VLA Antenna Azimuth Bearing Tests

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Very Large Array

VLA Test Memo #195

Introduction

A condition monitoring program for the VLA antenna azimuth bearings was established in 1992, after the azimuth bearing for antenna 21 failed. Replacing an azimuth bearing is very involved and requires much planning, personnel, and equipment, but prevents a possible field failure. This report attempts to determine the status of each bearing based on the findings of this condition monitoring program to date. This will help determine which azimuth bearings need to be replaced and prioritize the replacements.

Data for each VLA antenna azimuth bearing were collected from 1992 through 1995. The complete array-wide data were collected from four tests.

1. **Slop values** are differences in axial bearing movements between clockwise (CW) and counterclockwise (CCW) rotations[1] measured with a dial indicator.
2. **Grease samples**, visually inspected or sent for analysis, yield the amount of small particulate iron in grease from each bearing.
3. **Vibration analysis** measures vibrations from impacts caused by damage in the bearing.
4. **Pointing errors** may indicate problems in the azimuth bearing, especially if they are chronic.

We must establish the validity of the data for each test to interpret results and make conclusions based on them. We now have several years of consistently collected data and two new bearings to establish baselines. If results are repeatable year to year and follow expected behavior with a new bearing, then those results are probably valid and we can draw conclusions based on them.

Slop Data

"Slop" is hysteresis in the vertical position of the upper bearing race in measured from the lower. To measure it, two gage micrometers are mounted on the lower bearing race and set to measure up and down movement on the upper bearing race. The micrometers are set 180° apart from each other. A computer records the position measured by the gages at 1° intervals. The antenna is rotated completely around in one direction and then the other.

We assume that *spalling*, or gouging, on the bearing race will allow the upper part of the bearing to move with respect to the lower part. Hopefully, this will show up as a difference between the gage readings in CW and CCW movement.

Three array-wide slop surveys have been taken. In 1992 we measured only a 360° section of most azimuth bearings. This proved inadequate and the 1993 and 1995 tests were performed from CW limit to CCW limit.

Grease Sample Data

In 1991 through 1993, five array-wide surveys of azimuth bearing grease were collected. Three were sent to an outside laboratory to determine the percentage by weight of iron. Unfortunately, large flakes of metal are filtered out of the grease before analysis and do not contribute to the overall percentage. It is these flakes that are considered signs of spalling of the bearing race. The flakes can be easily collected with a magnet while rinsing grease samples with solvent, so we have ceased to send array-wide surveys out for analysis. There has been sporadic visual inspection, which does not result in an objective measurement. It certainly indicates metal loss in certain antennas and can reinforce the indications of the other tests.

After the antenna 21 failure, the antennas were greased more often and with more grease. The percentage of iron found in the grease is generally lower each year, probably because this enhanced lubrication is diluting the mixture.

Vibration Analysis Data

These data were collected by SKF condition monitoring using a transducer that measures vibration in Gs. The device to be measured is run for 160 seconds and then the data is Fourier transformed to get frequency information.

Problems such as spalling, worn gear teeth, and unbalanced loads or shafts will have a characteristic frequency. This frequency is determined by the rotational speed of the device being measured. Bearings measured with this instrument typically have higher rotation rates than the VLA azimuth bearings.

In the case of the azimuth bearing we are looking for a movement or low frequency vibration due to a defective roller, metal flake, or defect on the bearing surface. We can estimate this frequency at full slew as 0.07 to 0.1Hz.[2]

Unfortunately, the SKF instrument puts a high pass filter of 5Hz on the vibration transducer, which limits detection to high frequency components of the defects. A custom vibration analysis optimized to look for VLA azimuth bearing defects may yield better results.

