MMA Memo #268
Measuring the Primary Mirror Surface Using a Laser Coordinate Measuring Machine

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Abstract

I discuss the possibility of using a Helium-Neon laser coordinate measuring machine (CMM) to measure the surface of the primary mirror on the prototype ALMA (MMA/LSA) antenna. Because the ALMA primary mirror approximates a concave spheroid, it appears possible to achieve 5 to 10 micron measurement accuracy by placing the measuring head near the mirror's average center of curvature (the accuracy which can be achieved on a concave spheroid is much higher than for other surface shapes). Since the measuring head is placed relatively near the telescope, surface measurements can be made at different telescope elevations from a measurement tower of only modest height; this presents the best possibility for measuring the gravitational deformation of the primary mirror on a prototype antenna before production antennas are ordered and prior to achieving a working two element millimeter interferometer. In order to determine what accuracy is typically achieved by this system and what environmental conditions produce the best results, I propose that test measurements be made at the prototype antenna site.

1 Introduction

The major purpose of testing the prototype ALMA antenna is to determine that the design meets performance specifications prior to proceeding into the production run of antennas. While many of the antenna performance specifications (such as wind or thermal pointing for example) are very difficult to verify completely, measurement of the surface error is much more straightforward. The main goals here are to determine that the surface accuracy is stable with time, and also that it is not excessively degraded by gravitational, wind, or thermal loading. Of these three loading conditions, the gravitational loading performance is far easier to verify than the others, and it is probably the largest in magnitude. In contrast, the wind and thermal loading conditions are very hard to control or even measure, and furthermore will vary rather rapidly in time.

This memo discusses the possibility of using a HeNe laser coordinate measuring machine (CMM) to measure the accuracy of the primary mirror of the prototype antenna. The laser CMM can quite easily provide the accuracy required to achieve good aperture efficiency at millimeter wavelengths; a $\lambda/20$ surface RMS at 300 GHz corresponds to 50 microns RMS. However, if a measurement accuracy of about 10 microns RMS can be reached using the laser CMM, we will achieve far more significant results. First, we can determine whether the surface, once set, remains stable with time. Second, by using a tower of modest height to measure the surface at high and low elevations, we can measure the gravitational performance of the antenna; this would be one of the most significant tests which could be done on the prototype antenna (unless the LES-9 satellite is kept operating beyond its currently scheduled Jan. 2000 shutdown date, the laser CMM is the best hope for measuring gravitational surface error prior to achieving a working interferometer). Finally, in the process of measuring the primary mirror to assure good stability and gravitational performance, we can iteratively improve the surface to achieve high aperture efficiency and we can verify the proper behavior of the panel adjusting process.

2 The Proposed Measurement of the ALMA Prototype Antenna

This memo discusses using one particular instrument, the SMX Corporation Tracker 4000 CMM, to measure the surface of the primary mirror (at least one other similar product is available from Leica Geosystems). The SMX Tracker 4000 has a tracker head which tracks the movements of a retro-reflector and periodically records its location. The retro-reflector location is determined by measuring the angular location of the reflector as seen from the tracker head and by measuring the radial distance to the retro-reflector using a laser interferometer. The retro-reflector can be moved along any path over the surface which is being measured.

The specified radial accuracy (1 sigma) for the Tracker 4000 is 2 microns plus 0.8 microns per meter of optical path. Laboratory measurements at SMX show good agreement with and comparable accuracy to Hewlett-Packard and Renishaw laser interferometers (Bridges, 1999). Radial accuracy in the SMX laboratory is limited mainly by air temperature variations along the measurement path; for a HeNe interferometer, the variation of wavelength with air temperature is 0.94 microns/m/C near standard temperature and pressure conditions. Transverse accuracy of the Tracker 4000 is specified to be 12 microns plus 5 microns per meter of optical path. Transverse accuracy of 5 microns per meter corresponds to about 1 arc second accuracy of the angle encoders in the tracker head.

