MMA Memo 232: A Simple Method to Improve Pointing on the MMA Antennas

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Abstract

I present a novel method for improving the pointing accuracy of a telescope subjected to various environmental loads. The method involves separating two of the functions of the typical telescope mount structure into separate parts; the main structure carries loads, as usual, while a second structure carries essentially no load, but provides a stable reference frame from which accurate measurements are made. The separation of these two functions is analogous to the use of an "active" support for a telescope mirror, except in this case we consider a system with only two degrees of freedom (azimuth and elevation) and in this case the antennas already have the two actuators (the drives) and the two encoders (additional sensors can be added as needed to measure additional deflections). The proposed system can have significant advantages over laser metrology of antenna deflection.

1 Introduction

One of the most challenging performance objectives for the Millimeter Array (MMA) antennas is attaining 1/30 of a beam width RMS pointing accuracy at 300 GHz under typical observing conditions (for a 10 m dish, this corresponds to 0.8 arcsec RMS). The most likely site for the MMA, the Atacama desert in Chile, has average wind speed of about 6 m/s. For the air density at the 5000 m elevation of this site, a 6 m/s wind gives a force on a 10 meter diameter dish of approximately 1600 N (360 lbs) when the dish faces directly into the wind. This force is enough to deflect a telescope mount by an amount approaching 1 arcsec, unless the mount is very carefully designed and rather heavy. Similarly, solar illumination usually heats one side of the mount more than the other side. This also causes unacceptable antenna deflections – easily several arc seconds under low wind conditions. Achieving the required 0.8 arcsec RMS pointing accuracy under typical observing conditions is probably the single most challenging performance goal for the Millimeter Array antennas. By comparison, meeting the surface accuracy requirement of 25 μm RMS appears to be more easily accomplished, particularly because carbon fiber reinforced plastic (CFRP), which has a much smaller coefficient of thermal expansion and a higher stiffness to mass ratio than steel, is becoming more commonly available and more affordable.

This memo describes a new approach for achieving better telescope pointing through the use of a separate "reference structure" in the telescope mount, and compares the likely performance of this scheme with other possible methods.

2 The "Reference Structure" Concept

A traditional telescope mount supports the dish, provides drives to point the dish toward different directions on the sky, and encoders to measure the direction in which the dish points. The new idea proposed here is to separate two of the mount functions, namely the load bearing function and the measurement function, to be accomplished individually by separate structures. The measurement function is served by a non-load bearing structure which I will call the "reference structure". When the load bearing and measurement functions of the mount are separated, changes in the environmental loads on the mount will still cause mount deflection. However, the reference structure, which does not carry this load, does not deform significantly, and thus contributes no measurement error.

Separation of the load bearing and measurement functions of the mount is analogous in some ways to the "active" mirror support found on some modern telescopes. The active mirror support typically has dozens of computer controlled actuators which maintain an accurate reflector surface despite the deflection of the mirror supporting structure due to changes in gravitational loading with elevation, or any other load change. Correcting the telescope pointing errors due to mount deformation is a simpler problem than maintaining a good mirror surface because there are only 2 degrees of freedom (the elevation and azimuth motions of the mount) rather than dozens, and furthermore many key pieces of our "active" system are already in place, namely the drives and the axis encoders. We need only supply better information to the encoders (or supplemental information to the pointing servo) to achieve improved pointing.

The environmental loads on the antenna fall mainly into two categories: thermal loads and wind loads. The thermal loads tend to cause larger pointing errors than wind loads, but the thermal loads change on longer time scales which probably makes them easier to correct.

3 The Proposed Implementation on the MMA Antennas

One possible design for the MMA antenna might be similar to that shown in Figure 1. Each yoke arm contains a CFRP "reference structure " shaped like an inverted "V". The elevation encoder is attached at the top of this structure and the base of each leg attaches to the yoke near the azimuth bearing. Two displacement sensors, for example linear variable displacement transducers (LVDTs), are located at the top of each structure, and measure vertical and horizontal deflections (the horizontal component perpendicular to the elevation axis) of each yoke arm with respect to the reference structure. Figure 2 shows more details of the LVDT and encoder installation at the top of one yoke arm.

