Submillimeter Array Technical Memorandum

Number: 26
Date: Sept. 25, 1990
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Pointing Specifications for the SMA Antennas: The Proposed Philosophy

Summary

The pointing and tracking specifications for the Submillimeter Array antennas can be defined in such a manner as to permit clear communication of the requirements to potential vendors. Furthermore, the necessity to provide for a viable acceptance procedure leads to an obvious separation of responsibility between the antenna manufacturer and the customer.

Introduction

Considerable confusion exists in the area of the pointing and tracking specifications for the SMA antennas or, for that matter, any other antenna system. The goal of the customer, CfA, is to procure antennas that are able to point their patterns within a specified uncertainty under a variety of conditions. This pointing problem involves many aspects. First, there is the uncertainty in referring a direction to the terrestrial reference frame after applying corrections for refraction, time of the observation, etc. This is normally quite small. Secondly, there is the larger uncertainty caused the mechanical and optical deficiencies in the instrument itself. Further complications arise because we are willing to accept a differing level of instrumental errors under varying environmental conditions. Our specifications for the antenna, must clearly communicate to the manufacturer the magnitude and character of the instrument errors we can tolerate and communicate this information in such a manner that it can be clearly measured for the purposes of contract fulfillment. The purpose of this document is to outline a system of specification that can accomplish that purpose.

The Problem

The pointing and tracking specifications can be explained by means of Figure 1. Let us assume that we are looking at the coordinate plane of the sky. It is irrelevant at this point whether we are dealing with equatorial or terrestrial coordinates. Our pointing specification for the antenna will state that we must be able to point to an arbitrary location with an error zone defined by some error radius represented by the shaded circles. The error may or may not be symmetric in the particular coordinate space chosen. Its diameter will only be of the order of a few arc seconds for any submillimeter antenna. At some point in time, t+A, the antenna will have moved and again be required to point to the new position with essentially the same degree of accuracy. We can calculate the current and future positions at any time and send the antenna in the correct direction by calling for a track rate given by the slope of the line between the two positions.

If we assurne that the pointing errors at the two different points in the sky are basically uncorrelated, which is by far the worse case, the antenna will try to follow an average path between the two points given by some line that can intersect the error circles. The actual tracking error will be worse than this due to deviations of actual track from nominal rate. These deviations will be caused by the instrument's inability to cope precisely with varying disturbances such as wind and friction. In the case where the antenna is not moving, the two positions are identical and the tracking error will manifest itself as the ability of the antenna to hold a fixed position.

A problem in specifying the pointing and tracking develops when the errors represented by the pointing error and the errors which arise along the predicted track line are not clearly differentiated. The pointing specification to be usable, is best specified in the absence of disturbances. This means, in practice, that it is the ability to point to fixed locations in a terrestrial reference frame in the absence of wind. The tracking specification, on the other hand, determines how much you are willing to allow the antenna to deviate from the predicted tracking paths, or the fixed points, in the presence of disturbances such as wind, friction,

