6 arcsecond Pointing at VLA?

VLA Test Memo 218

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Updated Version, April 21, 1999
(Disregard Previous Version)

Summary:

Test memos to date about VLA pointing have assumed the hardware is working correctly. In this report, we relate how various hardware problems can and are degrading VLA pointing. We convey a plan to correct the problems and possibly improve pointing to 6 arcsecond. The performance of one VLA antenna, Antenna 9, indicates that the tracking (dynamic pointing) performance can be as good as 5 arcsec rms.

6 Arcsecond Goal

Forward gain and thus signal amplitude varies as a function of pointing error which in turn introduces errors in flux scaling and calibration. Gain variations are minimized by maintaining pointing error under 10% of the width of the primary beam. The FWHP at Q band on the VLA is 60 arcseconds so that we would like to keep pointing errors under 6 arcseconds as explained below. A driving force in justifying a major upgrade to the VLA instrument is the efficacy of operation at K (26 GHz) and Q (46 GHz) bands where the beam widths demand accurate pointing.

The VLA pointing measurement procedure involves measuring the position of 40 to 80 celestial objects, whose positions are known very accurately, by finding the centroid of five points, four at the expected half power of the measurement and one on the expected bore sight. The measurement of each object takes two minutes, five seconds. Spending more than the minimum time on any one object is wasteful as the SNR for each solution is very high and repeated measurements of the same object simply replicates the same results.

There are currently 12 coefficients available in the pointing look-up corrections, but only a subset of these 12 are corrected in a typical pointing run. Pointing run results are currently displayed on a bar graph. The results show a running average of recent tests.

Vivek Dhawan recommends establishing two pointing specifications:

1. The first would be pointing without reference corrections; that is, "pointing with all known systematic effects encapsulated in the a priori model, but NOT using just-in-time corrections." Called "blind pointing" by Rick Perley, this specification is the best fit to residual errors measured by the pointing measurement procedure described earlier. For the VLA, 6 arcseconds, as specified above, is adequate for current use, though 1/20 to 1/30 beamwidth isrequired for mosaic-ing. 6 arcseconds is clarified to mean the quadratic sum of the rms pointing residuals in El and AZ as measured by the pointing tests in current use measured at night under

the best conditions. How long the antenna holds 6 arcseconds needs to be studied and specified, but is not part of this report.

2. The second or "best pointing specification would include, a) use of recently derived full set of coefficients and b) residuals examined AFTER reference pointing. Pointing errors of a couple of arcseconds can be achieved in this manner but the errors are a function of separation between source and calibrator, time after measurement, antenna, location on the sky, etc. How the functions change the pointing error needs to be better understood, but is not part of this report.

The "360 Degree Oscillation" Problem

Control cables in the VLA antenna wrap up in azimuth; the telescope motion is thus limited to 540 degrees. But 540 degrees of wrap up means there is a 180 degree overlap in azimuth position where the on-line system must know if the telescope is approaching the clockwise limit of motion or the counter clockwise limit. A mechanical switch that rotates with the yoke provides the "which side of wrap up" information. If the mechanical switch, commonly referred to as the "flipper", fails or is bumped into the wrong position, the on-line system becomes confused and the absolute encoder position will appear to oscillate 360 degrees. The telescope itself does not oscillate, but the data will be flagged and the telescope becomes unuseable.

At the VLBA, the encoder electronics provides for 720 degrees of absolute position encoding instead of a "flipper." An additional bit will be added to the VLA electronics to eliminate the flipper. Also, a linear actuator is being installed during overhauls to eliminate the troublesome limit switch mounting ring.

The "512/1024" Tracking Problem

The absolute position encoders on the VLA use a conventional 3-phase synchro for the most significant bits and a multi-pole resolver for the least significant bits. A synchro is a rotary transformer with a single primary winding on the rotor and three stationary secondary windings spaced 120 degrees apart. A resolver is a type of synchro with at least two stator poles spaced 90 degrees apart. The Farrand Inductosyn (tm) resolver used at the VLA is a high precision 512 pole device. An electronics package converts analog signals from the syncro (coarse encoder) and from the Inductosyn resolver (fine encoder) into digital position information. The LSB of the combined 20-bit result indicates 1.25 arcsecond movement.

