I would have expected from the thermal time constants of Table 6 of about 2 hours, and from Fig. 9a which shows practically no period with constant temperature.

5. Sun Shields

During the middle of April 1980, experimental sun shields were installed on the pedestal tubes of Antenna 17; sheet metal cylinders at 3 inch spacing around the tubes, with an open slot at the downward side, painted white in and out. Later on, the 3-inch spacing between tube and shield was partly filled with foam. Measurements were taken simultaneously at the shielded antenna 17 and the unshielded antenna 6. Temperature differences were derived between identical tubes at both antennas. Fig. 9a shows an example of the recordings. How effective is this shielding?

First, we ask the most direct question: by which shielding factor is ΔT reduced? Fig. 9b shows some way in which the 20 available readings may be evaluated. We cannot explain the difference between the two results shown, maybe it is within the scatter. We just use the average factor, $(0.48 + 0.24)/2 = 0.36$. Thus, regarding the temperature differences of the pedestal tubes, we see a considerable improvement of about a factor of three.

Second, on six days with astronomical pointing runs, see Fig. 7, we can compare the average pointing error of the shielded antenna 17, $\Delta\phi_{17}$ = (16.9 ± 4.9) arcsec, with the average pointing error $\Delta\phi_{all}$ = (13.1 ± 2.7) arcsec of all 15 to 24 antennas together, for the same six days. There is no indication of any improvement; both $\Delta\phi$ agree within their errors. As an explanation, I would suggest the fact that the shielded pedestal tubes are only one contribution out of many, and that this contribution disappeared in the noise. This negative result, together with the good thermal shielding factor of three, seems to show clearly that improving only one item is not good enough.

IV. SUGGESTIONS

1. Present Results

First, we may conclude that the observed deformations and pointing errors of the VLA antennas are just as large as to be expected from sun and wind; there is nothing amazing about them. From higher winds, we expect errors $\Delta\phi \geq 23$ arcsec for about 1/3 of the time, and for calm sunny days we expect errors between 15 and 40 arcsec depending on illumination details, with about 27 as average, and the yoke may deform even more than the pedestal. The tiltsensor readings confirm the importance of the yoke deformation, and they agree well with the expected maximum and rms deformations. The astronomical pointing runs show a single large error of 58 arcsec, but the rms of all 173 errors is again about 20 arcsec.

Second, the measurements and notes were not specific enough to allow a separation between thermal and wind deformations. For larger deformations with available weather data, sun and wind came mostly from about the same direction, the deformations pointing away from both. This separation, however, is badly needed for future planning.

Third, the pointing runs show mostly a small uncorrelated scatter (9 arcsec rms only) about a larger systematic offset (17 arcsec rms). This looks really very promising. If the systematic effect could be handled somehow, the remaining residual pointing error would only be small.

2. Prevention and Correction

In general, there are two ways for improving the systematic errors. First, one can try to remove the cause, which seems possible with the thermal shielding. Second, one can measure the cause and correct for it, which may be necessary regarding the wind deformations. Wherever possible, preventing is better than correcting.

The previous experiment with thermal shielding was quite successful, yielding about a factor of three, and a still more effective method was suggested in Socorro: cycling water (and antifreeze) through all tubes of the pedestal. I suggest to spray 1.5 inch foam onto the tubes and I-beams of the pedestal, and to fasten plane foam plates onto all sides of the yoke. We had very good success at the 140-ft with 1.5 inch of Urethane foam. Bill del Giudice suggested available preformed foam shieldings for tubes, which would be best if not too expensive.

How much shilding do we need? We may approximate the daily (unshielded) temperature variation by a sine wave $T_o(t) = A_o \sin(\Omega t)$, with $\Omega = 2\pi/(24 \text{ hours})$. If the shielded system has a thermal time constant τ, we have a forced oscillation of the type which has friction but no inertia. It has a reduced amplitude A_s and a time lag θ, with $T_s(t) = A_s \sin(\Omega t - \Omega\theta)$, where the delay is $\theta = \tau$ for small τ and $\theta = (1/4)$ period for large τ, and in general

$$\theta = \frac{1}{\Omega} \arctan(\Omega\tau) \leq 6 \text{ hours} \tag{28}$$

and the reduced amplitude is

$$A_s = \frac{A_o}{\sqrt{1 + (\Omega\tau)^2}} . \tag{29}$$

If we demand, for example, a reduction by a factor of ten, we need from (29) a thermal time constant

$$\tau \geq 38 \text{ hours, for } A_s \leq A_o/10. \tag{30}$$

We consider a plane wall of steel, with foam on the structural outside and no heat loss on the interior side, which holds for yoke and pedestal plates and approximately also for the pedestal tubes. We call h the specific heat of steel and ρ its density, and s the wall thickness of the plate. The foam shall have a thickness f, and Urethane has a low heat conductivity of $c = 0.12$ BTU/(hr, ft^2, °F/inch). Then it can be shown that the thermal time constant is

$$\tau = \frac{h\rho}{c} s\ f = 41 \text{ hours } \frac{s}{\text{inch}} \frac{f}{\text{inch}} . \tag{31}$$

We use s = 1 inch wall thickness from Table 6, and in order to fulfill demand (30) we need about

$$\text{foam thickness } f \geq 1.0 \text{ inch.} \tag{32}$$

If the <u>wind</u> should be important, and since we cannot shield against it, we may consider corrections. This raises two questions: What should we measure? How do we derive the corresponding corrections from the measured quantities? In all of the following suggestions, we need the structural stiffness, for all possible telescope pointings and all force directions and torsional moments. We would probably also need a long series of field tests, for checking purpose and for final calibration. First, one could simply measure wind speed and azumith and telescope elevation, deriving the resulting forces and moments from wind tunnel data, whose application to our antennas may be a weak point, but the final calibration could correct for it. Second, one could measure two torques directly by reading the currents at the two drive motors, azimuth and elevation, but this misses the third torque component which is perpendicular on those two, and it misses the worst case of Table 2, the first line with face-on wind and zero elevation, which yields no axial torques but a large force. Although incomplete by themselves, the torque measurements may be useful in addition. Third, one could measure at four places of the dish surface the pressure and the pressure difference (front - back) which, I think, should give sufficient information for all pointing cases, for torques and for forces. But before working out all the details, we should first know how important the wind really is.