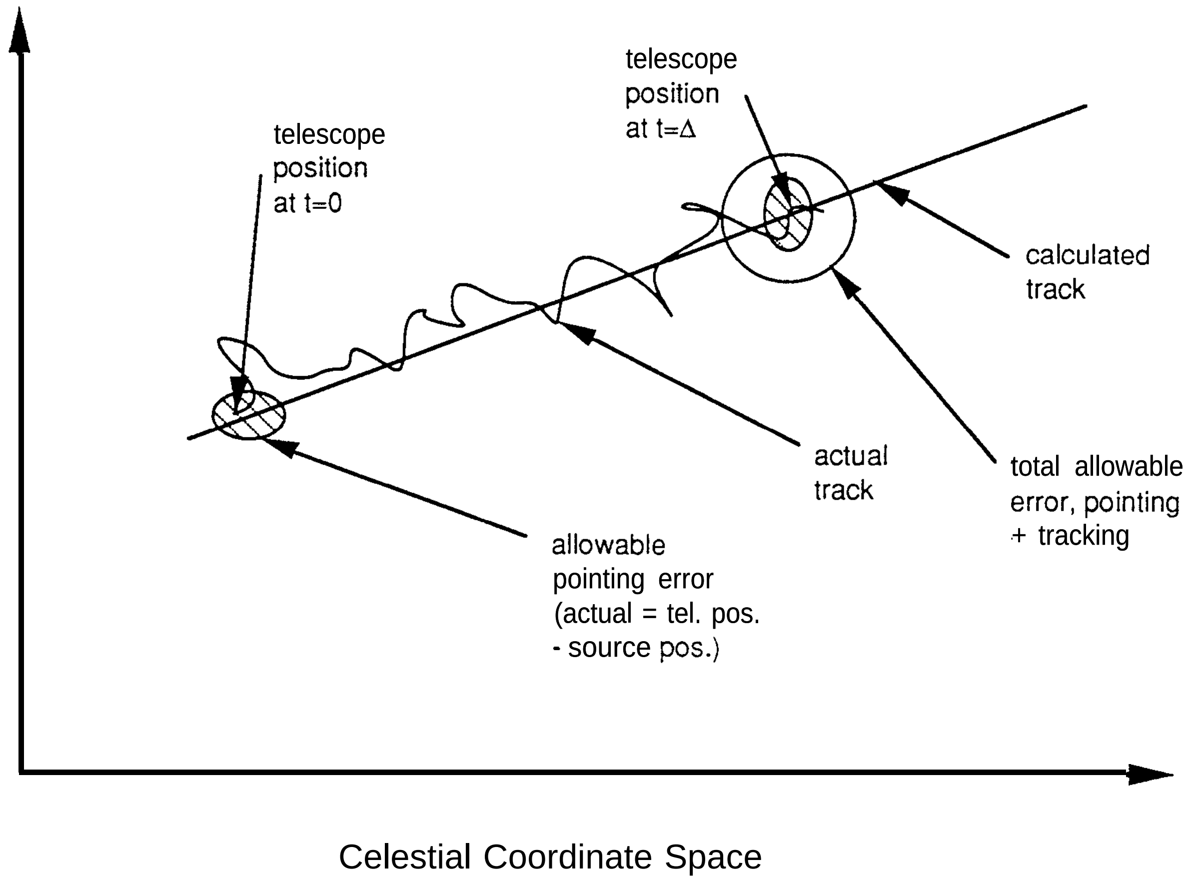

Figure 1: Representation of the Pointing and Tracking Errors

cogging, etc. Both will need to be specified in the correct thermal environment, which will be important at these accuracies. This definition effectively divides one specification into the static errors and the other into the dynamic errors. As long as the tracking specification and the tracking acceptance testing includes the representative set of dynamic disturbances, you are free to discuss a pointing error strictly for the static case. The advantage of this formulation is that it conveniently separates the problem into those factors that can be solely the responsibility of the vendor and those for which only a joint effort can complete the problem.

How Specified

The problem of specifying the pointing and tracking specifications is quite different. The pointing specification, being at the limit of modeling capability, can not be directly measured at the manufacturer's plant, at least to any degree of satisfaction. In fact, it will probably be several years before the learning curve on pointing begins to plateau as you get more and more sophisticated in your development of the models. We must instead infer the antenna's intrinsic ability to point by the measurement of relevant mechanical parameters. On the other hand, tracking specifications can be measured by the vendor at the vendor's plant, provided that the proper range of disturbances can be arranged to occur.

A) <u>The Pointing</u> The size of the pointing error circle will be determined by our ability to measure or to model all of the mechanical deficiencies. Given these modelled values we will then be able to predict to which coordinates the antenna encoders must be set in order to direct the beam of the antenna to the given direction in the sky. Mechanical factors which must be included are:

1. <u>Tilt:</u> The tilt of the antenna will be very significant in determining the

3) Transverse misalignment: The transverse misalignment is caused by the radio beam of the antenna being offset from the right angle to the elevation axis. It results in a simple azimuth error which is a function of elevation. It can only be determined by the measurement of celestial source positions after final alignment of the antenna and will not play a part in the acceptance testing.

4) Encoder Errors: Any encoder errors other than a simple offset from zero are not easily separated from the other terms in the mount model. We must demand encoders with an accuracy, as opposed to resolution, equal to the task, i.e. with at least with an accuracy of 1/2 x E. Furthermore, the reading of the encoder on the fly, velocity errors, should not introduce significant corrections for all but the most extreme source positions. A simple eccentricity term will be probable from any attachment to the antenna, and can be tolerated provided it is not more than a few times E.

5) Bearing Wobble: Bearing wobble, as opposed to a simple eccentricity term, is very hard to fit from the observation of sources. We can tolerate a reasonably simple function in the azimuth axis, because we can use the electronic level to decipher the pattern. Wobble in the elevation axis is almost impossible to fiid. Elevation bearing wobble must be kept to <<E.

6) Lateral Misalignment : Nasmyth or Coude mirrors can introduce what has been called a lateral misalignment whereby there is an elevation error which is a function of elevation. Fortunately, the effect is a simple sine or cosine function. Since this is an optical effect, it too will not be a factor in the acceptance testing.