With a desired measurement accuracy of 10 microns rms over the dish surface, the quoted transverse accuracy will not be adequate for the general case of an arbitrarily shaped mirror. However, for our special case of measuring a concave paraboloid, the transverse accuracy is of no consequence if we are just a bit careful. To minimize the significance of the tangential accuracy contribution, we simply place the tracker head near the average center of curvature of the paraboloid. As a particular example, for a 12 m diameter f/0.38 paraboloid, if we place the tracker head on the dish center line, a distance 10.46 m from the vertex, the maximum rate of change of radial distance with angle is only 1.5 microns per arc second, as shown in Figure 1. Thus a 1 arc second angular measurement error is of negligible contribution to the total measurement error. In this special case the total accuracy of the measurement is limited entirely by the radial measurement accuracy of the CMM.

The radial accuracy of the CMM's HeNe interferometer will ultimately be limited by optical path length fluctuations in the atmosphere, which are primarily due to temperature fluctuations. The magnitude of these fluctuations at several heights above the ground has been measured for a variety of optical seeing conditions from about 2 to 8 arc seconds near the Shane 3 m telescope at Mt. Hamilton (Gibson et al., 1984). At least for the Mt. Hamilton site, these measurements suggest that the noise level in the measurements due to optical path length fluctuations would be less than 1 micron RMS for time intervals of 100 seconds for the 10 m paths typically required to measure the prototype antenna mirror. A larger uncertainty for the mirror measurement accuracy may be the fluctuations on time scales longer than 100 seconds, and the level to which these can be removed by repeated measurements of the fiducials.

Figure 2 shows representative setups required to measure the primary mirror at low and high elevations. Measuring the primary mirror at high elevation (say 60 degrees, or even better, 120 degrees if the antenna can go over the top) requires a very stable measuring tower about 15 to 16 meters high; the low elevation measurement requires a stable tower about 6 to 8 m high.

The overall curvature of the primary mirror could be measured if the laser CMM has an absolute distance measuring capability, such as the SMX Tracker 4500. The accuracy of the Tracker 4500 for absolute distance measurements is about 31 microns at a range of 10 m, however this is quite sufficient for determining that the mirror is set adequately close to the proper parent paraboloid. It would also be nice to measure the flattening of the mirror when the telescope is moved to higher elevation. For this measurement, the 31 micron accuracy limitation in measuring the radius of curvature of the primary corresponds to a deflection uncertainty of about 6.8 microns at the edge of a 12 m mirror, which may be comparable to the total flattening of the dish when moving from horizon to zenith. Thus, it is difficult to measure the flattening of the dish with the precision required to confirm this aspect of the telescope engineering model. However, by measuring the absolute distance to points on the mirror surface near the vertex, and also to a fiducial point on the quadripod near the prime focus, the dish flattening with elevation may perhaps be measured more accurately. The overall dish flattening with elevation change is of no consequence to the telescope's optical performance as long as refocussing is allowed.

To attain the accuracy which is ultimately possible with this CMM requires mechanical stability of the telescope (which we already expect for any design which meets our performance specifications), mechanical stability of the tower supporting the tracker head, and careful measurement of air temperature along the HeNe laser path during the surface measurement process. Long term drifts in measured distances can be effectively removed by repeated measurements of several fiducials located on the dish (a fiducial could be defined, for example, by temporarily locating two pins on the surface against which the retro-reflector sphere can be precisely placed – this would locate the retro-reflector in all 3 translational degrees of freedom). Short term noise due to vibrations or rapid air temperature variations are removed by averaging many independent samples taken at a given location. Additional checks of tower stability can be made by measuring distances to reference markers on the ground. The VLA antenna barn can easily house the required test towers and the subject antenna and would provide protection from wind and solar loading. At the VLA site, these surface measurements could be made either indoors or outdoors, depending which environment gives the better results.

