K. Sowinski

VLA/VLBA Pointing Memorandum No. 101

UNSLAIN DRAGONS: THE EFFORT TO IMPROVE THE POINTING OF THE VLA AND VLBA ANTENNAS

C. M. Wade

27 March 1990

In a valiant last effort to get some useful work out of me before I retire, the local NRAO management has asked me to look for practical ways to improve the marginally satisfactory pointing of the VLA and VLBA antennas. I accepted the challenge with considerable diffidence, for the easy part of the job was done long ago. What remains promises to be tough. I only hope that the superficial resemblance of our antennas to old-time Spanish windmills does not make me look like Don Quixote...

I invite everyone who is willing and able to contribute to take part this noble effort. Not only does misery love company, but much of the adventure promises to genuinely interesting and hence rewarding. There are some very curious puzzles awaiting solution.

Problems and progress need to be documented in a timely manner for participants and serious onlookers. This is best accomplished, I think, by a dedicated memo series that serves as forum and bulletin board. Since the subject matter is essentially an internal NRAO problem, there should be no regular distribution outside the NRAO. Few of the memos will be finished documents appropriate for wide circulation.

The present literary gem is the first of the series. A few words of explanation (or exculpation) are in order. You will have noticed that the series starts with No. 101, following a practice urged in the early days of the VLA by Hein Hvatum. It is thought that this somehow imparts a superior dignity and credibility to the whole operation. Furthermore, you shortly will discover that the body of this document consists of a memorandum I sent a couple of weeks ago to certain well-known local authorities, followed by a couple of addenda. I use it to initiate the series because it accurately describes my current concept of the pointing problems.

Enough. Turn the page and read on.

MEMORANDUM

12 March 1990

TO: M. Goss, R. Perley, R. Sramek, P. Napier, C. Walker

FROM: C. M. Wade

SUBJ: Antenna Pointing Investigation

The present report summarizes the current state of my efforts toward improving the pointing of the VLA and VLBA antennas. The main points are documented, with no pretense to completeness or evenness of treatment.

At present, the VLA antennas point reliably to about 15 arc seconds under benign conditions (night, low wind). Experience to date with the VLBA antennas suggests that they point about as well as the VLA. To exploit fully the high-frequency capabilities of the antennas, we should point them with an accuracy of about 5 arc seconds, which means reducing the solid angle of the "cone of uncertainty" by 1 to 2 orders of magnitude. Whether this can be done, and if so with what limitations, has yet to be determined.

The antennas are not perfectly rigid. They continually bend and warp in response to sun, wind, and ambient temperature. They sit on foundations that are somewhat unstable. Azimuths and elevations are read with shaft encoders of finite resolution and finite reliability. The various effects are significant on time scales that range from seconds to months or years. When examined in detail, the pointing of an antenna is seen to be a messy business.

I. THE FORMAL POINTING MODEL

The standard pointing model used for the VLA and VLBA considers imperfect axis alignments, quadrupod sag, and simple encoder errors. Component errors are expressed as functions of azimuth and/or elevation, with coefficients ("pointing constants") obtained from observations of radio sources. The model appears to be a subset of an algorithm I gave George Grove in a memorandum dated 22 February 1974. It works fairly well for pointing down to about half an arc minute, but its limitations become serious when more accuracy is needed. In part, this is because effects ignored by the model are significant at higher accuracy. Worse, the constants are not necessarily constant, and the possibility of their variation must be taken into account.

Despite its shortcomings, the model is useful, even indispensable, for visualizing the problems of pointing an antenna. I have drafted a memorandum which gives the complete derivation of the algorithm. I have been in no hurry to finish it because it would be of interest to few people.

Here I will review the main terms of the algorithm, indicating the particular problems associated with each. Notation is as follows:

A, h	azimuth, altitude
[δA], [δh]	respective error terms
C1 ... Cn	formal constants

(A) Encoder terms:

$$[\delta A] = C1 + C2 \cos A + C3 \sin A$$

$$[\delta h] = C4 + C5 \cos h + C6 \sin h$$

C1 and C4 are simply zero-point errors. The trigonometric terms express the imperfect centering of an encoder on its axis (analogous to the error caused by faulty centering of a watch dial on the axis of the hands).