Tracking tests performed routinely on each VLA antenna identify periodic encoder errors. Periodic errors on Inductosyn resolvers are common as a function of one times the number of poles, the so-called "512" error, and two times the number of poles, or the "1024" error. In the tests, called PN3DB, a source is tracked with an offset so that a periodic error in the encoder will show up as a source amplitude variation. Figure 1, an example of a PN3DB test, has four columns, AZ1, AZ2, EL1, and EL2. AZ1 is the amplitude in arcseconds of an azimuth encoder error that varies as the number of poles or 512 cycles per fine encoder resolution. AZ2 varies as twice the number of poles or 1024 cycles per resolution. EL1 and EL2 are comparable errors for the elevation encoder. The encoder errors cause antenna pointing errors.

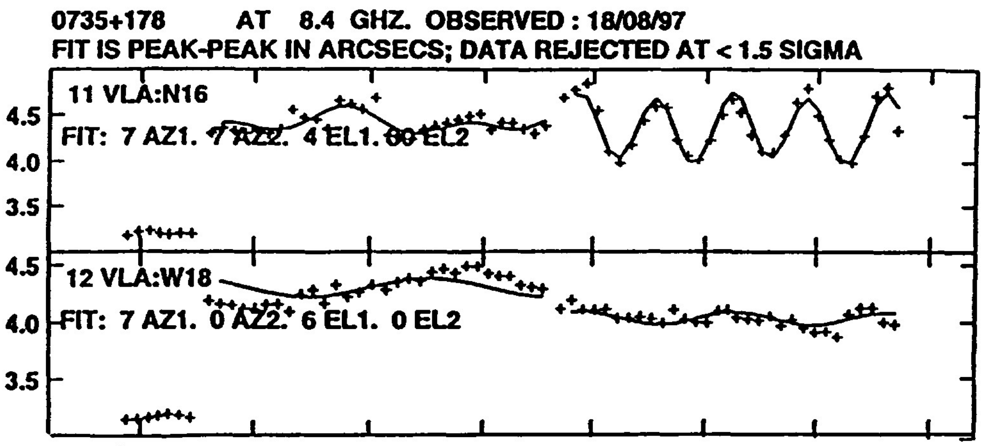

Figure 1 - Example PN3dB Test Results

Comparison of the amplitudes of the two sine wave outputs of a resolver provides the absolute encoding; the amplitudes vary as a function of position but 90 degrees out-of-phase. Each cycle of the sine wave corresponds to one pole on the resolver. Because the fine encoder has a very weak coupling between the rotor and stator, the small output signals must be amplified. If there is a mismatch in amplifier gains, the maximum amplitudes of the two signals will differ, and a periodic encoder error will be introduced. The resulting position error varies for every cycle of the sine wave, hence the name "512" error. The "1024" error is introduced by a DC offset between the two sine wave outputs, see Figure 2.

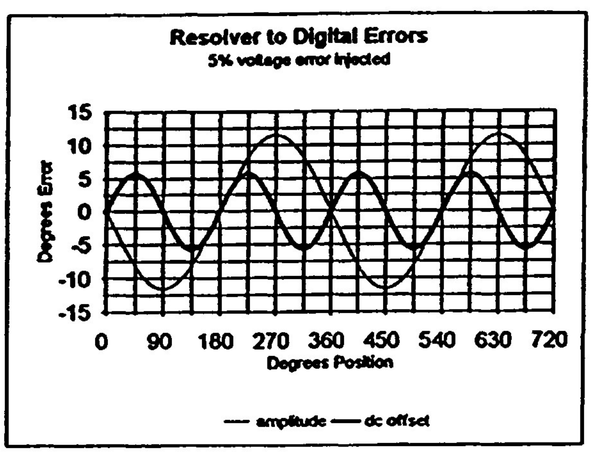

Figure 2 - Simulated 512/1024 Errors

To correct the "512" tracking error, the maximum amplitudes of the sine waves must be carefully adjusted to be equal at a scale of 1.5 microvolts / arcsecond of error. The amplifiers in the current electronics package drift with time and temperature so that adjustment must be made as often as twice per year with seasonal changes. For both "512" and "1024" errors, correction is not attempted until PN3DB tests demonstrate an error exceeding 6 arcseconds; the threshold was 10 arcseconds until Q band receivers were installed.

A new encoder electronics design, initially proposed by Dusty Clark of the UA/SAO MMTO in Tucson, uses monolithic resolver-to-digital (R-D) converter chips. Ron Weimer of NRAO modified Clark's design and built a circuit using the R-D chips for the VLA encoders. The new design should dramatically reduce the 512/1024 periodic encoder position errors by having operations on both sine wave outputs on a single chip providing better temperature stability and equalizing of any amplitude variations. Bob Broilo has been assigned to develop a two-axis prototype of the Clark/Weimer circuit for testing on telescope by July '99.