3. Future Measurements

Before we can actually start any improvements, we need more measurements. They should be sufficiently specific (sun versus wind), coordinated (simultaneous different readings and weather), and numerous (statistical significance).

If possible, it would be good to have a number of, say, three dedicated test antennas which do not take part in the astronomical VLA program during these tests:

1. Unshielded, as a reference;
2. Foam shields for yoke, pedestal plates and tubes;
3. Water circulation in pedestal tubes, or some other suggestion;

The three antennas must be located on the same arm (same orientation of pedestal), not too far from each other nor from the weather station. All three must point in the same direction.

I would suggest to plan two separate test runs, one for thermal deformation and one for wind deformations, with the antennas not being moved during the whole duration of one run, except for wind-enforced stow position (where whatever measurements still are possible should still be running). Which run comes first should be decided with respect to the prevailing monthly weather conditions.

For the thermal run, I would suggest to consider an azimuth due north, and an elevation of about 35° in summer and higher in spring, as explained in Fig. 10. The duration of the thermal run should not be a specified time, but it should last until we have a specified sample of, say, a dozen of clear (100%) and calm (≤ 9 mph) days, preferably two dozen if that is feasible.

For the wind run we may choose a SW-pointing since the stronger winds mostly come from there, and zero elevation for face-on wind, see Table 2. The duration should last until we have at least a dozen or two of nights with high winds (≥ 25 mph); if that turns out impractical, we may also use high winds in daytime if the sky is completely overcast, no sun at all and thick clouds, see (24) for comparison. We also need a similar number of calm nights (≤ 9 mph) which is less demanding.

Regarding the measuring equipment, I would like to suggest the following, if that is not too many:

<u>Thermistors</u>:

1. N, 2. E, 3. W } long 12" tubes pedestal
4. S plate pedestal
5. front, 6. back } yoke
7. S, 8. N } support leg

<u>Tiltsensors</u>:

1. base, 2. top } of yoke
3. near dish vertex
4. Cassegrain

<u>Weather</u>:

1. wind speed
2. wind direction, degrees
3. ambient air temperature
4. some measure of sunshine, omnidirectional (temperature difference between black and white sphere).

<u>Time</u>:

1. year-month-day (plus day number)
2. local standard time (not daylight-saving, not universal)
3. maybe: daily note about sunrise and sunset?

Readings should be taken every 1/2 hour, recording always all 12 readings of each antenna plus weather and time, no matter which test run is on. Plus once a day recording the date, and sunrise and sunset. All records together on magnetic tape, including the weather.

Good data presentation is essential for proper diagnosis. We need a general-use program, yielding selective kinds of difference, average and rms, and producing demonstrative listings and graphs.

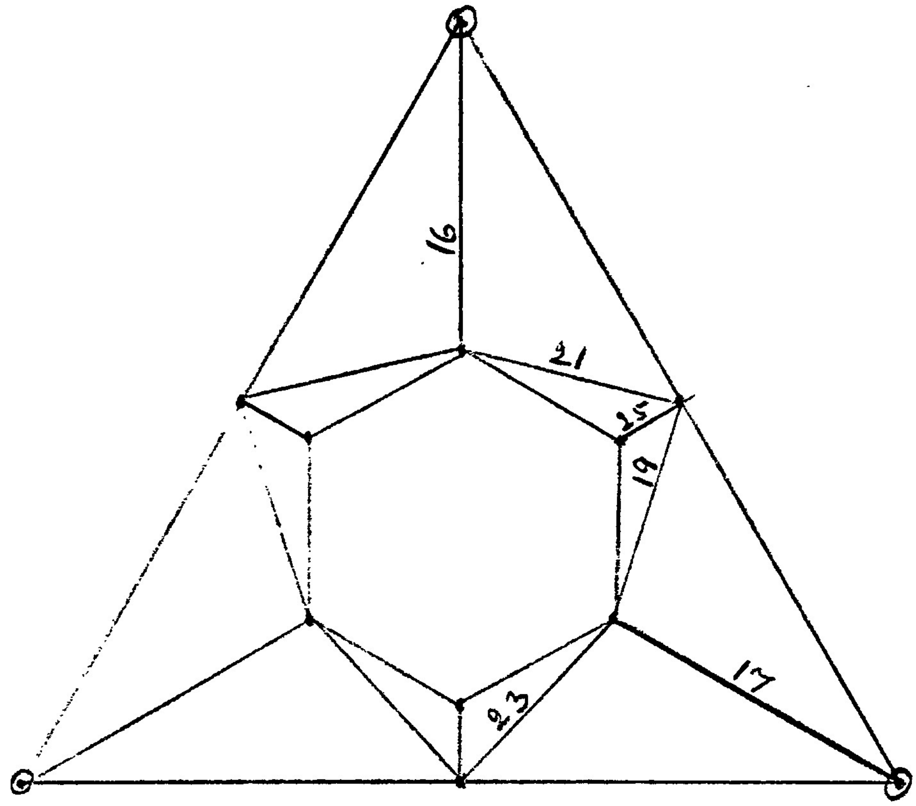


Fig. 1. Antenna pedestal, members used in L. King's thermal analysis. ⊙ supported points of base. Top view.