C1 ... C6 should be quite stable unless the encoders are physically disturbed, say during maintenance. They might vary with temperature, however; this needs to be checked.

(B) Zenith terms:

The zenith error is analogous to misalignment of the polar axis of an equatorially mounted instrument. Normally the azimuth axis should point precisely to the local zenith. There is an important exception in the case of the VLA, where the station pads were set to make the azimuth axes of the antennas parallel to the vertical at the intersection of the array arms. I am guilty of proposing this aberration back in 1974, when I imagined it would simplify pointing. Now I'm not so sure.

The expressions for the zenith terms are

$$[\delta A] = (C7 \cos A + C8 \sin A) \tan h$$

$$[\delta h] = C8 \cos A - C7 \sin A$$

Note that the same coefficients serve both axes, with suitable adjustment of sign.

C7 and C8 are not reliably stable, because changes of orientation have been demonstrated for several foundations (both VLA and VLBA).

Temperature changes should have little effect on C7 and C8 at a VLBA station, because the azimuth axis is normal to the plane of the track, which rests directly on the very massive concrete foundation. In the case of the VLA, however, the azimuth axis is normal to the plane of the azimuth gear, which rests on supports that are exposed to the sun, so thermally driven variations in C7 and C8 are quite likely.

An important source of error is roughness or non-planarity of the track (VLBA) or azimuth bearing (VLA). Nothing in the model allows for this, which introduces repeatable azimuth-dependent changes in C7 and C8. The problem has to be faced, since it is known that there is a 120° azimuth term in at least some VLA antennas, and a 180° term has developed in the Pie Town VLBA track during the past year.

(C) Perpendicularity terms

Ideally, the elevation axis should be precisely at right angles to the azimuth axis, and the collimation axis (the "optical axis" of the antenna) should be precisely at right angles to the elevation axis. The elevation axis rotates on the azimuth axis, and the collimation axis rotates on the elevation axis. The corresponding imperfections of alignment are called respectively "axis perpendicularity error" and "collimation error". These have little effect on elevation except close to the zenith, but they are important for azimuth:

$$[\delta A] = C9 \tan h + C10 \sec h$$

The first term is due to axis perpendicularity, and the second is due to collimation.

The pointing models used with the VLA and the VLBA omit the axis perpendicularity term. I don't know why; the omission is justified only if someone has measured C9 carefully for each antenna, and shown it to be negligible in every case. If this was ever done, I have not heard about it.

Axis perpendicularity is vulnerable to differential heating of the support paths to the two elevation bearings from the plane that defines the azimuth axis (namely: the two sides of the yoke for the VLA, or of the structure between the track and the elevation bearings for the VLBA). The effect ought to be appreciable, especially on a clear day when the sun is low.

Collimation error is sensitive to differential heating of the quadrupod legs. It is subject to rapid jitter under windy conditions. It may vary as a function of elevation if the guy wires are tensioned incorrectly.

(D) Quadrupod sag

This comes from gravity pulling on a cantilevered mass, hence there ideally should be no azimuth term. The intuitive relation

$$[\delta h] = C11 \cos h$$

seems to fit such measurements as exist. It should be measured properly, however. In particular, we need to look carefully for lateral motion associated with the sag -- this has occurred in other antennas. Such lateral motion causes an elevation-dependent collimation error.

(E) Other terms

My 1974 memo included atmospheric refraction terms in elevation. Refraction is handled separately by the on-line systems, so I will not treat it further. One must remember, however, that incompletely modelled refraction can cause significant pointing errors (meaning the beam points to where the source is not), particularly at low elevations.

Backlash is not supposed to occur in our antennas, and it probably doesn't. I think we should look for it anyway, at least when there are strong gusty winds. It would have the effect of imposing a quantized, bi-stable jitter in both coordinates.

II. ANTENNA FOUNDATIONS

Since foundation motion redirects the azimuth axis of the antenna, it is an inherent part of the pointing problem.

(A) VLA

The visible portion of an antenna foundation consists of three massive concrete piers rising 6 to 7 feet above ground level. Most of the foundation, of course, is below the surface. Each pier extends downward anywhere from 21 to 37 feet, the exact amount depending on the local properties of the soil. The piers are flared at the bottom to spread the load. The triad of piers is tied together a few feet below the ground surface by heavy transverse grade beams. Over half of the foundations (40 out of 72) are of Type B, which have underground radial wing walls to enhance resistance to lateral motion. The entire structure is engineered to provide an antenna platform that is stable in position, dimensions, and orientation.