Pointing Data

The slop tests show a movement of the upper bearing race with respect to the lower race. This movement seems to be dependent on the direction of rotation. Since the antenna yoke is affixed to the upper bearing race, and the elevation encoders are mounted to the yoke as a reference, slop can manifest as an elevation pointing error. Likewise, an azimuth pointing error can occur if one corner of the bottom of the yoke moves, twisting the top of the yoke in azimuth. The on-line software to correct the pointing does not consider vertical azimuth hysteresis, and the pointing error will appear in both Pre-fit and Post-fit RMS values. The error will be repeatable but localized to certain azimuth positions.

We can estimate the amount of pointing error. This value will not predict the Pre-fit and Post-fit RMS values because of the localization of the errors in azimuth, and the other factors contributing to the pointing errors. A typical local slop value for a "bad" azimuth bearing is 0.01". Trigonometry shows that this can cause 20 seconds of arc elevation error or 13 seconds of arc in azimuth. The worst antenna has up to 0.03" slop, or 1 minute of arc elevation, 40 seconds of arc azimuth.

If there is a correlation between antennas with lots of slop and antennas that are repeating bad pointers, then pointing data can help determine azimuth bearing status. We may be able to show that a new azimuth bearing will contribute significantly to better pointing on certain antennas.

Test Data

All the collected data in processed form can be found in the Appendix.

Interpreting the Data

There has been only one azimuth bearing failure, antenna 21 in the spring of 1991. Unfortunately, there are no slop or vibration data from before the failure to tell us how relevant these tests are, or how to interpret them. But, it is clear that an antenna that is emitting large flakes of metal needs attention. For example, the antenna 9 azimuth bearing had large flakes of steel in the grease. When this bearing was taken apart after being replaced, there were large areas of spalling. Similarly, large steel flakes (bigger than 1mm) were collected from the grease of antenna 21 soon after failure. Thus, metal emission is the most important indication of a bad bearing.

Unfortunately, we have no objective measurement of metal flakes in the grease, and we need a method of prioritizing these antennas. We can use the other tests once we establish the usefulness of their results.

One way to check the usefulness of these tests is by consistency. Since the azimuth bearings are large steel objects that move slowly, we will assume that they change little over the span of a year. Thus, a test that gives consistent results each year is probably more useful than a test that yields random data. The repeatability of the data was objectively measured by cross-correlating data between testing dates and measuring the linear dependence. A linear regression was used to estimate the dependence. To illustrate this, some antennas from 1992 to 1993 are plotted in Figure 1, with the calculated regression line.

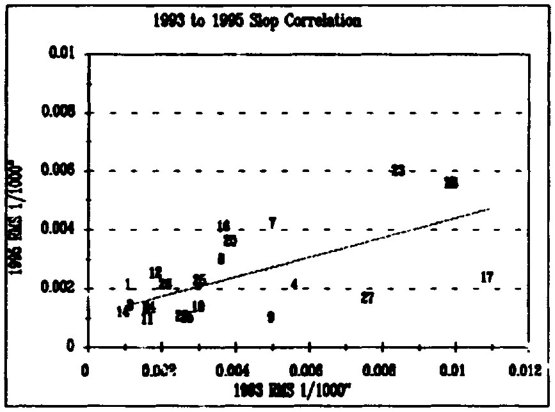


Figure 1: Correlation between 1993 and 1995 data

To measure how well the regression line fits the data, I used a value generated by the regression algorithm called R^2. An R^2 of 0 indicates a very poor fit and 1 indicates a perfect fit. The example above yields an R^2 value of 0.42.

If we calculate a linear regression on two sets of data from a test taken the same way at the same time, it produces a typical "good fit" R^2 value that accounts for the intrinsic variability inherent in the test. This value can help judge the fit between different tests and different dates. We have two opportunities to get this typical R^2 value with data already collected:

1. Slop data is always recorded twice for each antenna.
2. Two grease samples for each antenna during February 1992 were sent for analysis.

After performing regression, we obtain $R^2_{Slop} = 0.65$ and $R^2_{Iron} = 0.60$. These values represent typical linear fits for their corresponding tests, and we can now compare test dates and methods.

Table 1 summarizes the R^2 results of the regression analysis between testing dates.