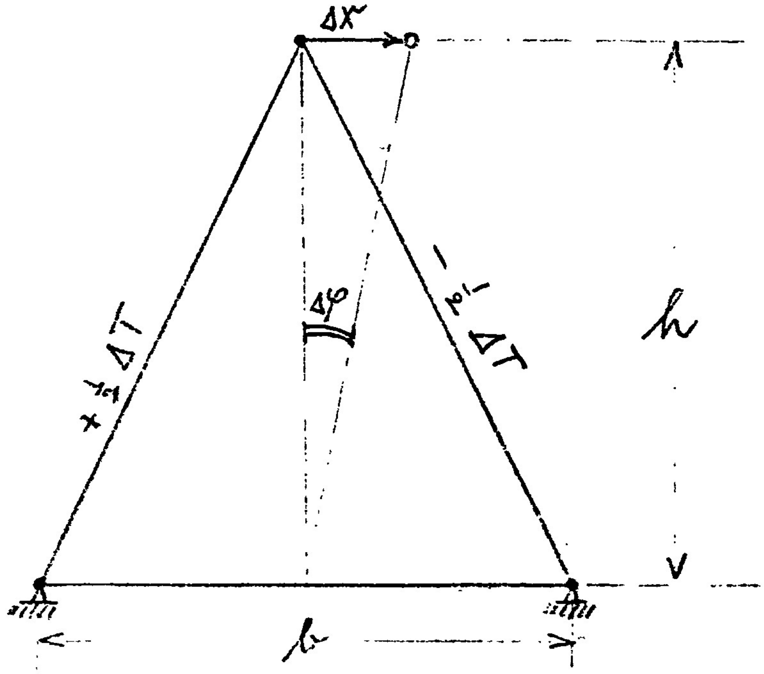


Fig. 2. Simple model for thermal estimates of yoke and feed legs. Side view.

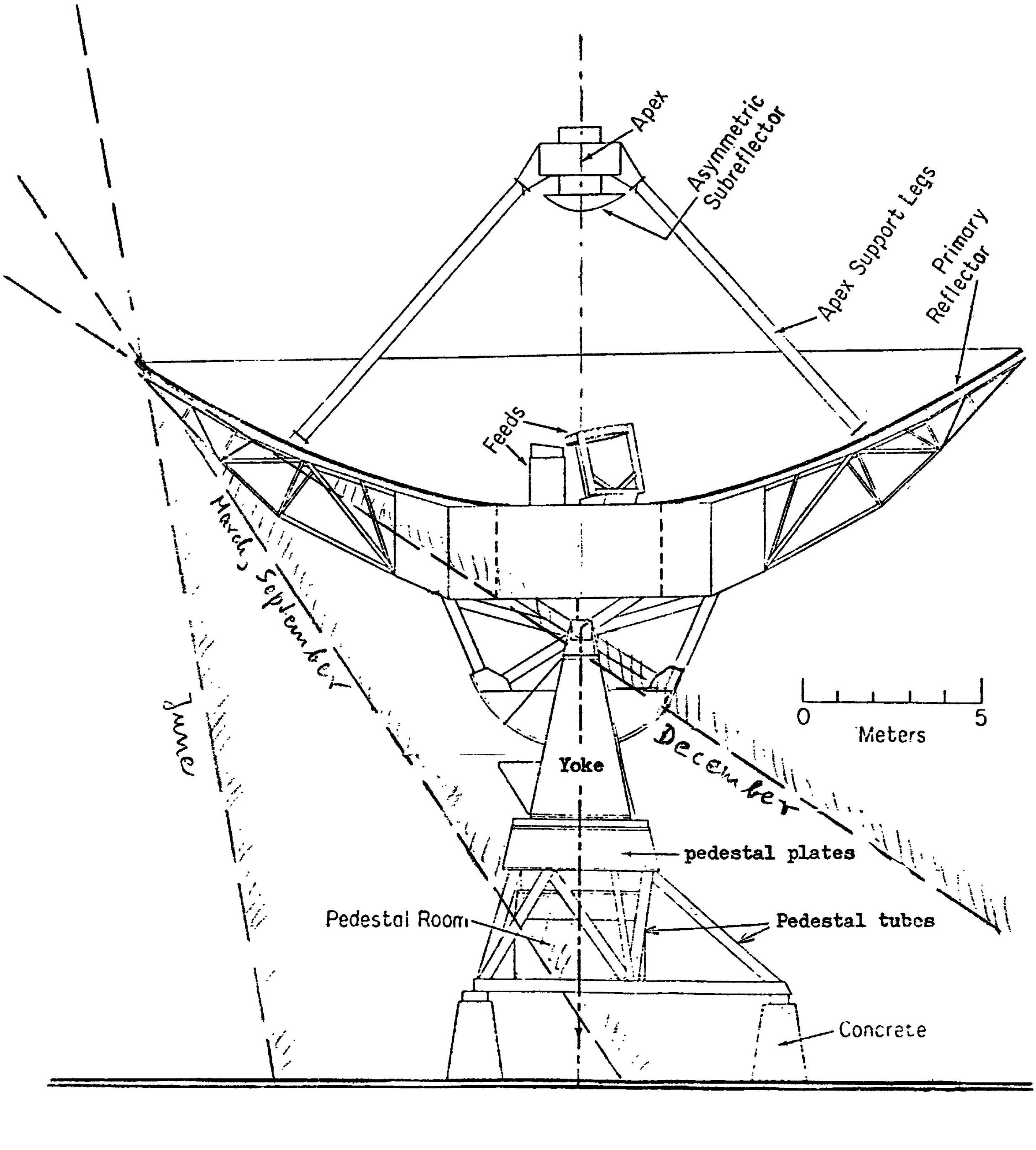


Fig.3. VLA antenna, with sun and shadow border, at noon.

Yoke and pedestal get more sunshine in winter than in summer.