3 Proof of Concept using a Mockup Antenna

Performing test measurements of a mockup telescope is probably the best way to determine which conditions provide the best measurement accuracy and to learn what that accuracy is. One obvious test would be to repeatedly measure distances along several paths between a 6 m tower and another structure which has several fiducial locations which simulate locations on the primary mirror surface. This would simulate measurement of the mirror with the telescope at low elevation. These measurements should be done outdoors at a representative site at the VLA and inside the VLA antenna barn to determine which environment and what weather conditions, time of day, etc. gives the best results. Another possible test would be to measure from a much taller tower or higher location within the VLA antenna barn to gain some experience with the measurement accuracy to be expected for a mirror measurement with the antenna at high elevation.

Several organizations should be able to perform tests to determine the effectiveness of this approach. First, the SMX Corporation gives free demonstrations of their instruments. They will provide a demonstration at our site, possibly staying for 2 or 3 days if necessary. The contact person is Jeff Freeman, Manager Western Regional Sales, 619-592-6595. Second, Sandia National Laboratory, located relatively nearby, has SMX equipment. The contact person is Tony Bryce, 505-845-0932. Third, Servco Industrial, of California is a commercial metrology consulting firm. The contact person is Glen Anguline, 800-549-3116.

4 Summary

1. A laser CMM such as the SMX Tracker 4500 can be used to measure the primary mirror surface to very high accuracy by placing the measuring head near the center of curvature of the primary mirror. This approach does not require modifying the quadripod, secondary mirror drive, or changing the telescope weight and balance, all of which could change the mirror shape; in contrast, a special purpose receiver placed at the prime focus certainly changes weight and balance and the loading of the the quadripod, and requires disassembly of some systems near the secondary mirror.

2. The measurement accuracy is sufficient to achieve high aperture efficiency at 300 GHz, and to gain experience with the panel adjustment process.

3. The accuracy will be limited mostly by temperature variations along the measurement path; test measurements of a telescope mockup can be used to determine what conditions give the best measurement accuracy and to suggest what the limiting accuracy may be.

4. This approach provides the best hope for measuring the gravitational performance of a single prototype antenna given that LES-9 is scheduled for shutdown in January 2000.

5. The cost to buy the Tracker 4000 is $161k, but many consulting firms exist which specialize in making these measurements; it is probably wise to demonstrate the system performance in a suitable test before considering a purchase of the instrument.

5 References

Bridges, Robert, SMX Corp product development scientist, 610-444-2300, private communication.

George N. Gibson, James Heyman, John Lugten, Walter Fitelson, and Charles H. Townes, Optical path length fluctuations in the atmosphere, Applied Optics, 23, pp 4383, 1984.