Table 1 R^2 values from year to year

	1991 to 1992	1992 to 1993	1993 to 1994	1994 to 1995
Pointing		0.49	0.42	0.58
Vibration		0.01	0.02	
Slop		0.13		0.42
Iron	0.48	0.48		

These R^2 values indicate that pointing RMS values and iron content are fairly consistent from year to year. Slop is less repeatable, especially from 1992 to 1993, which is not unexpected because most of the measurements in 1992 were not done limit-to-limit.

The vibration analysis has no repeatability so far. The vibration data were taken at different places in the antenna's rotation each year, with different circuitry, and the instrument cuts off the relevant low frequency information. Thus, the vibration data collected so far cannot be used to determine the status of an azimuth bearing.

We can further check to see if a test behaves as expected when a new bearing is installed. When we install a new bearing, we expect it to have little slop, no iron in the grease, improved pointing and reduced vibration.

Antenna 21 had its bearing replaced in the fall of 1991 and antenna 9 in the summer of 1994. The 1995 data ranks antenna 21 with the lowest slop, and antenna 9 is tied for third lowest. Antenna 9's slop dropped from 0.005" RMS to 0.001" RMS with a new azimuth bearing. The grease from antenna 21 contained 1.56% iron in June 1991, and grease from the new bearing contained only 0.05% iron in March 1993. Therefore, the slop and iron content results are consistent with those expected from new bearings.

Pointing data for antenna 21 before failure were collected differently, and I cannot draw any conclusions about this antenna. However, there is consistently gathered pointing data for antenna 9 from before and after the bearing was installed. The post-fit RMS values for antennas 7 - 11 are summarized in Table 2.

Table 2 Post-fit RMS, Azimuth and Elevation averaged, arcsec.

ant	2/92	5/92	7/92	9/93	11/94	4/95
7	8	-	7.45	10.9	10.9	11.2
8	8	8.5	-	7.15	7.35	8.65
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	8	8	5.1	5.7	6.25	6.7
11	7.5	7.5	3.65	6.8	5.7	7.4

* New azimuth bearing

The post-fit RMS for antenna 9 certainly dropped after the summer of 1994. This is evidence that a new azimuth bearing will improve pointing, but these errors can have many different causes. For example, look at antenna 10 after 5/92. Most of the antennas dropped substantially for the 7/92 pointing run, but rebounded by 9/93. Antenna 10 still has lower Post-fit RMS values.

Results

Table 3 compares the top five bad azimuth bearings for each test except vibration analysis. The "Hicks" column is a ranking by pointing put together by Phillip Hicks, for comparison.

Notice that a bearing that performs badly will generally do so from year to year, and from test to test. We can make a list of the overall top five worst azimuth bearings by counting the number of times each antenna appears in Table 3, ignoring two of the pointing columns to avoiding weighting pointing too much. This is done in Table 4.

Table 4 Overall top five worst bearings

antenna	number of times appearing in Table 3
23	8
1	7
18	7
7	5
17	4

We have many samples of flakes collected from various antennas, and these are summarized in Table 5. The amount of metal collected cannot be used for meaningful comparisons because of variability in the way the azimuth bearing was cleaned since the last greasing.

Table 5 Metal flakes collected from azimuth bearings

date	antennas
3/91	16, 17, 18, 21, 23, 28
4/93	9
1/95	16, 17, 23
2/95	1, 13, 15, 16, 17, 28
3/95	23

Table 3 Top five worst antennas for each test

Slop			Iron			Pointing				
92	93	95	91	92	93	92	93	94	95	Hicks
1	17	23	1	23	1	23	1	23	18	7
23	28	18	23	18	18	1	23	1	1	23
17	18	28	4	1	23	8	17	18	7	18
18	23	7	15	16	15	18	7	13	17	1
16	7	16	28	22	9	7	24	17	2	17

Conclusion

The azimuth bearings for antennas 1 and 23 perform badly, and are still losing metal. These bearings may fail, and there is good evidence that their pointing will improve if the bearing is replaced. I recommend that we replace the antenna 23 azimuth bearing in the summer and fall of 1996, and then replace the antenna 1 bearing the next year.