For an antenna similar to the design shown, the deflection of the relatively large yoke dominates that of the more compact base, so that correcting only the pointing errors due to the yoke deflection is sufficient to correct the bulk of the total mount pointing error. However, the tilt of the antenna base and foundation can be corrected by placing two-axis tilt meters near the azimuth bearing close to the azimuth axis. It is useful to have a tilt meter which rotates with the yoke to simplify the problem of measuring the azimuth axis tilt given the possibility that the tilt meter may have instrumental drift. However, it is also essential to have a two-axis tilt meter which is mounted on the non-rotating base because tilts measured by the rotating tilt meter will be unreliable during the high angular acceleration maneuvers the antenna can make (a rotating tiltmeter must be located within 0.01 mm of the azimuth axis to have an error of less than 0.1 arcsec for angular acceleration of 24 degrees/s/s).

Because the elevation encoder is connected to the top of one reference structure, an elevation pointing error which would have resulted from bending of the yoke arm is automatically eliminated (if desired, elevation encoders could be placed on both reference structures for redundancy or for measuring the difference in motion between the two arms, which might prove to be a useful diagnostic). The elevation pointing errors resulting from tilting of the antenna base and foundation are removed by measuring the net tilt near the azimuth bearing and applying a small correction to the elevation encoder reading.

The azimuth pointing errors which would result from yoke deflection are corrected by incorporating the displacement measurements from the 4 LVDTs at the top of the reference structures. The LVDTs which measure vertical motion correct for the tilt of the elevation axis which would produce an azimuth pointing error. The LVDTs which measure horizontal motion (perpendicular to the elevation axis direction) of the elevation axis correct for the azimuth pointing error which would result from the wind-up of the yoke arms about the azimuth axis. The azimuth pointing error which results from the tilt of the antenna base and foundation are corrected by the tiltmeter measurements. This scheme does not correct for the azimuth pointing error which results from wind-up of the antenna base, but this is small for the triangular base shown. Also not corrected is the pointing error due to twisting of the entire antenna foundation about the azimuth axis – avoiding this error would require reference markers on independent foundations, which may be difficult to achieve for a portable antenna.

Unwanted vertical and horizontal translation of the entire antenna dish cause changes to the instrumental phase of the interferometer. The contribution to these motions which arise from bending of the yoke are also measured by the LVDTs. Translations which result from tilting of the base and foundation can be corrected by the tiltmeter measurements. However, translational motion of the base is not corrected by the scheme proposed here.

By carrying the A-frame structure all the way down to the azimuth bearing, one can, in principle, remove all of the elevation pointing error contribution due to bending of the yoke. In practice, it may be more practical to remove most, but not all, of the contribution by carrying the A-frame to more convenient spots fairly close to the azimuth bearing, as Figure 1 illustrates. The elevation pointing error is then not completely corrected, but it is easily reduced to a very acceptable level. The azimuth pointing errors may still be nearly perfectly corrected since the LVDT readings could be applied to the pointing with an empirical scale factor which gives best results.

It is interesting to note that the elevation error due to yoke bending is corrected in a fundamentally different way than all the other pointing errors just described. It is corrected "directly" and automatically because the elevation encoder is measuring an angle from a more suitable reference – no additional sensors are used. The other corrections rely on additional sensors, and are "indirect" in that the pointing servo must include them as corrections to the main encoder reading. These indirect corrections have greater flexibility in that they can be applied with any scale factor (an empirically determined factor might be found which gives better correction than an oversimplified theoretical model) or even ignored. The price paid for this flexibility is simply the cost and risk of having additional sensors.

4 The Magnitude of Possible Corrections

A finite element model of a yoke similar to that shown in Figure 1 has been used to estimate the amount of correction which can be expected from the yoke reference arm. In general, the reference arm structure reduces the pointing error due to deflection of the yoke by about 60% to 80%, depending on the loading case. For the antenna design discussed here, this is the largest part of the total mount deflection. Tilt due to deflection of the base and foundation is the next largest part of the mount deflection and can be significantly corrected by tiltmeters mounted near the azimuth bearing. Further study is required to determine the severity of structural deflections which occur above the elevation axis, and whether they should be corrected.