7) Flexure or sag. The largest correction to antenna pointing may be flexure. For the static case, flexure is probably all related to gravitational deflections and is a simple function of elevation. It is unlikely we can design any acceptance tests to properly measure flexure from celestial observations, since we will have the other terms to decouple as well. Our only hope here is to make use of sound mechanical design practices to insure that the resulting flexure is reasonable. By reasonable, it should be of a simple character and low enough in value that we do not expect any hysteresis effects in the structure. I leave it to the mechanical engineers to place the correct constraints and to provide static tests that will verify whether the structure is acting in accord with expectation.

8) Thermal Deformations: The real wild card in the pointing issue is thermal deformation of the structure, Changes in the structure which are a) not measured by active sensors; or b) so short term as to be unmodeled, could be devastating to the antenna pointing. Ideally, we would like a constant temperature structure, like enclosing the pillars in the receiver room. Where this is not possible we can chose isothermal solutions on symmetric structure. And where that too fails, we put the sensors, such as the electronic level, where they can measure as much as possible of the resulting deviation. Only limited testing of the subsystems, like ventilation, will be possible at the vendor's plant. The basic solution for thermal stability must be in place before construction starts. The ability to handle thermal changes in the pointing model will probably be the limiting factor in the performance of the instrument.

Although the thermal deformations may be hard to quantify, we can test the mount at the manufacturer's plant for some of the results we require. This testing will be done with the concept of drift. The damage to the pointing model from thermal parameters is caused by changing the orientation of the mount. Many of these orientation parameters will manifest themselves in tilts or mechanical deflections that can be measured either with the electronic levels mounted on the structure or theodelites viewing fixed targets. Tests which measure the change in tilt of the mount from full shade to full sun and from midnight to noon could be used to verify the stability of the mount.

The determination of parameters by the fitting of celestial sources is time consuming, and quite limited in the case of the parameters determined only in the radio wavelengths due to the relative lack of sources. It is unlikely that we will want to measure more than about two dozen sources on a regular basis. This limitation places constraints on the character of the terms in the pointing model. Specifically, all the terms should be analytically known and well behaved and stable in time. Terms where both the character and size of the deviation are unknown, such as bearing wobble, are virtually unmodelable from a stellar source residuals. On the other hand, simple functions such as non-orthogonality can be determined quite accurately. Our specifications for the pointing of the antenna will reflect themselves in individual limits on the size and character of those mechanical factors that can be measured at the vendor's plant. From these measurements we will infer that we have a mechanical system that can be pointed, in the absence of disturbances, and will take responsibility for doing so at the site. Errors in our assumptions will not be apparent until some time after acceptance of the first antenna, but corrections in subsequent units may be possible due to the phased manner in which we expect to do the antenna procurement. Note also that the pointing specification will be the same for precise and degraded operations, since we have moved all of the disturbing functions to the tracking specification.

B) Tracking: Unlike the pointing, the tracking specifications can be verified at the vendor's site and will be the sole responsibility of the vendor. The tracking spec, or the deviation of the track from a given line, can normally be measured as an error signal at a test point in the servo system. This assumes that the system is stiff enough and sufficiently well attached to the ground that the servo error signals indeed represent the tracking errors, which should be the case if our antennas are to work properly. The most difficult aspect of all will be the verification that there are no dynamic deflections in the structure which are not seen by the servo and yet are large enough to cause tracking problems in the radio beam. We have a higher incentive to verify mechanical stability than most instruments, because any problems in the structure which can manifest themselves in the tracking, will also probably manifest themselves in the phase stability. Again, good theoretical analysis and the verification of the structure design with static loads will be important. We will also want to place optical theodolites at selected points within the structure to monitoring its stiffness in the presence of wind. Particularly careful thought will be necessary to verify the adequacy of the secondary support structure due to the high magnification of the optics. Once the structural stiffness is established at fixed pointing orientations, deviations of track along arbitrary track lines can be safely assumed to have the same character, if the gain parameters of the instrument are not varied.

The acceptable limits for these track deviations will be specified at the time of procurement and be part of the acceptance testing. This does imply the assembly of at least one of the instruments at the vendor's plant in an area which can be subject to representative winds. However, since the antennas are transportable, positioning the device at appropriate locations should not present a serious problem. In addition, we can expect to specify a number of values supporting the tracking capability such as the locked rotor resonance frequency, the drive torque, and the feedback resolution, to insure the chosensolution is acceptable to the long term goals of the project.