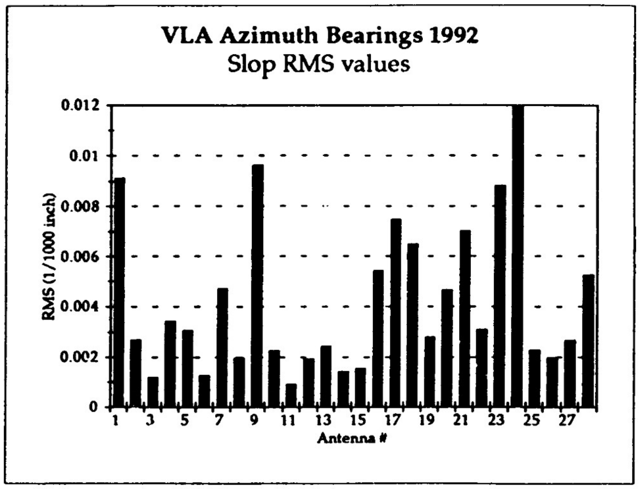
Antenna 17 is a bad pointer and is losing metal, which indicates that it is a candidate for replacement in the future. Antennas 18 and 7 perform badly and their grease shoud be checked to see if they are still losing metal. By the time the bearings in antennas 1 and 23 have been replaced, we will have 2 more years worth of data and will be able to prioritize these antennas more clearly.

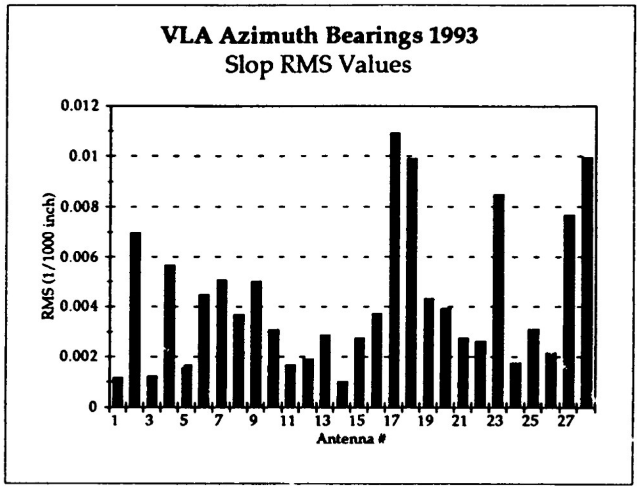
Endnotes

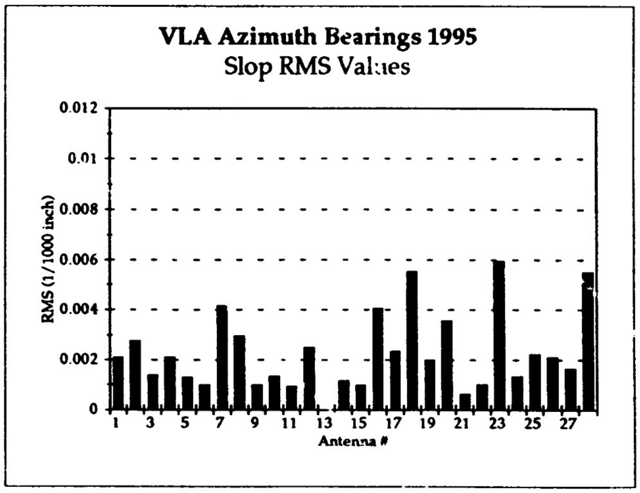
1. Broilo, Robert M., VLA Antenna Azimuth Bearing Tests 6/1/92-6/24/92. NRAO. Socorro NM: 1992.