The piers are capped by heavy steel plates to which the antenna foot plates are bolted. The upper surfaces of the three plates at each station were adjusted initially to lie in a common plane. The plane was inclined toward the center of the array to render it parallel to the horizontal at the array center. The tilt can be quite large, as much as 11′19″ at the ends of the east and west arms.

It was discovered late in 1989 that the relative heights of the plates at station E7 are wrong by as much as 3/8 of an inch, and that their surfaces are no longer coplanar or even parallel. Quick checks of stations N20 and N24 showed that the relative heights of their plates are also in error by several tenths of an inch (plate orientations were not measured at N20 and N24). The unpalatable but unavoidable conclusion is that at least some VLA observing stations are not stable in shape and orientation. The zenith error is over 3 arc minutes at station E7. Stations E7, N20, and N24 are all of Type B and hence should be especially stable.

It would be helpful to know when the changes took place. Are they the result of settlement that took place early, under the first loadings with the 240-ton weight of an antenna? Are the foundations continually readjusting themselves, with true stability never being reached? The answer probably can be found in the pointing notebooks which the Operations group maintains in the VLA control room. Unfortunately, the data are not arranged in a way that permits quick perusal. I have extracted the values measured for the zenith terms during 30 months (July 1987 through December 1989), and even this limited data set tells us something:

1. Changes in excess of 1 arc minute from the original alignment have occurred at about half of the stations (33 out of 72). Only 7 stations, however, have changed by more than 2 arc minutes.

2. The worst stations are W36 (>5′); N24 (>4′); N28 and E7 (both >3′); N18, N20, and W40 (all >2′). The four on the north arm are contiguous, lying in a stretch of 2000 meters roughly centered on US Highway 60. This suggests a localized problem with the soil. It is also interesting that the two on the west arm are adjacent. All of these "bad" foundations are of Type B.

3. Appreciable changes in station orientation often occur between successive occupations. This implies a kind of hysteresis, such that the piers shift in not altogether repeatable ways under the alternating stresses of loading and unloading.

4. In a number of cases, the orientation of a station has changed during a single occupation. The shift sometimes is slow and steady. More often it is

abrupt (as much as an arc minute in a couple of weeks).

The above results come from a superficial review of a subset of the historical pointing data on file. There clearly is much of value that can be learned from a more complete and systematic analysis. I think we should construct a database which includes all pointing constants back to the beginning, and that it should be updated after each pointing run. It will be a rather tedious job, but worth the effort.

The instabilities must reflect characteristics of the old lake sediments that underlie most of the VLA (the outer stations on the east arm and a couple on the west arm sit on former shore terrace deposits, which are quite different). The old lake muds contain a large amount of montmorillonite clay, which swells and shrinks drastically with changing moisture content.

(B) VLBA

The VLBA foundations are rings, 52 feet in diameter. Details differ from site to site because the design is adjusted to local subsurface conditions, but they are always massive, consisting typically of 600 to 650 tons of heavily reinforced concrete. Half rest on more or less solid rock (Kitt Peak, Los Alamos, Saint Croix, Hancock, Mauna Kea). Two are on glacial till (North Liberty, Brewster). Three are on deep unconsolidated sediments (Pie Town, Fort Davis, Owens Valley).

Eight carriage bolts at 45° intervals around the periphery of the foundation plus an external bench mark near the boundary fence are installed at each station. A few times a year, the heights of the carriage bolts relative to the bench mark are measured precisely (typical accuracy, 0.002 inch) with a Wild N3 level and an invar rod. This provides a very exact history of the stability of the foundation in height and orientation. In a couple of instances, the foundation seems to be rising; one suspects that in fact the bench mark is settling.

There are now enough data on the first four sites that we can say something about their behavior:

1. <u>Pie Town</u>: Progressively changing tilt since the initial measurement in February 1988. Net shift was 17" toward the southwest by December 1989. During 1989, a warp developed, and it continues to grow. It is seen as a double sine wave component in carriage bolt height (highs at 160° and 340° azimuth, lows at 70° and 250°). Stidstone's term "potato chip distortion" describes it nicely. The amplitude of the double sine wave had grown to

0.010 inch by December 1989, up from 0.004 inch in July 1989 and <0.002 inch in January 1989. Stay tuned...