A vendor has offered to construct the new design at a cost of $150,000, half the cost of installing an older electronics package currently used on the VLBA. We can also develop and build the design internally which will allow us to expand the capabilities of the new encoder electronics system, address RFI issues, and save half the cost proposed by the vendor. The typical cycle to install a new design on the VLA antennas is four years, setting completion date for updating all 28 antennas at December 2003.

Three bits of resolution can be added to the prototype design to determine if the current 20 bit limit on position encoding is in the encoder itself or in the supporting electronics.

The "1.2 Degree Oscillation" Problem

The coarse encoder or synchro on the VLA position encoders counts revolutions of the fine encoder. To do so, the LSB (least significant bit) of the coarse encoder overlaps the MSB (most significant bit) of the fine encoder. A phase adjustment must be made to synchronize the operation of the overlap bits; the adjustment can vary with time and temperature. An overlap bit error (bit 13 error) causes the antenna to move a degree off source.

To reduce the problem with the overlap bits, the synchro will be replaced with a higher accuracy resolver and the algorithm of the overlap bits will be changed to smooth synchronization. The improved stability of the new Clark/Weimer electronics design will also help. As well, the electronics can be built so that the phase relationship of the overlap bits can be altered under command from the on-line system to provide quicker recovery from an error should one occur.

Encoder Mechanical Problems

There are several mechanical problems with the absolute position encoders. The first of these problems is simply a maintenance issue. The internal bearings within the encoders have reached the end of their useful life. Encoders with defective bearings require excessive torque to turn and can introduce pointing errors of several arcseconds. These bearings are currently being replaced during the antenna overhaul cycle at a rate of eight antennas per year with a completion date of December 2003. To date, approximately half of the antennas have had their encoder bearings replaced at a cost of $3000 dollars per telescope. Because of the impact on pointing performance and cost, an effort to protect these bearings in the future is strongly indicated. In particular, the elevation encoders have been subjected to adverse environmental conditions. These encoders are located within a protective box, but it is not adequately sealed from the elements. Both moths and sand have been removed from the encoder bearings. These foreign objects greatly reduce the service life of the bearings.

Poor mating between the encoders and the elevation drive axles also contributes significantly to the pointing error. A flexible coupling is used to reduce the forces induced on the encoder from misalignment with the axle. Tests on new encoders showed that the flexible couplings currently in use can compensate for misalignments of only 0.006" laterally and 5 arcminutes in angle. The encoders were initially aligned to this precision, but this precision has not been maintained. In the current elevation encoder installation, it is impossible to maintain this alignment. The encoder mount and enclosure housing are mechanically coupled together and the housing is used as a step.

The problems with encoder bearings and couplings clearly demonstrate the need for a redesigned elevation encoder mount and enclosure. This mount should be entirely decoupled from the enclosure. The enclosure should be sealed in such a way to protect the encoder from insects and sand. Modern electroformed bellows couplings should also be used to reduce the effect of encoder alignment. It may even be possible to eliminate the Kerksite-filled box that currently connects the axle to the encoder. This Kerksite connection often gets loose and requires replacement; such was the problem with Antenna 23 which introduced a pointing error in excess of 20 arcseconds. The estimated cost of a redesigned elevation encoder mount and enclosure is $1400 per antenna.

It may be necessary to improve the azimuth encoder coupling, too, if tests show that the cable wrap up is interfering with the encoder pole or if compliance is found in the pole or mount.

Azimuth Bearing

Four azimuth bearings have been replaced since discovery of bearing damage in 1992. Of the four telescopes receiving new bearings, all showed pointing improvement on the order of 6 arcseconds or better after the bearing swap. Four to five more telescopes show pointing errors symptomatic of azimuth bearing problems; these bearings appear bad from tests and are scheduled for replacement. It is thought by some that the bearing damage is a result of inadequate lubrication, but that we have an adequate maintenance program in place now that reduces the likelihood of further bearing damage. Grease samples and dynamic bearing measurements support this claim.

Antenna 9, the very best pointer, has a new Rotek bearing, while Antenna 23, one of the worst pointers, also has a new Rotek bearing. Tests of the Antenna 23 bearing show movement, but not enough to cause the pointing errors being measured.

Azimuth bearings are replaced at the rate of one per year, so the 4 - 5 additional bearings thought to be bad will be replaced by December 2004 at a cost of $45,000 each if a new bearing is necessary or $20,000 each if a refurbished bearing will suffice.