2. Full slew rate is 40° per minute, or 9 minutes per revolution. There are 161 rollers, oriented so that 80 roll along one pair of bearing races, and the other 81 roll along the other. The rollers move at 1/2 the rotational velocity of the bearing. Thus, the period of rollers hitting defects on the bearing surface is 13.5 seconds. Similarly, a defective roller will revolve every 6.5° and cause movement every 9.8 seconds.

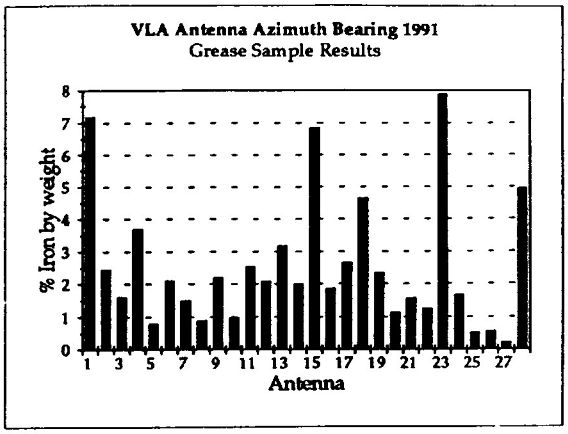
Ant	Slop RMS 1992	1993	1995
1	0.0091	0.0012	0.0021
2	0.0027	0.0070	0.0027
3	0.0012	0.0012	0.0014
4	0.0034	0.0057	0.0021
5	0.0031	0.0017	0.0013
6	0.0012	0.0045	0.0010
7	0.0047	0.0051	0.0042
8	0.0020	0.0037	0.0030
9	0.0096	0.0050	0.0010
10	0.0023	0.0030	0.0013
11	0.0009	0.0017	0.0009
12	0.0019	0.0019	0.0025
13	0.0024	0.0029	err
14	0.0014	0.0010	0.0012
15	0.0015	0.0027	0.0010
16	0.0054	0.0037	0.0041
17	0.0075	0.0109	0.0023
18	0.0065	0.0099	0.0055
19	0.0028	0.0043	0.0020
20	0.0047	0.0039	0.0036
21	0.0070	0.0027	0.0006
22	0.0031	0.0026	0.0010
23	0.0088	0.0085	0.0060
24	0.0120	0.0017	0.0013
25	0.0023	0.0031	0.0022
26	0.0020	0.0022	0.0021
27	0.0027	0.0077	0.0016
28	0.0052	0.0100	0.0055