2. Kitt Peak: No change since the first measurement in February 1988. Most recent check was in June 1989.

3. Los Alamos: Slowly increasing tilt to the north since initial measurement in May 1988. Net tilt increased to 9" by the end of January 1990. The mystery is why there should be any change at all, since the foundation rests entirely on bedrock. The rock is typical Bandelier Tuff, which LANL has found to possess excellent bearing properties. The tuff is slightly porous and may be compressing unevenly under 850 tons of foundation and antenna; if so, why does it take so long to finish? The foundation was poured over three years ago.

4. Fort Davis: A tilt of 6" developed within a year of the first measurement in January 1988, and it has remained stable in magnitude since. The direction, however, wanders around within the quadrant from west to north. It was toward due west in February 1990.

Some data exist for North Liberty, Owens Valley, and Brewster, but not enough as yet to warrant discussion.

III. Mechanical behavior and stability of antennas

Structural distortions above the foundation affect collimation, axis perpendicularity, and (VLA only) direction of the azimuth axis. Except for quadrupod sag, the pointing model assumes a perfectly rigid structure, i.e. that the various constants are indeed constant. Real antennas, however, writhe about in response to thermal and wind stresses. Unmodelled changes due to loose bolts or asymmetrical tensioning of structural members can cause appreciable pointing errors.

Although in principle some distortions can be deduced from radio pointing data, wind and temperature ordinarily vary on time scales short compared with the time needed to acquire the data, and therefore their effects will largely be washed out. It is far better to make direct structural measurements that are designed to isolate specific effects. Such measurements include, but are not limited to, the following:

1. Quadrupod sag. Determined from theodolite observation of a target on the subreflector. Sag ideally should affect only elevation, but azimuthal components were found in the 140-foot and 300-foot antennas at Green Bank and in the 12-meter dish on Kitt Peak. In each case, there was appreciable hysteresis in the motion. The azimuthal shifts and the

hysteresis went away after looseness in the quadrupod supports was corrected. It is important to look for similar problems in the VLA and VLBA antennas. The effect of azimuthal motion is to introduce an unmodelled term in the collimation error, and the effect of hysteresis is to make the pointing corrections a function of the direction of antenna movement (in both coordinates). We have a single VLA measurement, made in high wind on Antenna 11 in December 1989. Because of the wind, the target jittered badly against the cross-hairs. Nevertheless, the data support two useful inferences: (1) the sag in going from the zenith to the elevation limit is close to 10 mm, which is about what the antenna design predicts, and (2) the lateral motion, if any, is less than 3 mm. The data were too noisy to permit any conclusions about hysteresis. Such measurements are best made when the antenna is in the AAB.

2. Subreflector rotation in the vertical plane. The mounting of the subreflector is designed to rotate slightly about its horizontal axis as the elevation changes, to compensate somewhat for quadrupod sag. A single measurement by Clint Janes and me (on Antenna 21 in the AAB, 10 January 1990) was consistent with design expectations. I expect this is an unlikely source for pointing trouble, but we should remember to check it in specific cases of hard-to-understand errors.

3. Perpendicularity error. There are really two problems here. First, there is the error due to imperfect assembly of the antenna, which can be measured directly by observing star transits with a theodolite mounted on the antenna. This is better than using radio measurements, which do not separate collimation and perpendicularity errors very cleanly. Second, there is a variable perpendicularity error due to unequal heating of the structure supporting the two ends of the elevation axis. This can be evaluated, under various thermal conditions, from tiltmeter data.

4. Direction of the azimuth axis. At the VLA, this is ideally toward the true zenith of the array center, for all observing stations. For the VLBA antennas, it is the direction of the local zenith. Experience with tiltmeters installed over the elevation bearings of VLA antennas 6 and 22 and the Pie Town VLBA antenna has been very encouraging. It appears that the azimuth axis can be monitored almost in real time with an accuracy of about 3" at Pie Town, and hence presumably at other VLBA stations as well. The azimuth axes of the VLA antennas, however, are far more vulnerable to thermal changes; tiltmeter measurements under a range of conditions must be made before we can quantify the thermal effects well enough to allow for them.