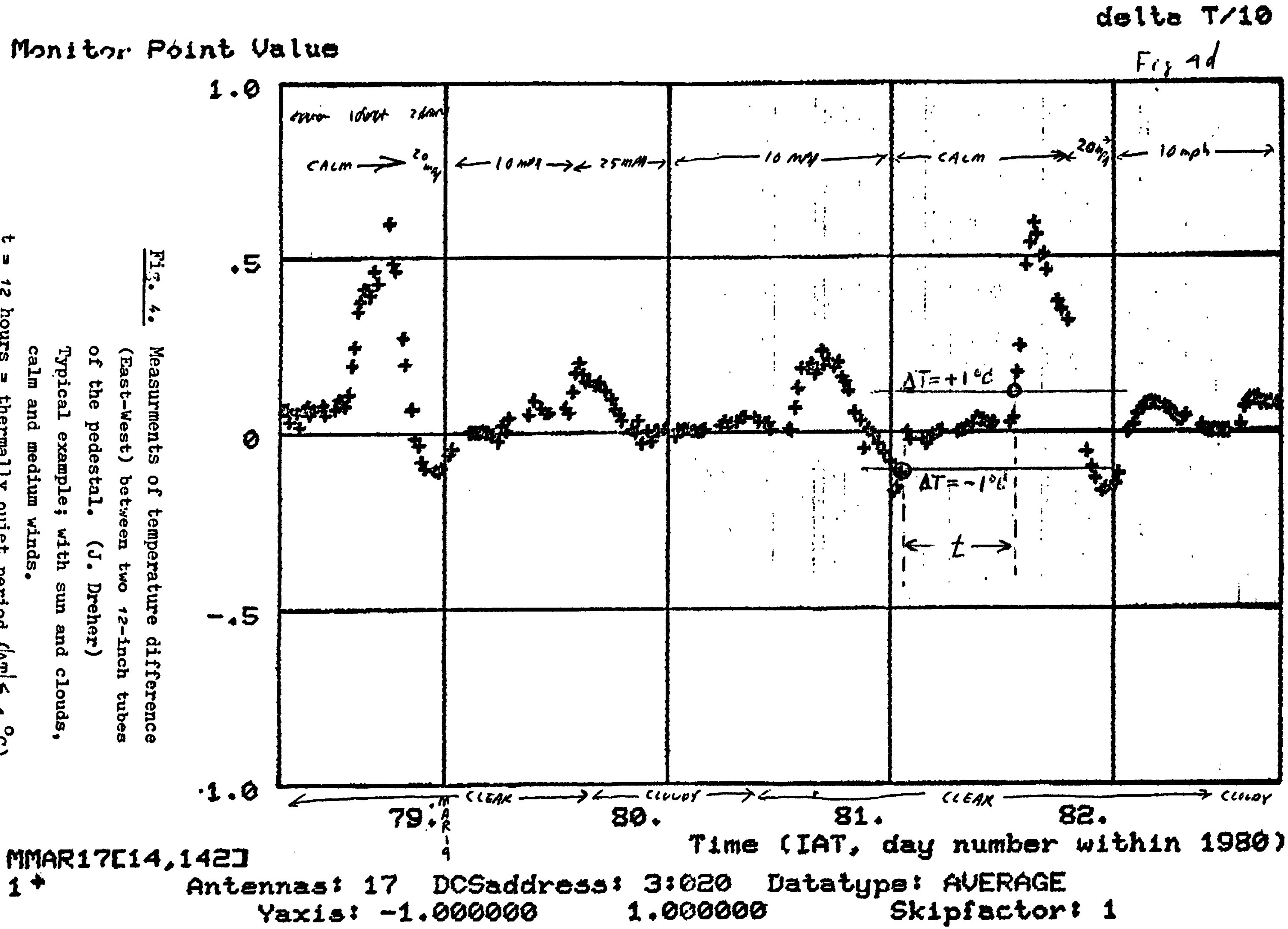


Fig. 4. Measurments of temperature difference (East-West) between two 12-inch tubes of the pedestal. (J. Dreher) Typical example; with sun and clouds, calm and medium winds.

t = 12 hours = thermally quiet period ($|\Delta T| \leq 1\ ^{o}C$).

