LASERS: a real time antenna metrology system for the Large Millimeter Telescope

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ABSTRACT

The Large Millimeter Telescope *Alfonso Serrano* (LMT) is a 50m-diameter radio telescope for millimeter-wave astronomy. The performance of large radio telescopes like the LMT is often limited by their response to deformations caused by thermal gradients within the antenna structure. In this paper, we describe a development project to build a real time metrology system for the LMT. The *Large Aperture Surface Error Recovery System* (LASERS) will measure, on time scales of a minute in real time, the shape of the antenna's primary mirror and the location of its secondary mirror to high accuracy. The LMT's existing active systems may then be used to maintain precise alignment of the telescope's primary surface and its secondary.

Keywords: Radio Telescopes, Thermal Behavior of Radio Telescopes, Millimeter-wave Telescopes, Antenna Surface Deformation, Telescope Alignment, Telescope Design

1. INTRODUCTION

The LMT is a 50m-diameter millimeter-wave radio-telescope that operates at wavelengths between 4mm and 1mm. The telescope utilizes an active primary surface consisting of 180 surface segments which are controlled by actuators in order to maintain the shape of the primary reflector against deformations due to gravity and environmental influences. The large collecting area of the LMT, combined with large-format (~kilo-pixel) continuum cameras and multi-pixel heterodyne arrays, provides a complementary capability to the Atacama Large Millimeter Array (ALMA), and as the largest single-dish millimeter-wavelength telescope operating at a wavelength of 1mm, the LMT offers outstanding opportunities to explore and understand the physical nature of our Universe[1,2].

Figure 1. Views of the Large Millimeter Telescope at its site atop Sierra Negra in the state of Puebla, Mexico. The location of the telescope is shown in the right-hand panel.

The ultimate performance of a large telescope like the LMT is often limited by its response to thermal gradients that develop within the antenna structure[3]. These gradients lead to deformations of the primary reflector surface, which in turn

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cause a loss of antenna gain. Thermally induced deformations may also change the relative position of the secondary and primary mirrors, leading to antenna focus and pointing errors. The performance of the LMT is currently limited by such effects, and as a result, scientific work at the telescope is limited to the ten hours at night when the telescope is relatively thermally stable. Moreover, even during nighttime conditions, the antenna still develops internal temperature gradients as it cools, and the resulting deformations require corrections every few hours to achieve the best performance.

The LMT's active surface system is able to realign the surface continuously, and so it is only for lack of an ability to measure the deformations that we are not already able to optimize the surface. At present, we measure major changes in the primary surface shape using astronomical measurements[4] with a technique akin to the *out of focus holography* technique[5,6]. Deformations are also inferred from structural temperature measurements, and we have been actively working to characterize and calibrate this technique[7]. However, both of these developments have limitations. Astronomical measurement of surface shape often take fifteen minutes to complete and so can struggle to converge to a solution during times when the structure changes rapidly. Inferences about structural changes based on the temperature of the structural members require significant "calibration" of the technique and ultimately will only be as good as the underlying model. Clearly the best solution is to *directly* measure, in real time, the shape of the antenna and the relative positions of its optical elements. In this paper, we describe the *Large Aperture Surface Error Recovery System* (LASERS) which is being developed to provide this real time information.

The purpose of the LASERS project is to develop a system that will: (1) measure the LMT's primary surface deformation so that the active surface may be used to remove transient deformations imposed by thermal gradients within the structure; and (2) measure the location of the LMT's secondary mirror with respect to the primary so that the relative position may be maintained to high accuracy. The system under development relies on an instrumental capability originally developed for monitoring alignments in large particle accelerators and currently being built into large optical telescopes[8,9,10] for alignment of optical elements in the telescope structure. Our proposed alignment system is based on the Hexagon Absolute Multiline Technology (AMT) System[11], which provides a means to make highly accurate measurements of the distances between points on the antenna structure. We will describe below how a set of distance measurements made with the AMT device may be used to measure changes in the shape of the antenna surface and secondary position so that this information may be fed back to the antenna control system to maintain the alignment of the primary surface and the secondary.

2. LASERS REQUIREMENTS

2.1 Timing

The measurements are intended to allow correction for deformations of the antenna structure by thermal gradients which arise naturally through diurnal heating and cooling of the structure as well as direct heating of the structure by the Sun during daylight hours. Observations of the development of temperature gradients throughout the diurnal cycle show that large steel structures in the antenna react to their environment on the time scale of hours, whereas lighter weight and more exposed structures, such as the secondary mirror supports, can react on time scales of just minutes. Thus a fundamental requirement for the instrument is that it must be capable of carrying out a complete set of measurements on minute time scales.