Likely values

Let us look at a possible set of specifications to scale the size of the relevant parameters.

The scientist will not care whether he or she is dealing with a pointing or tracking error. What will be their concern is that the antenna remain pointed within some reasonable fraction of a beam width at the chosen position. Our primary beam width is of the order of 14 arc sec at the highest frequency. Adopting a limit of even one fifth of a beam width will cause us to use a pointing specification of 3 arc sec for the deviations from the correct location. This total error must be divided into a pointing component, a tracking component, the modeling errors, and the auxiliary sensor errors. It is clear that the problem is formidable indeed.

Assume we have a total error budget of E for precise operations and one of E' for degraded operations, describing the deviations from the desired position in the coordinate plane. E' will be about 2-3 x E, since we would like the degraded operations to allow demanding work at the lower frequencies, where the beam widths are some 3 times greater, and good enough to do less demanding work at the highest frequencies The pointing and tracking errors (P and T) in each axis must contribute to a value not greater than the specification, where we can expect that, for uncoupled errors

$$E = \sqrt{(P_\alpha^2 + T_\alpha^2)\cdot\cos^2(\text{elev}) + P_\varepsilon^2 + T_\varepsilon^2}$$

and

$$E' = \sqrt{P_\alpha^2 + T'^2_\alpha\cdot\cos^2(\text{elev}) + P_\alpha^2 + T'^2_\varepsilon}$$

where: a and ε refer to the azimuth and elevation axes of the antennas. We have assumed the static pointing errors (P) are the same in both cases. In theory, all the terms in E or E' could be equal, but in practice the division between the components may be much different. For instance, the azimuth axis is much heavier than the elevation axis and typically will have a tracking error much worse due to the lower resonance frequency. In addition, most of these observations will be done at elevations in excess of 30 degrees, lowering the effect of an azimuth error by cos (elevation). Thus, it is most cost effective to allow most of the tracking deviations to accumulate in the azimuth axis such that $T_\alpha >> T_\varepsilon$ and $T'_\alpha >> T'_\varepsilon$. The pointing errors can be similar in both axes with no compromise. Adding the fact that the pointing in light air conditions is probably more difficult than the tracking, i.e. $P_\alpha >> T_\alpha$, and one solution for the relative magnitude of the components immediately becomes apparent,

$$P_\alpha \cong P_\varepsilon \cong E \div \sqrt{2}$$

and

$$T'_\alpha \cong E' \div \cos(45^{o}) \cong 3\text{-}4 \times E$$

In these assumptions, tracking errors in azimuth dominate in high winds, while pointing errors limit the accuracy in light winds. Further mechanical and servo analysis is necessary to refine these ideas to the most cost effective trade off which best balances the cost. We are not concerned with how the vendor wishes to divide what we call the tracking errors, but we must be confident that the amount left for the pointing is commensurate with the totals for E and E'

Consequences on the Mechanical System

The specifications for the SMA antennas are far closer to the specifications for optical telescopes than radio antennas. As such we can draw upon some experiences developed by optical astronomers.

1. The resonance frequencies of the instrument axes must be quite high to compensate for wind loading. For instance, at one point the MMT had only a resonance frequency in azimuth of -2 Hz , which was found to be unacceptable for wind loading.[1] Experience with a Goertz Heliostat on Haleakala at 3 Hz found it too unable to effectively fight wind loading. A survey of acceptable values at optical telescopes will probably confirm values higher than 6 or 7 Hz. We may gain some averaging from the size of our structure, but this gain will be more than offset by the fact that we will have an entirely exposed structure, unlike its optical counterpart.

2. Providing this level of frequency response at the arc second level requires feedback. Gaining a few extra bits by going to exotic absolute encoders on the shaft is not adequate. A high resolution feedback loop with the order of 0.1 arc second resolution is crucial to maintaining high servo gain and good response at

[1] B. L. Ulich and J. T. Riley, Multiple Mirror Telescope Observatory Technical Report No. 4, March 1980.

the wide dynamic range that is encountered in an alt/az tracker. Fortunately, the feedback signal need not have high accuracy, only high resolution , since the position loop can be continually updated by an absolute encoder mounted directly on each axis.

3. The feedback loop must be out of the strain path. We don't want to know where the motors are going but where the antenna is going. While the drive motor system must be extremely stiff, it can never be trusted to measure the antenna response.