5. Temperature effects on collimation. These can be deduced from theodolite tracking of a target on the subreflector, with concurrent temperature sensor readings from points on

the quadrupod legs, all taken with the antenna in a fixed position. Horizontal shifts affect the coefficient of the collimation term, while vertical shifts are equivalent to changes in the zero-point error of the elevation encoder.

IV. Tasks and Priorities

I have treated the pointing battle so far as mostly a single-handed effort. The job is too large to completed by one man in a reasonable amount of time, and more people will have to become involved before long. There are two main stages to the task. First, we have to understand the behavior and limitations of our antennas; this is the investigative phase. Second, we must apply our understanding to the practical improvement of antenna performance; this we can call the development phase. We are still very much in the first stage.

I will close this report with a catalogue of first-stage items which need attention in the near future. Most have already been mentioned. The list includes:

(a) VLA pointing history database. Measured pointing constants from the earliest days of the array down to the present need to be extracted from the records kept in the VLA control room, and put into a PC database in a form convenient for analysis. Once established, the database should be kept up to date.

By whom: Preferably the VLA Operations group, with inputs from CMW. Marc Price may participate.

Time estimate: 10 to 15 man-days, judging from the time I needed to assemble the data for 30 months worth of zenith terms.

When: Start as soon as possible, since the information is of immediate value.

(b) Documentation of pointing model. I should distribute the full derivation of the formal pointing model. Discussion of sources of variation in the coefficients, and likely ranges and time scales of variation, will be included.

By whom: CMW.

Time estimate: 3 to 5 man-days to finish.

When: Rough draft already exists. Not urgent; I will try to get the report out by late spring.

(c) VLBA antenna foundations. Present monitoring of tilt by means of precise levelling should continue, with each station being checked about twice a year.

By whom: CMW or Sidney Smith, as convenient. The N3 level requires skillful handling, and there are some especially tricky things about measuring the VLBA foundations. I don't think we have many people who can be trusted to do it right. Ramon Gutierrez could do an acceptable job with minimal training. Data analysis and documentation will still be by CMW.

Time estimate: Single measurement requires about 2 hours on the antenna, plus another hour or two for data analysis and record-keeping. One person can do the measurement, although it goes faster with two (one to operate the level, and one to move and align the invar rod over the carriage bolts). Call it half a man-day per station every six months, not including travel.

When: We have already been doing this for two years. We should continue until the tiltmeters make level measurements redundant, or as long as the effort is worthwhile for other reasons (for example, keeping track of foundation warps).

(d) VLA observing stations. Selected stations should be measured at intervals with the N3 level to monitor their stability. We need to determine the orientation of the best-fit plane defined by the three pier plates and the deviations of the plates from co-planarity. The best and worst stations, as indicated by the history of the pointing coefficients, should be included.

By whom: VLA antenna group, with participation by CMW. Ramon Gutierrez or CMW can handle the N3. Data will be analyzed by CMW.

Time estimate: 25 to 30 minutes per measurement per station, with a three-man crew (instrument man, rod man, recorder) and cooperative weather. Estimate is based on experience measuring E7 last year. Data analysis and documentation will take about 30 minutes per measurement.

When: Begin by reviewing history of the zenith pointing coefficients, then select a sample of stations to measure. Experience with these will guide planning for further work. Start during the spring of 1990.

(e) Tiltmeter monitoring of azimuth axis (VLA). Tiltmeters are now in place and usable on antennas 6 and 22. The devices, installations, and first results were described in VLA Test Memorandum No. 154 (Clint Janes and Arthur Sittler, December 1989). The most urgent task is to make a series of box runs under a variety of conditions, especially when the sun is low and clear, in order to learn how solar heating affects the direction of the azimuth axis. Temperatures at a number of thoughtfully chosen locations on the structure below the azimuth bearing will have to be recorded concurrently with the box runs. The hope is that we will learn how to model the thermal effects well enough that we can use thermistor data to keep track of the azimuth axis in real time. An important by-product will be a better definition of the 120° azimuth term.

By whom: VLA operations group, with participation by CMW, both for observing and for data analysis.

Time estimate: Difficult to make prior to getting reasonable experience. I think we should collect 10 to 12 hours of data with each of the two antennas, assess carefully, and use the knowledge thus gained to plan further work. A complication in laying out the work is that weather and sun angle are critical.