VLA Azimuth Bearings 1992
Slop RMS values

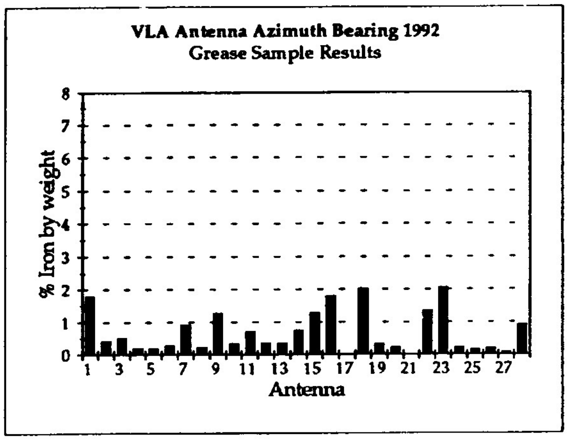

VLA Azimuth Bearings 1993
Slop RMS Values


VLA Azimuth Bearings 1995
Slop RMS Values

Iron % by weight				2/92		
antenna	3/91	5/91	6/91	sample1	sample 2	3/93
1	13.3	2.99	5.21	1.79	1.28	3.91
2	2.07	3.23	2.08	0.41	0.38	0.19
3	2.96	0.99	0.82	0.51		0.14
4	8.29	2.26	0.57	0.19	0.26	0.18
5	0.87	0.98	0.47	0.18	0.22	0.085
6	2.46	2.39	1.44	0.27	0.2	0.14
7	1.14	1.96	1.4	0.92	0.39	0.45
8	0.46	1.21	0.94	0.22	0.48	0.32
9	2.49	2.4	1.72	1.27	0.23	0.48
10	0.73	1.21	0.99	0.33	0.27	0.15
11	1.66	3.37	2.54	0.69	0.6	0.24
12	3.38	1.81	1.06	0.35	0.58	0.12
13	4.19	2.63	2.69	0.36	0.19	0.18
14	2.09	2.72	1.15	0.74	0.17	0.16
15	7.21	8.62	4.67	1.27	1.97	0.7
16	3.12	0.95	1.48	1.79	0.52	0.19
17	2.19	3.1	2.66			0.26
18	1.66	6.08	6.16	2.02	2.24	2.29
19	4.28	1.66	1.04	0.31	0.2	0.25
20	1.23	1.27	0.92	0.22	0.32	0.011
21	1.21	1.93	1.56	new	new	0.052
22	1.04	1.74	0.97	1.35	0.87	0.15
23	10.5	10.6	2.52	2.07	3.29	2.28
24	2.87	0.57	1.55	0.22	0.26	0.43
25	0.32	0.71	0.47	0.15	0.15	0.15
26	0.33	0.69	0.63	0.19	0.17	0.26
27	0.14	0.35	0.15	0.078	0.037	0.033
28	6.19	5.42	3.22	0.91	0.64	0.004



VLA Antenna Azimuth Bearing 1991
Grease Sample Results



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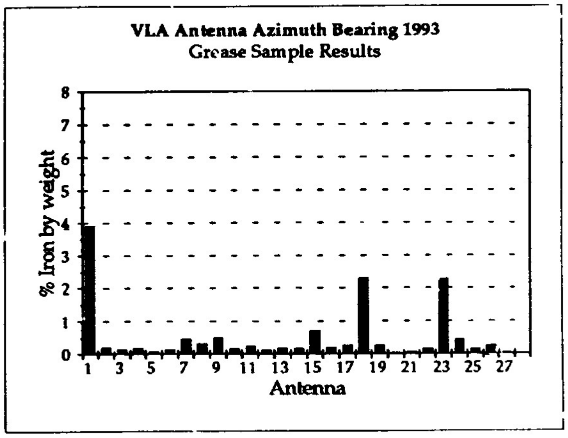
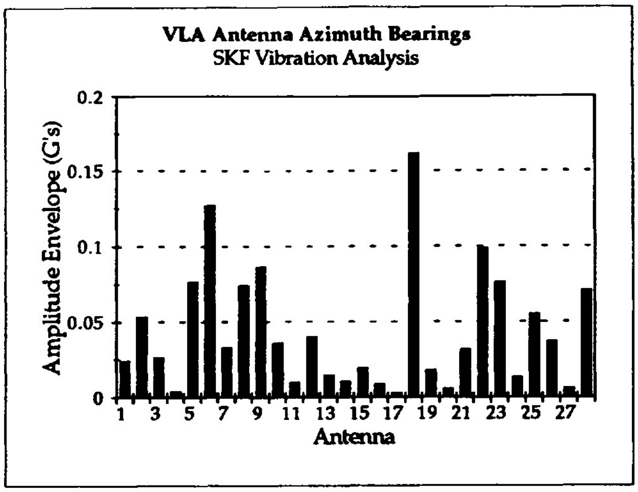
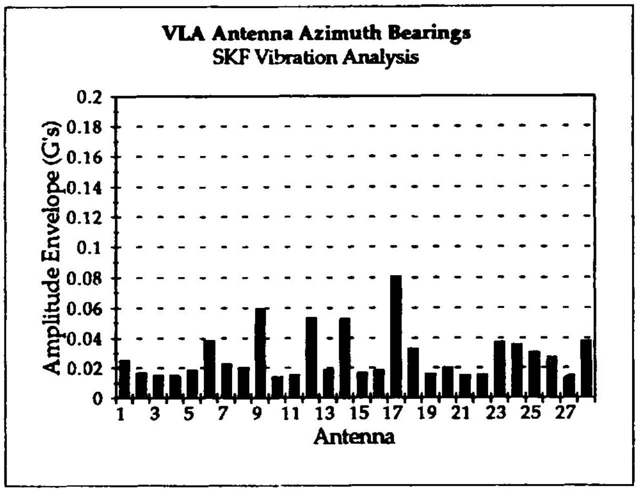
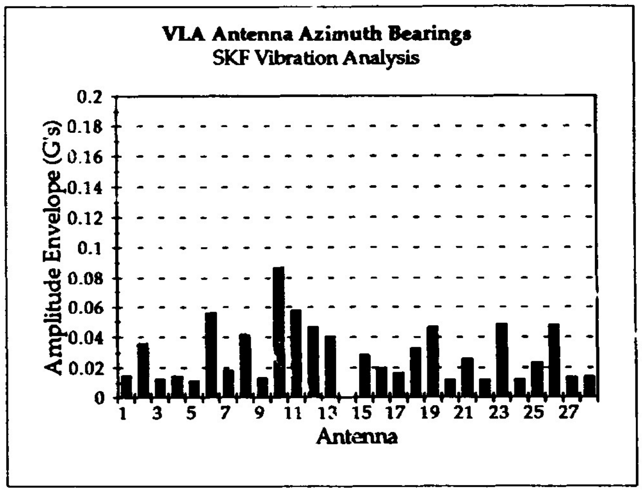