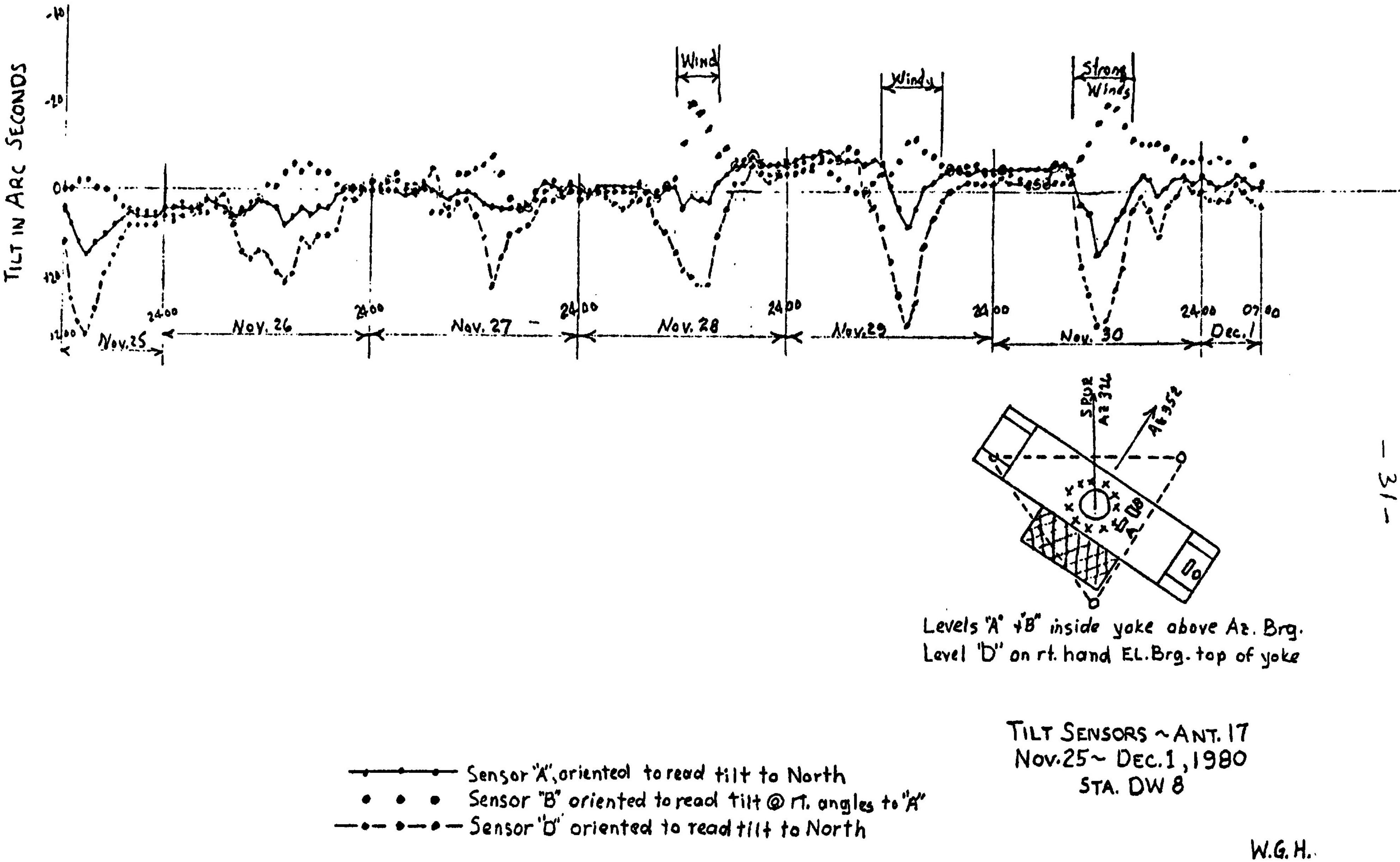
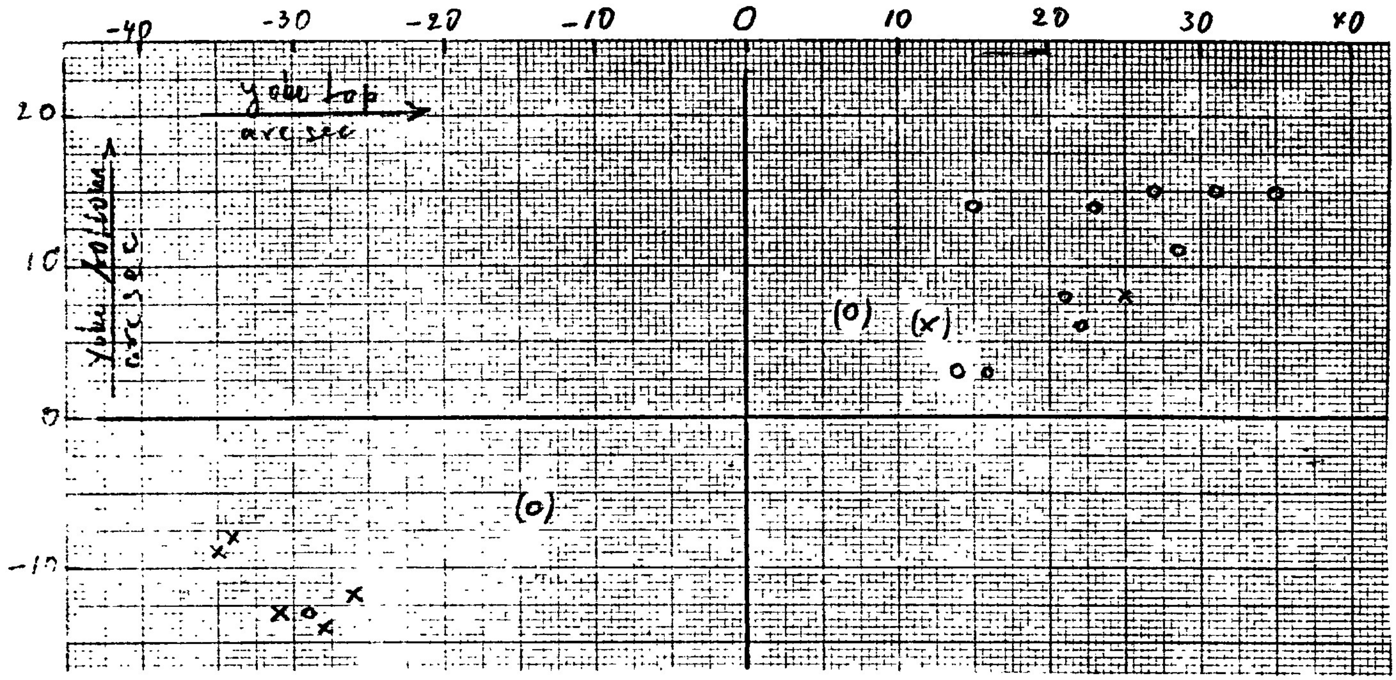


Fig. 5. Example of tiltmeter readings, antenna 17 with sunshield and foam (Bill Horne).
No weather records available. "Wind" means ≥ 15 mph, "Strong Winds" 25 - 30 mph.



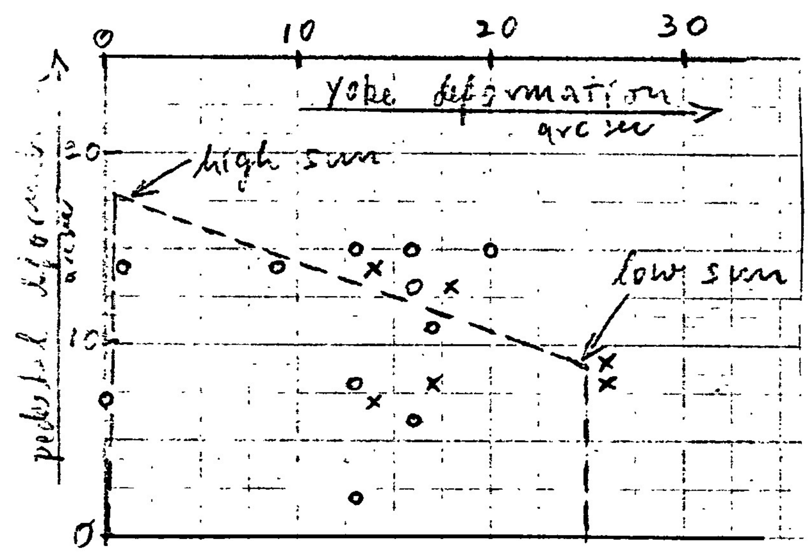


Fig. 6. Thermal deformations measured with tiltsensors (B. Horne), for sunny, calm days; o = winter, x = summer.