When: Start as soon as practical, and then give high priority to the job until we have enough information to show the general nature of the thermal effects.

(f) Tiltmeter monitoring of azimuth axis (VLBA). At present only the Pie Town antenna is equipped with tiltmeters, and this probably will remain true for many months. Box runs should be made every few weeks (preferably at night) to track the motion of the foundation. The transverse tiltmeters, in conjunction with the temperature sensors on the structure, can be used to evaluate the effect of temperature differences on the perpendicularity of the azimuth and elevation axes (see item (h) below). We should begin to experiment with using tiltmeter and temperature data in real-time antenna pointing.

By whom: VLBA operations group, with heavy involvement by CMW and, I hope, by Craig Walker in planning and data analysis.

Time estimate: Hard to make without more experience and without closer definition of the detailed objectives of the measurements. We should start by learning how rapidly we can make box runs without serious loss to data quality. We could achieve a great deal if we could have the antenna for about 18 hours twice a month for a couple of months.

<u>When</u>: We should start very soon, because the results will be of immediate value for planning future work.

(g) <u>Quadrupod sag</u>. This needs careful attention, because it has caused problems heretofore with three other NRAO antennas. The vertical component should be measured to verify that it is consistent with design predictions. The presence of a horizontal component, or of hysteresis in any direction, is strong evidence of structural problems that need to be tracked down and corrected. Sag ought to be measured as a matter of course for all VLBA antennas, preferably early on. In the case of the VLA, I suggest that we measure the sag for each antenna when it is in the AAB for regular overhaul. If problems are found frequently, we will have to rethink this rather leisurely style.

<u>By whom</u>: CMW, with Sidney Smith and Bob Stidstone, for the VLBA antennas. The antenna group, with CMW, for the VLA antennas; the theodolite work could be handled very well by Ramon Gutierrez. Data analysis by CMW for both.

<u>Time estimate</u>: Including set-up time, each measurement will require 2 to 3 hours. I expect that each antenna will have to be measured only once.

<u>When</u>: I would like to institute sag measurements as a regular part of the AAB procedure for VLA antennas, starting now. There is no reason for great haste to measure sags in the VLBA antennas, although if problems are present we should find them prior to acceptance from the manufacturer. I suggest making these measurements when we next check the tilts of the foundations, thus avoiding the expense and hassle of extra trips. The measurement at Pie Town ought to be made before the service tower is removed, because it will be useful for installing the theodolite target on the subreflector. Target mounting is the nastiest part of setting up for this kind of measurement.

(h) <u>Axis perpendicularity</u>. The error of perpendicularity of the azimuth and elevation axes has two parts, one constant and one variable. The constant term results from imperfect placement of the elevation bearings, while the time-varying term is due to unequal heating of the structures supporting the elevation bearings. The constant term can be found directly by observing star transits with a theodolite fixed to the antenna. Such observations are necessarily made at night, when the structure should be nearly uniform in temperature, so the variable thermal term should be negligible. Measurement of the variable term is likely to be tricky. Daytime heating of the structure varies continually with relative sun angle, antenna shading, and the passage of clouds. Heat dissipation varies with the strength and direction of the wind. Different parts of the structure have unequal thermal time constants. The only practical sources information useful for real-time antenna pointing are the transverse tiltmeters -- which are affected also by the tilt of the azimuth axis and the constant perpendicularity error. Messy... In practice, the measurement will necessarily be a by-product of the determination of the orientation of the azimuth axis.

By whom: The VLA and VLBA operations groups, with heavy participation by CMW. Data analysis by CMW.

Time estimate: The variable component will not be dealt with here, since it will be extracted from tiltmeter data taken for other purposes. Observations of star transits for determining the constant term will take about 3 to 4 hours per antenna (including set-up time). I expect that each antenna will have to be measured only once. It should be a regular part of the check-out of each VLBA antenna. It is not obvious that every VLA antenna has to be measured; I suggest checking the few that have persistently large apparent errors of collimation (because these may really be the result of perpendicularity problems), and then deciding how best to proceed.

When: We should do the VLBA antennas when we next visit them to make other measurements. I see no great need for haste with the VLA; I suggest measuring a few when convenient during the coming spring.