2.2 Primary Mirror Measurements and Requirements

We have carried out a dedicated measurement program to determine the thermal behavior of the primary surface and the measurement accuracy required to recover the best surface shape. The LMT Metrology Team used photogrammetry to generate a series of maps of the primary surface under nighttime conditions[12]. The antenna was parked at a fixed elevation of 62 degrees and maps were recorded throughout the night on four separate nights. The results are illustrated in Figure 1. The surface maps present residuals to a best fitting parabola, and they show clear changes in the surface from night-to-night and within an individual night. The surface deformations are fit to Zernike polynomials, an orthogonal basis set, to characterize their behavior. The coefficients of the polynomial fits are shown in the inset figure, where we note that the largest and most variable is the "vertical astigmatism" term.

Inclusion of the vertical astigmatism term in a fit to the antenna surface accounts for most, though not all, of the surface deformation. For this reason, the LMT makes regular astronomical measurements to estimate the magnitude of this term during science operations in order to correct the shape of the antenna[4]. As the number of Zernike terms in a surface fit is increased beyond the vertical astigmatism term, we continue to see improvement in the overall RMS until approximately the 15th term, but no further gains are seen beyond this point. This observation confirms the predictions of the original finite element modeling of the LMT structure, carried out during its design phase, which indicated that thermally induced deformations would be of low spatial order. Analysis shows that for surface fitting errors to be sub-dominant in the system RMS, we must measure these Zernike polynomial coefficients with an accuracy of 10μm or better.

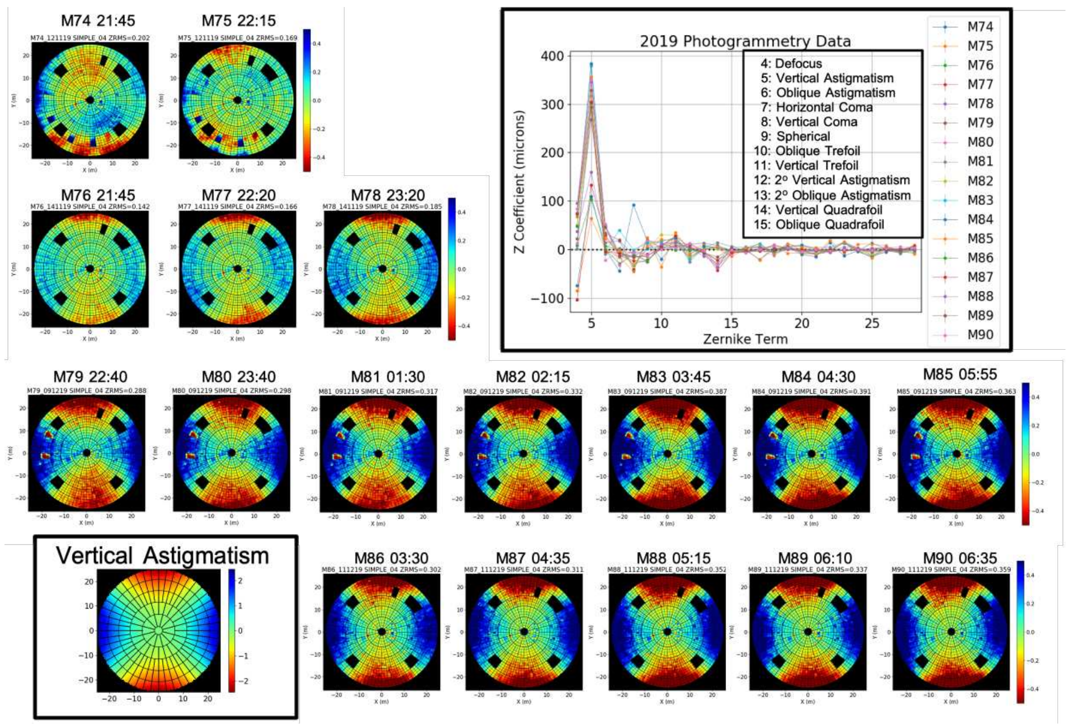

Figure 2 - Photogrammetry maps of LMT surface over four nights of measurements. Observations were made with the telescope fixed at an elevation of 62 degrees and no changes were made to the active surface between the maps. In all cases, the surface has had a best fitting parabola removed from the measurements. Each map has the local time indicated. The maps show clear changes in the surface from night to night and during the night. The vertical color scale is +/- 0.5 mm. The most obvious feature of the deformation is well modeled by an astigmatism (compare maps to the picture of the Zernike vertical astigmatism polynomial in the lower left corner of the figure.) For each map the surface is fit to a set of Zernike polynomials. This allows coefficients to be derived, along with the surface RMS remaining after each term is removed. The inset panel shows the values of the coefficients fit to the maps. It is clear that, beyond simple defocus, the vertical astigmatism term is the most important contributor to the deformation, though there is clear systematic behavior in the terms out to number 15. We find that fitting beyond fifteen Zernike terms yields only marginal improvements to the surface RMS.