a) Tiltsensor readings at daily maximum of top (Parenthesis: smaller secondary maximum). Simultaneous readings at top and bottom of yoke, both sensors with same orientation. Antenna in various azimuths, thus both signs occur (away from sun).

b) Deformations of yoke and pedestal at daily maximum. Broken line is expectation from structural analysis, Table 5.

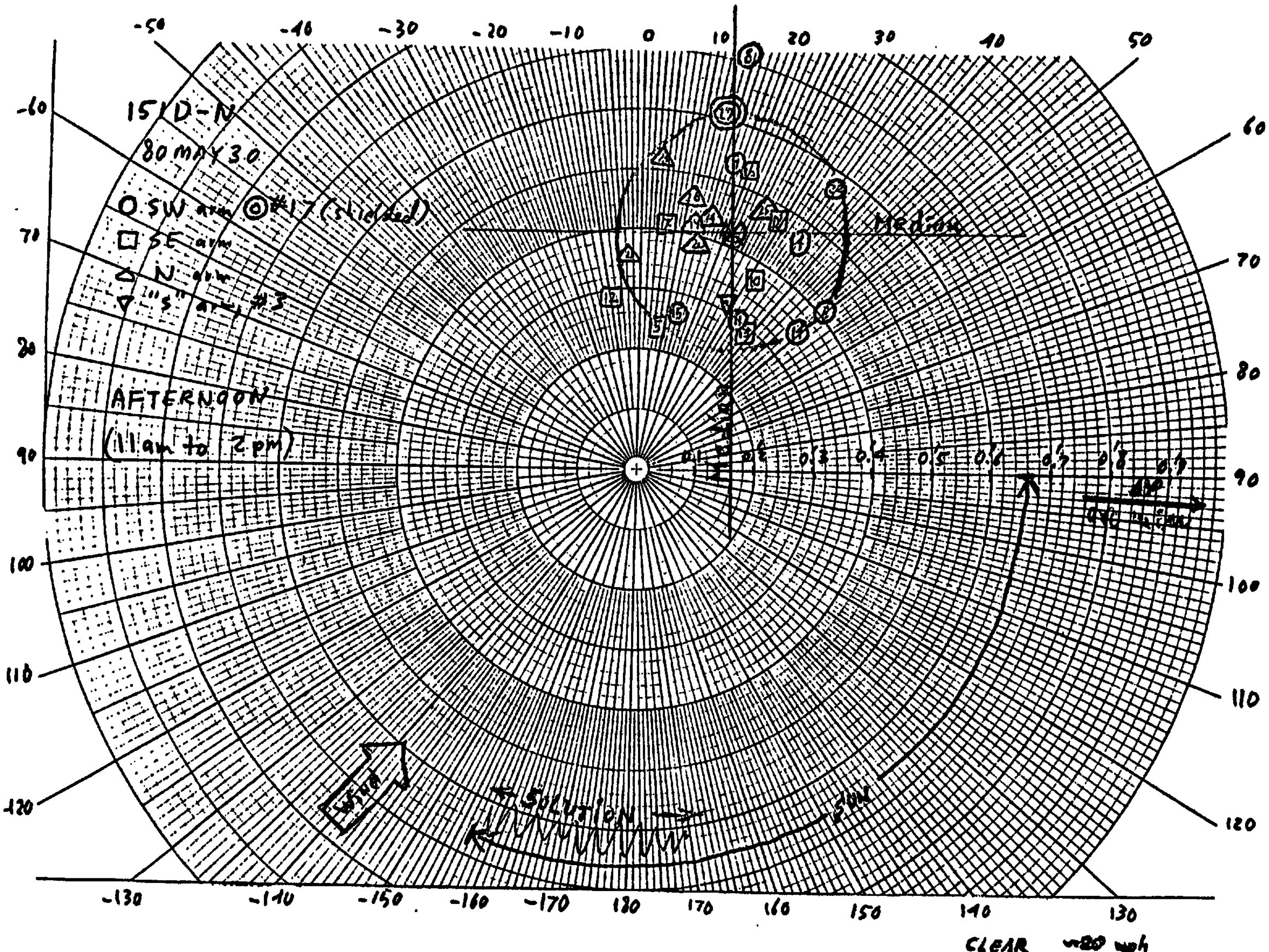
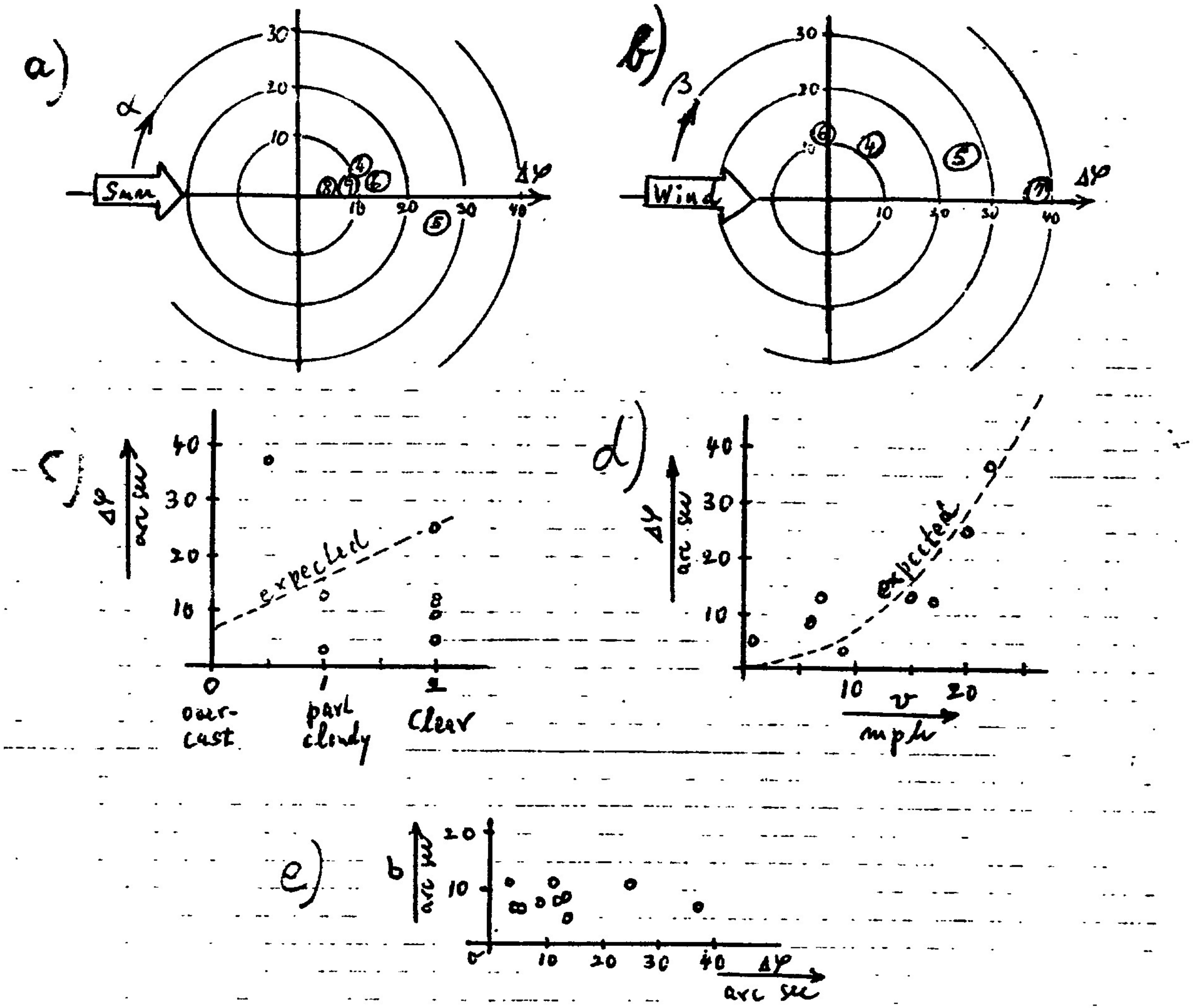