VLA Antenna Azimuth Bearing 1993
Grease Sample Results

	SKF Sep 93	Apr 93	May 94
1	0.02537	0.02445	0.01516
2	0.01664	0.05337	0.03576
3	0.01488	0.02617	0.01249
4	0.01526	0.00407	0.01449
5	0.0185	0.07666	0.01173
6	0.03824	0.12717	0.05607
7	0.0226	0.03265	0.0184
8	0.01988	0.07416	0.04205
9	0.05942	0.08659	0.01344
10	0.01431	0.03579	0.08688
11	0.01555	0.00991	0.05765
12	0.05303	0.04019	0.04673
13	0.01884	0.01461	0.04039
14	0.05284	0.01027	
15	0.01659	0.01921	0.02842
16	0.01831	0.00859	0.02012
17	0.08049	0.00323	0.01688
18	0.0329	0.16208	0.0329
19	0.01574	0.01807	0.04692
20	0.01988	0.00592	0.01211
21	0.01516	0.03131	0.02603
22	0.01526	0.09894	0.01201
23	0.0371	0.07659	0.04835
24	0.03533	0.01312	0.01268
25	0.03004	0.05505	0.02341
26	0.0268	0.03712	0.04816
27	0.01483	0.00603	0.01363
28	0.03767	0.07084	0.01411

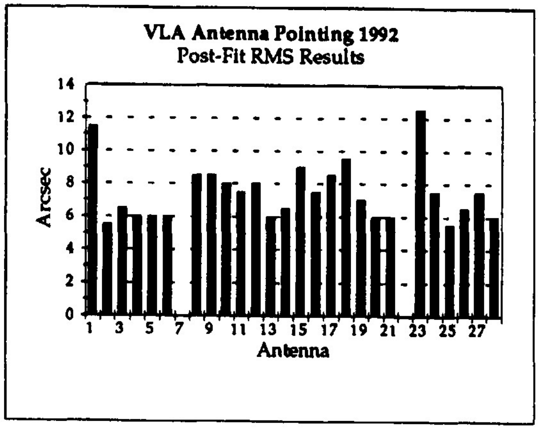


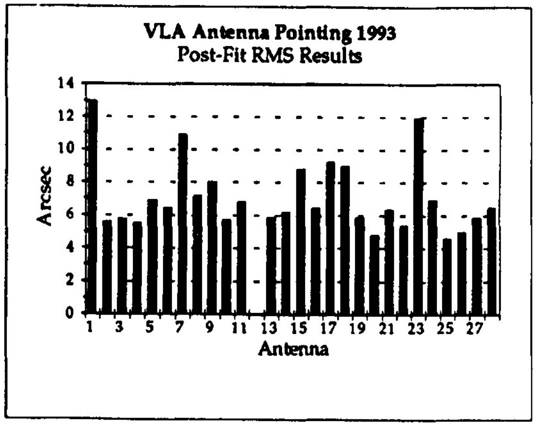




Pointing
Post fit RMS (arcsec)