The Disclaimer

Preliminary results from photogrammetry tests on Antenna 13 show non-repeatability in the primary panel positions indicating possible compliance in the backup structure. Though Antenna 9 apparently has the stiffness to support 6 arcsecond pointing accuracy, the tests on Antenna 13 may indicate that compliance of other antennas is insufficient to support the goal. Some telescopes may require intensive study to find the source of pointing problems and the cost to correct may prove prohibitive. Though it may be necessary to compromise the 6 arcsecond goal on some antennas, the projects outlined in this memo are expected at least to improve pointing in all cases.

Impact of Servo on Reference Pointing, Response to Wind

A student study group is reviewing the VLA servo design to determine if the frequency response can be improved without jeopardizing the stability. Based on the group's report and prototype, we may propose an upgrade to the servo system. Such work could be in place by December 2004 at a rough guess cost of $4000 per antenna. Improved response could lessen the time to do offset pointing corrections and stiffen the response to wind.

Response to Temperature Gradients

Tests show pointing errors of 20 arcseconds or more as a result of solar heating. These are slow diurnal variations that are currently corrected for by reference pointing. The tests show, however, that the temperature effects are predictable and repeatable leading to speculation that the pointing errors could be removed with expanded pointing coefficients on the on-line computer. The coefficients would be a function of the arm where the antenna is situated and the measured ambient temperature gradient.

Both Bagri (96) and Janes (89) report on large pointing variations with the antennas stationary and shut down as occurs over Thanksgiving and certain other holidays. This phenomenon may be symptomatic of a problem in the encoder or coupling and should be re-measured after the encoder coupling prototype is in place.

Conclusion

Figure 3 (page 7) shows the quadratic sum of AZ and EL pointing errors for VLA antennas based on an average of the most recent six pointing runs. All but one of the antennas has a quadratic sum worse than 6 arcseconds. Annotations show problems thought to be contributing to pointing errors on antennas with errors greater than 8 arcseconds.

The following chart summarizes the contributors to pointing error in the order of priority.

Contributor	Current error	Error Goal	Cost (M&S only)	Target
AZ bearings	>10 arcsec	<3 arcsec	$225k-	Dec '03
Encoder bearings	>10 arcsec	<0.5 arcsec	$45k	Dec '03
360 deg. osc.	downtime	0	$6k	Dec '02
1.2 deg. osc.	downtime	0	incl. in next item	Dec '03
512/1024 Tracking	6 arcseconds	<0.5 arcsec	$150k-	Dec '03
EL coupling	>20 arcsec	<0.5 arcsec	$40k	Dec '03
AZ coupling	?	<0.5 arcsec	?	
Other mech. prob	unknown	<1 arcsec	?	
Frequency response	f(wind)	half?	$120k	Dec '04
Temp. gradients	>25 arcsec	half?	$0	?

Antenna ID	Azimuth	Elevation	Quadratic Sum/Az & El	Comments
9	3.27	3.60	4.86	New Rotek
3	2.40	5.62	6.11	
4	4.23	4.68	6.31	
14	3.62	5.18	6.32	
26	3.23	5.58	6.45	
20	3.45	6.08	6.99	
21	3.87	6.02	7.15	New Kayden
12	3.25	6.47	7.24	
2	3.72	6.23	7.26	
22	3.75	6.35	7.37	
6	4.63	5.88	7.49	
5	3.13	6.82	7.50	
28	4.05	6.33	7.52	
19	4.40	6.40	7.77	
13	3.15	7.23	7.89	Needs El encoder bearing
25	3.10	7.37	7.99	Needs 10' Az bearing
10	5.22	6.38	8.24	
11	3.20	7.65	8.29	
1	5.67	6.40	8.55	Needs Az encoder bearing, has refurbished Kayden
8	5.28	7.03	8.80	Az encoder bearings, needs 10' Az bearing?
27	6.17	7.05	9.37	Needs Az & El encoder bearings
7	2.53	9.92	10.24	
15	7.02	7.48	10.26	10' Az bearing needs replaced
24	4.35	11.55	12.34	Needs El encoder bearings
17	7.02	10.33	12.49	10' Az bearing needs replaced
23	5.27	12.20	13.29	Elevation needs updated constants, has new Rotek
16	4.43	12.65	13.40	
18	6.95	11.65	13.57	10' Az bearing needs replacement

Figure 3 - X-Band Pointing Package

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