Fig. 7. Typical example of an astronomical pointing run, with n = 15 antennas. No. 17 is the shieded antenna. Shown is the deviation $\Delta\varphi$ from zenith for each antenna. The scatter is measured by the heavy circle which contains 2/3 of n inside and 1/3 of n outside. The systematical offset ⊗ is defined here by the median.



<u>Fig. 8.</u> Trying to understand the pointing runs (Fig. 7, Table 8).

a) Offset Δφ of the median, and sun angle α, all runs with clear sky (n = 5):
Away from sun.

b) Offset Δφ and wind angle β, all runs with v ≥ 12 mph (n = 4):
Away from wind.

c) Offset Δφ versus sky clearness, all runs with sky data (n = 8):
No expected correlation followed.

d) Offset Δφ versus wind speed, all runs with wind data (n = 8):
Following expected correlation.

e) Scatter σ versus offset Δφ, all runs (n = 10):
Scatter is small and uncorrelated.

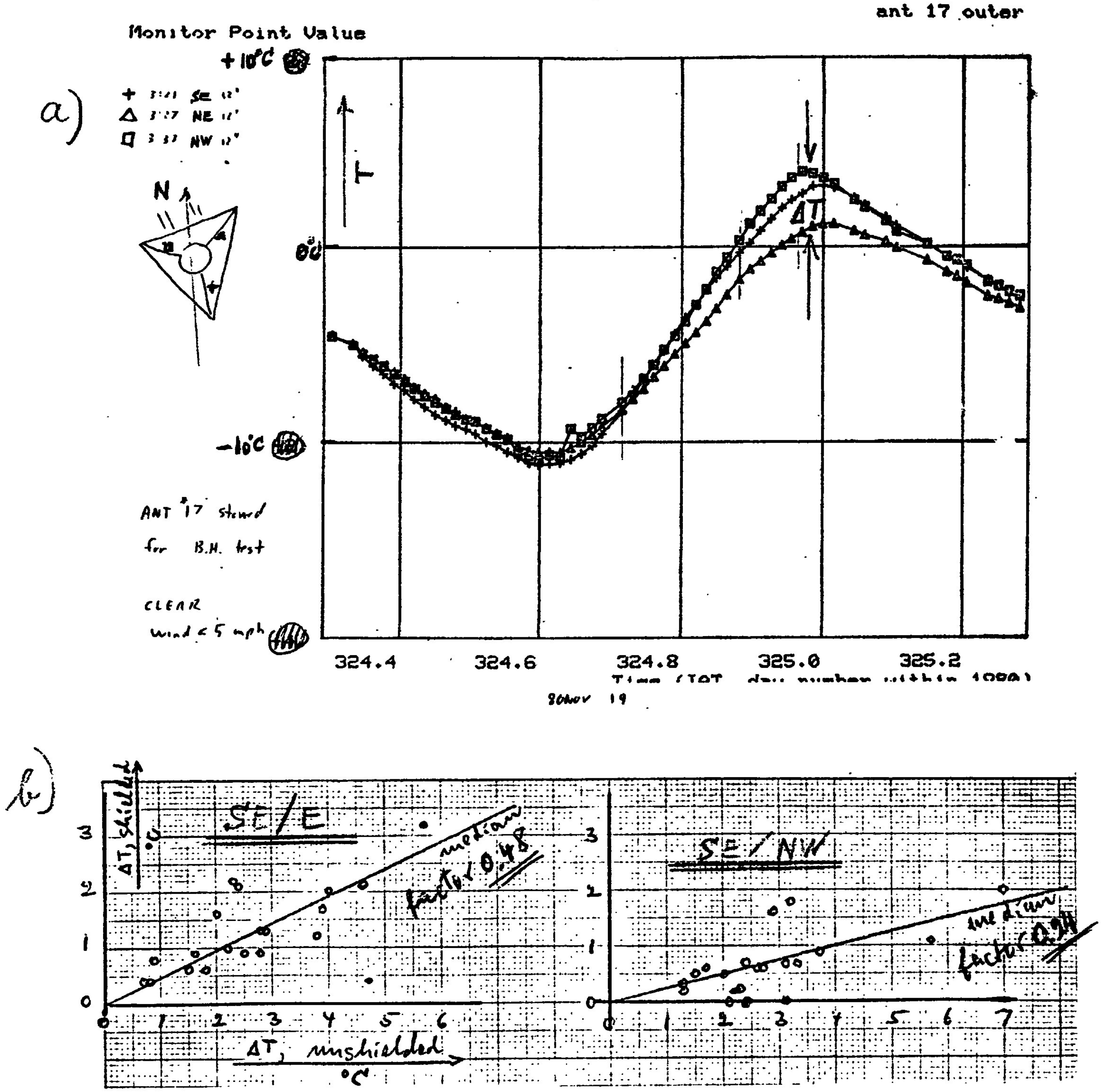


Fig. 7. Effect of sun shields on temperature differences ΔT.

a) A typical day at the shielded antenna 17, clear and calm. (J. Dreher)

b) Plotting ΔT of the shielded antenna 17 versus ΔT of an unshielded antenna 6, yielding an average shield factor of 0.36.

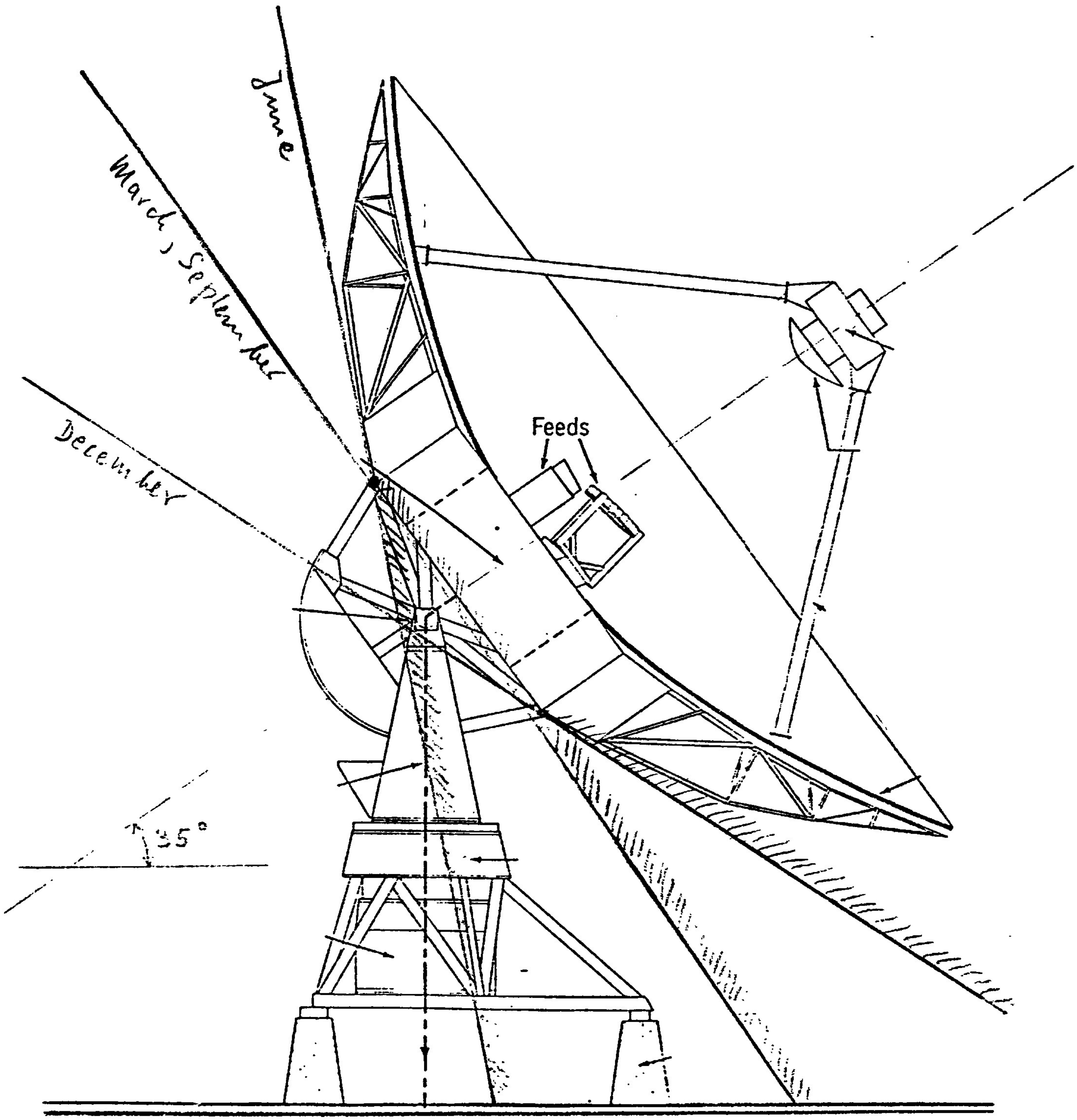


Fig. 10. Sun and shadow at noon, antenna pointing north.

Summer and 35° elevation seems best for measuring thermal deformations.