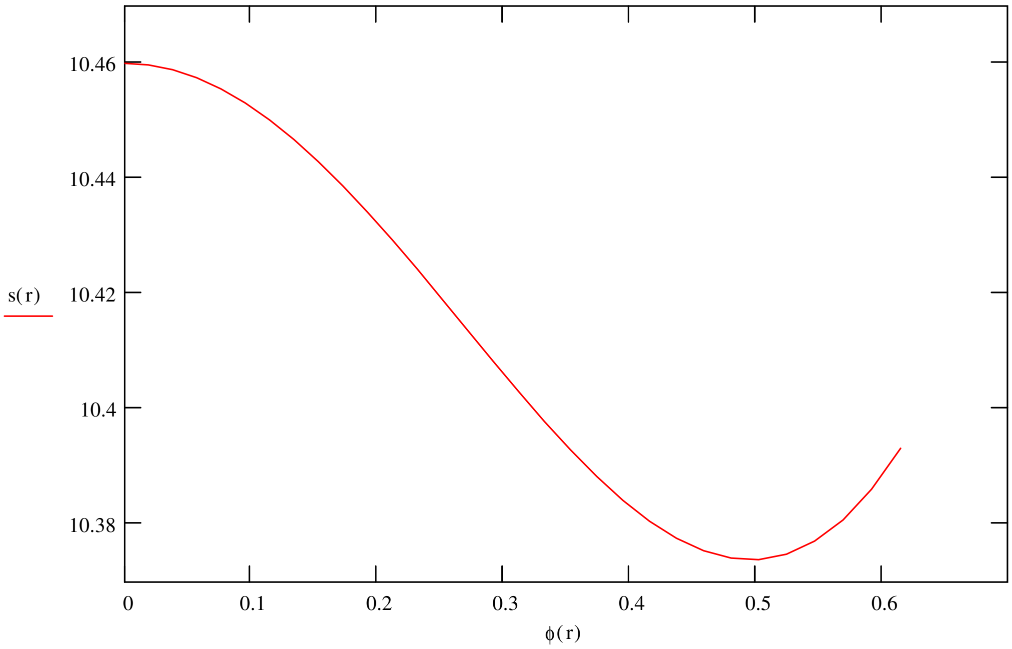

Figure 1: Radial distance as a function of tracker head angle when measuring a 12 m f/0.38 primary mirror with the tracker head placed 10.46 m from the vertex. The maximum radial distance change with angle is less than 1.5 microns per arc second.

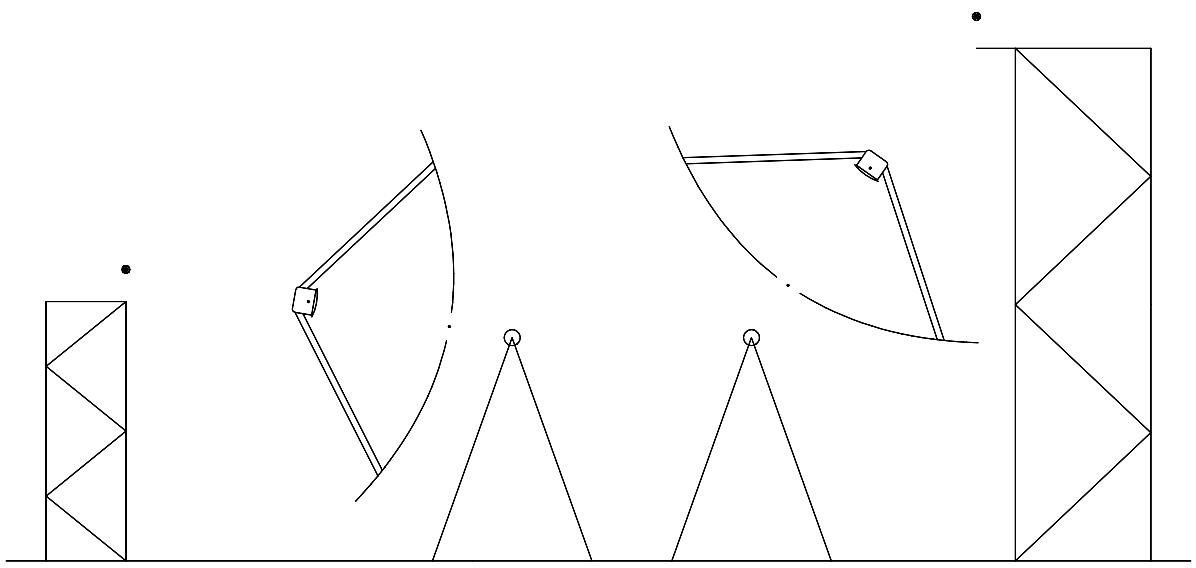

Figure 2: Two possible configurations for measuring a 12 m f/0.38 telescope at 10 degrees elevation (left), and at 55 degrees or 125 degrees elevation (right). The telescope mount is shown very schematically, but the primary mirror surface is accurately shown. Small circles indicate the locations of the primary mirror vertex and the prime focus. The larger solid circle shows the tracker head location on the telescope bore sight 10.46 m from the primary vertex.