For a 10 m diameter dish pointing directly into a 9 m/s wind, the lateral force on the top of each yoke arm is 1790 N (403 lbs). If the elevation encoder were attached to the top of the yoke arm a pointing error due to yoke bending of 1.12 arcsec would occur. However, with the elevation encoder attached instead to the reference arm, the elevation pointing error due to yoke bending is reduced to 0.21 arcsec. The pointing error due to tilting of the base is 0.48 arcsec. It is hard to know how perfectly the tiltmeters will correct this tilt. If we assume it is corrected at the 90% level, the base tilt contribution is reduced to 0.05 arcsec. The azimuth bearing compliance contributes 0.13 arcsec deflection which I do not attempt to correct. The moments applied to the dish are small for this dish orientation, so deflections of structure above the elevation axis are small. Thus for the dish pointed directly into the wind, the uncorrected pointing error would be about 1.73 arcsec, but with the yoke reference arm structure and tiltmeters this would be reduced to about 0.39 arcsec. The total translation of the dish (which would affect the instrumental phase if it were different from the other telescopes) for this loading case is 26 μm, but the corrections from the reference structure and tiltmeters reduce this to about 8 μm.

For the dish pointing toward the zenith, horizontal and vertical forces on the dish are much smaller than for the previous case, however the moment acting on the dish is significant. With a 9 m/s wind velocity and the elevation axis oriented perpendicular to the wind direction, a pointing error of 0.53 arcsec results. This is the net result of rotation of the main reflector plus subreflector tilt and decenter with respect to the (rotated) main reflector. Because the pointing errors due to subreflector tilt and decenter are of opposite sign, more detailed modeling of the quadripod and subreflector drive mechanism is required before zenith pointing can be deemed acceptable.

When the dish is pointed toward the horizon 90 degrees from the wind direction, the yoke loading tends to twist the yoke about the azimuth axis. Neglecting wind loading on the structure from all but the dish gives a pointing error due to yoke twisting of about 0.92 arcsec. Using the corrections measured by the reference arm displacement sensors reduces this to about 0.24 arcsec.

Pointing errors due to temperature gradients in the mount are expected to be larger than those due to wind loading depending on the degree to which the mount is shaded from the sun. However, these mount deflections are slowly and smoothly varying, so they are more easily corrected.

Care must be taken to assure that any reference structure has sufficient stiffness and sufficiently high resonant frequency to avoid significant deflections during telescope operation. Preliminary calculations indicate that an assembly consisting of a reference arm (shown to scale in Figure 1) acting in series with a low mass torque tube and a pair of short bellows couplings has negligible wind-up due to friction in encoder bearings which have an appropriate preload. A lowest resonant frequency of 30 Hz or more can be achieved for a reference arm/torque tube/bellows assembly.

5 Other Measurement Schemes

Another possible approach to measuring antenna deflection is by laser metrology. Temperature, pressure and humidity variations cause the optical path length through air to vary, resulting in measurement errors. For a helium-neon laser operating at $\lambda = 0.6329914\,\mu$m vacuum wavelength, the wavelength in air is well approximated by the following lengthy expression (Ernst, 1992)

$$\lambda = \lambda_0 * (1 - 2.8775 * 10^{-7} * p * \frac{1 + 10^{-6} * p * (0.613 - 0.00997 * t)}{1 + 0.003661 * t} + 3.03 * 10^{-9} * H * \exp(0.0575627 * t))$$

which depends on temperature, t (C), pressure, p (hPa), and percentage relative humidity, H (50% relativity is given by H = 50.). For air at 20 C, 1 atm pressure, and 50% relative humidity, the fractional change in wavelength is $\delta\lambda/\lambda = 9.4 \cdot 10^{-7}$ per C, and $\delta\lambda/\lambda = -2.7 \cdot 10^{-7}$ per hPa (1 atm = 1013 hPa), while the sensitivity to humidity changes is small. For the reduced pressure and temperature at 5000 m elevation, the temperature coefficient is reduced by about one third to $\delta\lambda/\lambda = 6.2 \cdot 10^{-7}$ per C.

Because atmospheric pressure changes will be similar from one antenna to another, pressure changes will have little net effect on the interferometer metrology. Significant temperature gradients within an individual antenna (or differences from one antenna to another) are likely, however. At 5000 m elevation, the sensitivity of a HeNe laser distance measurement to temperature changes is about equal to that for low cost uni-directional CFRP laminates such as

T300/5208 or moderate cost quasi-isotropic CFRP such as T50/EP. However, moderate cost laminates of T50/EP or M40J/954-3 can achieve more than an order of magnitude lower coefficient of thermal expansion by controlling the layup orientation and filling fraction of fiber. Besides the sensitivity to temperature variations being smaller for the better quality CFRP than for the HeNe laser, the time scale for temperature fluctuations of the CFRP structure can be much longer than for air. Thus, the CFRP structure should provide a higher quality, less noisy measurement than a HeNe laser distance measurer.