(i) Thermal effects on collimation. Differential heating of the legs of the quadrupod will in general cause both translation and rotation of the subreflector, which will be seen as changes in collimation. These are probably best determined by calculation from temperatures measured on the quadrupod supports. The rotation will be difficult to observe without special equipment, but the translation can be measured easily and compared with the calculated shift, providing a useful check on the calculation. The theodolite and target set-up are the same as for the sag measurements. In this case, however, one leaves the antenna at a fixed elevation and reads the target against the cross-hairs under different heating conditions on the quadrupod as indicated by the temperature sensors on the legs. I suggest measuring only the VLBA antennas, because the VLA antennas are not fitted with temperature sensors on the legs.

By whom: CMW.

Time estimate: Six to eight hours per antenna. The measurement should be made in clear weather, and the time period should bracket either sunrise or sunset.

When: Concurrently with the other measurements noted above for VLBA antennas.

(j) The "parked antenna anomaly". Durga Bagri has found that the outputs of the azimuth and elevation fine encoders on the first four VLBA antennas do not remain constant when the antennas are parked for extended periods with the brakes set. Instead, they vary continually, and the variations repeat with great fidelity every 24 hours. The changes are most rapid at sunrise and sunset. The details depend on the antenna and the stow azimuth, but the overall characteristics of the variations are much the same from one antenna to another. The range of variation is very large, as much as 25 arc seconds. I see this as Durga's puzzle, with myself as a very concerned spectator. In any event, I don't want to invest time and effort in experiments that depend critically on VLBA encoder readings until we understand the "Bagri Effect".

The reader surely will have noticed the extraordinarily frequent occurrence of my initials in the above recitation of work to be done, much of it quasi-simultaneously. This results not from conceit on my part, but rather from the fact that I am at present the only designated "expert" on this job. I am about to need help (non-psychiatric, one hopes). I will be calling on you gentlemen very soon to discuss the matter...

ADDENDUM I

On 15 March 1990, I had an interesting conversation with Pat Lewis about the anomalous behavior of certain VLA observing stations. After our discussion, he wrote down the main points he recalled about the early history of the ones that stuck in his mind. It is curious that the two "worst" stations noted in the attached memo both figure in his short list. Here is what Pat wrote, verbatim:

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Track from CN-7 to CN-9 (N14 - N16 - N18):

This area was often under water, especially the area immediately (100 ft) north and south of CN-9. Water often was over the ties for more than 10 months. We installed a French drain from CN-7 to CN-9 with a sump at CN-8. Water drains into the sump and is pumped out with an electric submersible pump.

BN-6 (N24):

I remember a problem with the concrete at this station. To the best of my recollection, the concrete underground piers were OK, that is, the concrete samples (test cylinders) tested within specifications. The tie beam concrete, however, did not meet specifications. A core was taken and tested and the decision was made to accept the concrete as poured.

BW-9 (W36):

This station is at the bottom of a small hill and when it rains, much of the run-off accumulates at and around BW-9. There is not much drainage area.

AW-7 (W56):

This station is built rotated slightly in a clockwise direction looking from the top. The error was discovered after the piers and tie beams had been poured.

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ADDENDUM II

Ken Sowinski and Clint Janes have reminded me that something like the "Bagri effect" occurs at the VLA (see page 9 of VLA Test Memorandum No. 154). The array was parked with the brakes set over the Thanksgiving holiday last year, but with continuous monitoring of the encoders on all 27 antennas. As with the VLBA, there were large (20 to 30 arc seconds) indicated changes in indicated elevation (although not in azimuth), and the variations were most rapid around the times of sunrise and sunset. Sowinski reports that Mike Kesteven says that similar effects have been found on the Australia Telescope.

During the Thanksgiving break, the tiltmeters on Antenna 22 were also monitored continuously, and changes as large as 40 arcseconds were seen in the cross-yoke direction. The changes correlate closely with ambient temperature. Janes and Sittler (Test Memo No. 154) show that the thermal expansion of the yoke can account quantitatively for the behavior of the tiltmeters. They suggest that thermal effects might also explain the variations of the elevation encoder outputs. I think an engineering analysis of the thermal behavior of the structures is in order. Perhaps we can borrow Lee King back from the GBT...

These anomalies simply must be understood. Is it significant that the encoders for the VLA, the VLBA, and the AT all came from the same manufacturer -- who is going out of business?