Figure 2 outlines a servo system for the SMA antennas modelled on the drive concepts from several operating optical telescopes. The pointing algorithms are in the CfA computer. The tracking response is in the hardware servo system and may or may not be implemented by means of a microprocessor. The general control sequence involves reading the current antenna position from the absolute encoder on the shaft, calculating the desired position at time t + A, and sending a rate of pulses or a fixed number of pulses to the up/down counter. If an optical tracker is used to augment either the position loop or the feedback loop, its signal would be interpreted by the computer and used to adjust the information to the up/down counter accordingly. These "outer loop" algorithms would be developed by CfA, as would the tilt meter, the clocks and the auxiliary sensors and the optical tracker. The vendor would deliver the tracking system as outlined within the dotted lines.

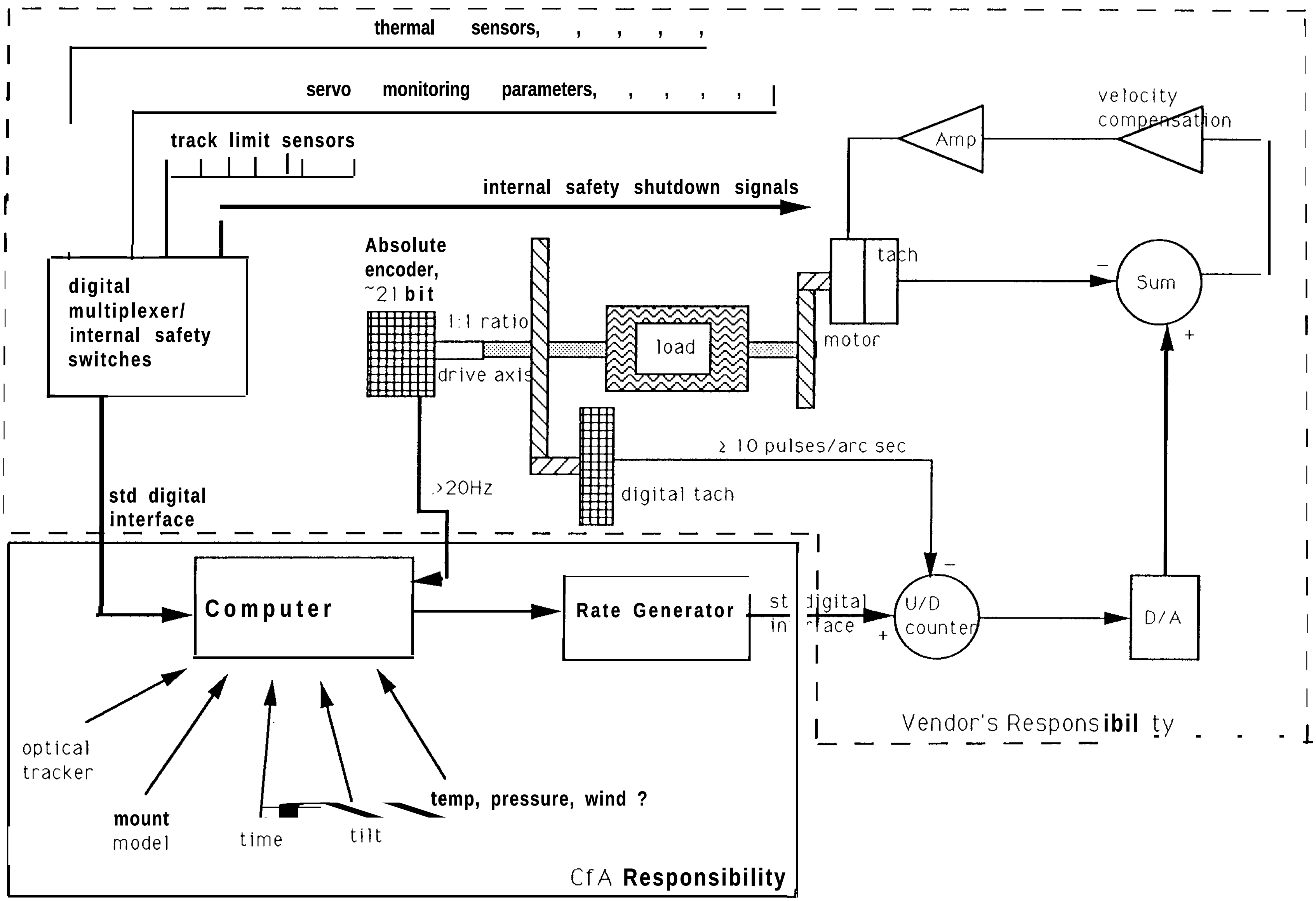

Figure 2: Schematic Representation of a one axis control system