2/29/92	5/6/92	7/8/92	9/7/93	11/21/94	4/26/95	antenna
10	11.5	6	12.95	11.2	11.3	1
6	5.5	6.55	5.6	7.2	7.4	2
5.5	6.5	3.75	5.75	6	4.7	3
4	6	2.6	5.5	5.55	5.95	4
6.5	6	4.1	6.9	7	5.75	5
4.5	6	ERR	6.45	6.3	6.35	6
8	ERR	7.45	10.9	10.9	11.2	7
8	8.5	ERR	7.15	7.35	8.65	8
8	8.5	4.85	8	5.8	5.5	9
8	8	5.1	5.7	6.25	6.7	10
7.5	7.5	3.65	6.8	5.7	7.4	11
6.5	8	5.5	ERR	8	8.4	12
4.5	6	ERR	5.85	5.4	6.25	13
5	6.5	5.2	6.2	5.5	6.25	14
6.5	9	5.9	8.8	9	8.2	15
6.5	7.5	11.5	6.45	5.45	7.05	16
8	8.5	6.45	9.25	9.8	10.2	17
8.5	9.5	ERR	9	11.7	13.15	18
5	7	6.65	5.85	ERR	5.15	19
5	6	7.45	4.8	5.35	5.35	20
6	6	4.45	6.35	6.5	6.5	21
ERR	ERR	2.55	5.4	5.95	5.65	22
12.5	12.5	ERR	11.95	15.05	ERR	23
6	7.5	4.55	6.95	7.95	6.45	24
6.5	5.5	3.55	4.6	4.6	5.85	25
5	6.5	ERR	5	4.35	5.85	26
5.5	7.5	5.4	5.85	6.2	6.85	27
4.5	6	ERR	6.45	6.8	6.55	28


VLA Antenna Pointing 1992
Post-Fit RMS Results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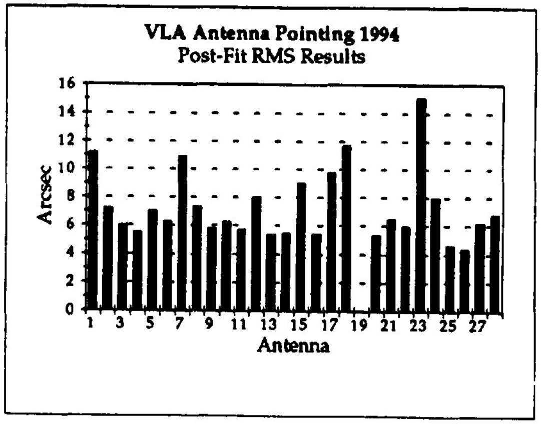
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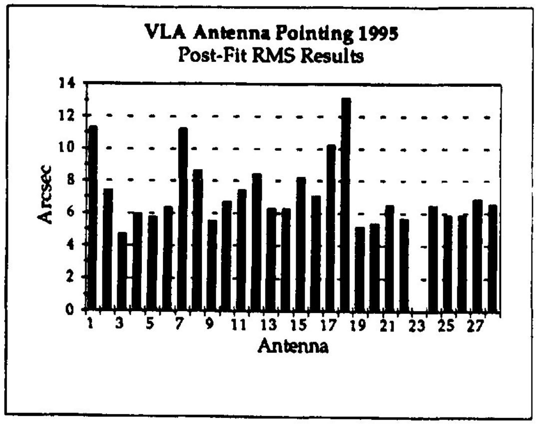
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