The possible use of optical techniques to measure changes in angles should also be considered. Those types of measurements are presumably sensitive to gradients in optical path length across the measurement beam, which I have not tried to quantify.

6 Conclusions

Separating the measurement function of a telescope mount from the load bearing function by building a separate "reference structure" can result in large improvements in pointing performance under wind and thermal loading. For the MMA antennas which have a relatively large yoke to accommodate a large receiver cabin, the proposed reference structure corrects only for yoke deflection which is the majority of the entire mount deflection.

CFRP structures can be designed to have a smaller thermal coefficient of expansion than a laser metrology system (where the optical path length is sensitive to the index of refraction of the air, and hence its temperature).

Acknowledgements

When originally proposed in 1995, the "reference structure" consisted only of a single structure in one yoke arm, which was intended to correct only the elevation pointing error. I thank Peter Napier, David Woody, Matt Fleming and the MMA antenna working group for discussions which lead to the further development of the idea into that presented here. I am grateful to Victor Gasho for his help in producing the figures.

References

Ernst, Alfons, "Digital Linear and Angular Metrology", verlag moderne industrie AG (1992), produced in collaboration with Dr. Johannes Heidenhain GmbH.

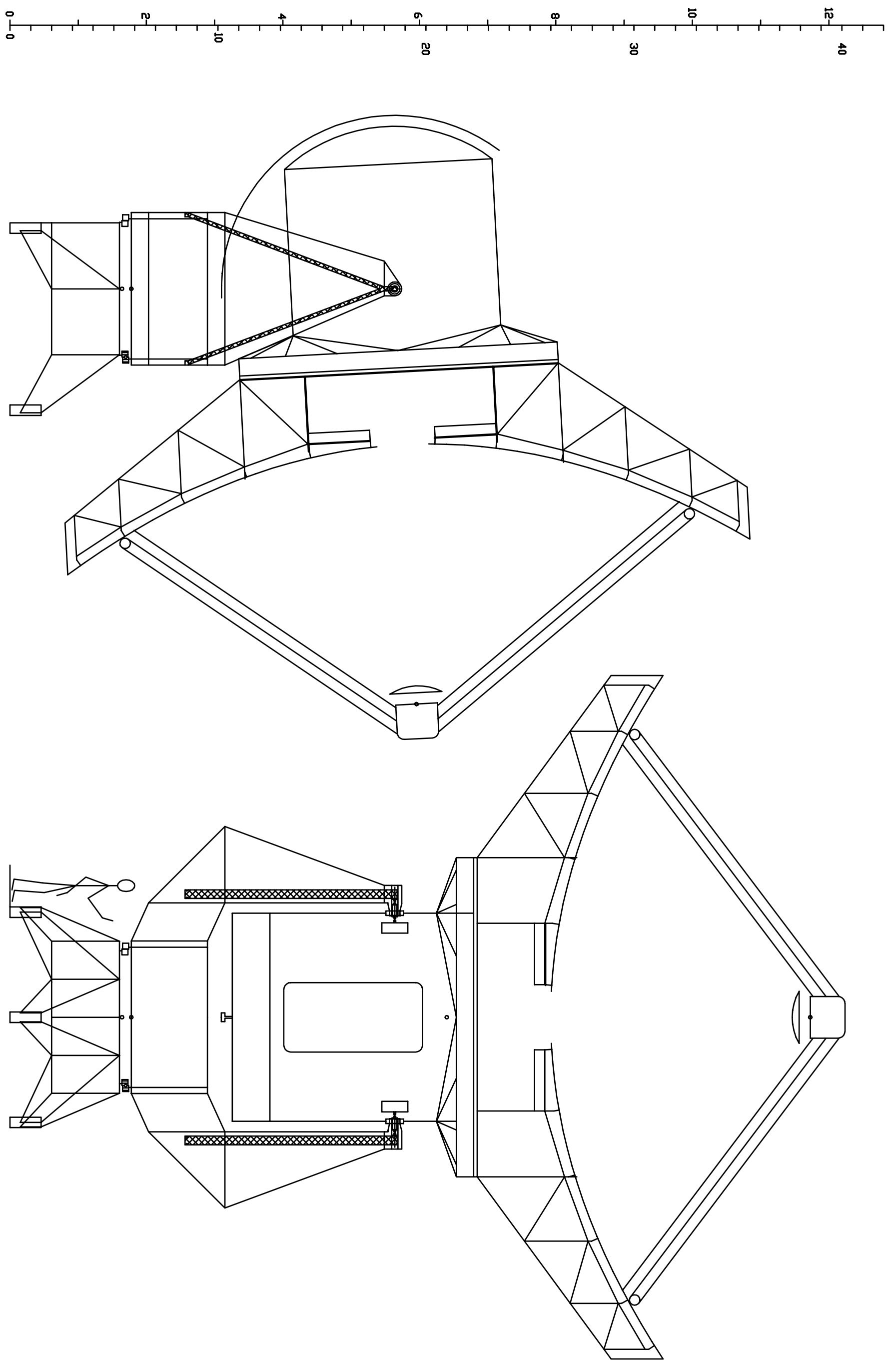

Figure 1: One possible implementation of a non-load bearing reference structure. In this example, the reference structure consists simply of a pair of CFRP arms (indicated by the shaded regions), located in each side of the yoke. Atop each arm are a pair of displacement transducers which measure vertical and horizontal motions of the yoke. The elevation encoder is attached to an arm through a pair of bellows couplings and a torque tube.

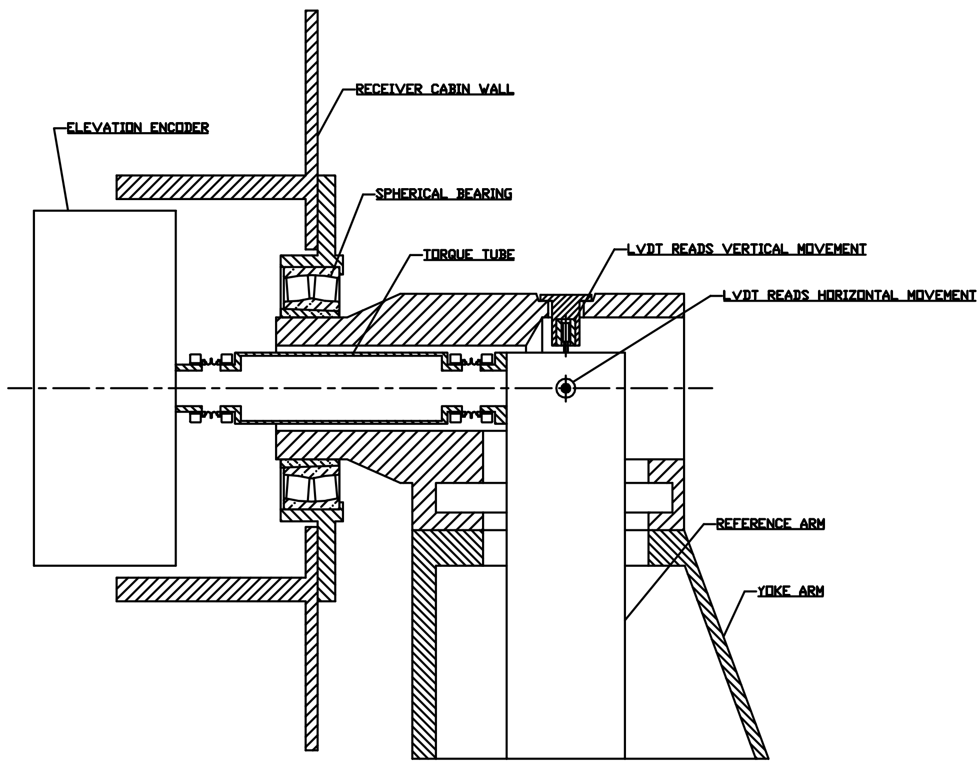

Figure 2: Cross section of the top part of a yoke arm and the nearby receiver cabin. The rotor of the elevation encoder is connected to the top of the CFRP reference arm by a torque tube and a pair of short bellows couplings. A pair of Schaevitz 050 HR linear variable displacement transducers is shown in the desired orientation, however details which allow their adjustment and alignment are not shown.