2.3 Secondary Mirror Location Requirements

One of the major temperature differences within the antenna structure occurs between the secondary mirror support legs (the tetrapod) and the other structural elements of the antenna. Relative positioning of the secondary mirror with respect to the primary is critical to the overall performance of the telescope. Lateral errors in secondary position at the level of 115 microns result in pointing errors of 1 arcsec, and a tilt of the secondary mirror of 11.5 arcsec leads to a 1 arcsec pointing error. Errors in secondary position along the optical axis of the parabola lead to decrease in gain, with a position error of 100 microns resulting in a 1% gain decrease at a wavelength of 1.3mm. Thus, errors in the location and orientation of the secondary must be kept at the level of 10 microns in order to be consistent with a goal of sub-arcsec pointing at the highest observational frequencies

3. LASERS OBJECTIVE AND APPROACH

3.1 LASERS Objective

In the modern era, many large telescopes rely on active measures to maintain accurate alignment of the primary surface and other optical elements. The LMT was built with an active primary surface so that its large collecting area could adapt itself to account for structural deformations. The active surface is now used to maintain alignment of the parabolic surface under different gravity loads at different elevations, and it is also used to estimate the magnitude of the most serious thermal deformation using astronomical observations during science operation[7]. Given a real time system for measurement of the primary mirror shape and the location of the secondary, the LMT's active systems will be able to make the real time corrections necessary to maintain the internal alignments within the telescope.

3.2 Selection of Measurement Approach

One possible technique for real time measurements involves the use of “Terrestrial Laser Scanner” (TLS) devices, which are capable of scanning over a large target area and producing a point cloud of measurements to map the antenna surface[13,14]. A recent application of this is underway at the Green Bank Telescope[15,16,17], with operational use of the system expected to begin soon. The TLS approach offers many positive features for real-time surface measurement. For example, the point cloud that results from the measurement covers the full surface at high resolution and would in principle allow even the relative alignment of individual reflector panels to be identified and corrected. However, while TLS systems are appealing due to their capability of scanning over a large target area and producing a high-density point cloud of measurements, this approach requires placing a complex instrument at a location on the telescope where it can see the entire surface. Notable previous experimental work with a TLS at the 100m Effelsberg telescope[13] and the Onsala 20m telescope[14] involved placing the instrument near the secondary mirror or on one of the secondary mirror supports. In these experiments, a portion of the antenna aperture is blocked by the instrument, and measurements from a single location cannot see the entire surface. Thus, while the off-axis geometry of the GBT lends itself well to the use of a TLS instrument, the LMT, being an on-axis telescope, has no convenient volume for a TLS instrument that does not block the aperture. Moreover, an important operational consideration for use of a TLS at the LMT’s mountain site would be that of providing appropriate protection for a complex and expensive instrument suspended from a point near the secondary under poor weather conditions.

Given the above considerations, we have sought to develop a different measurement approach: the use of precise point-to-point distance measurements on the structure. The Giant Magellan Telescope metrology group[8] has provided a good statement of the rationale for making telescope optical alignment measurements using a network of absolute distance measurements and enumerated the advantages of such a system over the use of laser trackers or scanners for telescope metrology. This paper and others[9,10] also identify a commercial device that we have chosen to employ in the LASERS project. The Hexagon Absolute Multiline Technology (AMT) System is a laser ranging system which delivers precise (relative accuracy 5×10^{-7}) point-to-point distance measurements. This system[11] offers several useful features for the practical implementation of the metrology system we have described above. A distance measurement involves placement of a laser beam collimator and a retroreflector on the antenna structure. The retroreflector is a passive device, and so may be placed in positions (such as at the secondary mirror position) that would be difficult to access. The collimator end of a measurement is fed by optical fibers from a central unit which may be located away from the devices on the surface. Therefore, the fibers can be easily routed from an environmentally controlled location to the surface location where they are required. A feature of the AMT system is that it allows transmission of the beam through vacuum windows. We are in the process of developing a design for the LMT that can be mounted on the antenna surface and secondary mirror and sealed behind windows to protect its optical elements against the weather conditions at the LMT site. In summary, we find that these operational advantages and general lack of moving parts in the system, offer significant advantages over approaches making use of terrestrial laser scanners.

We now describe how this approach can be used to estimate the shape of the LMT primary surface and location of the LMT's secondary mirror.

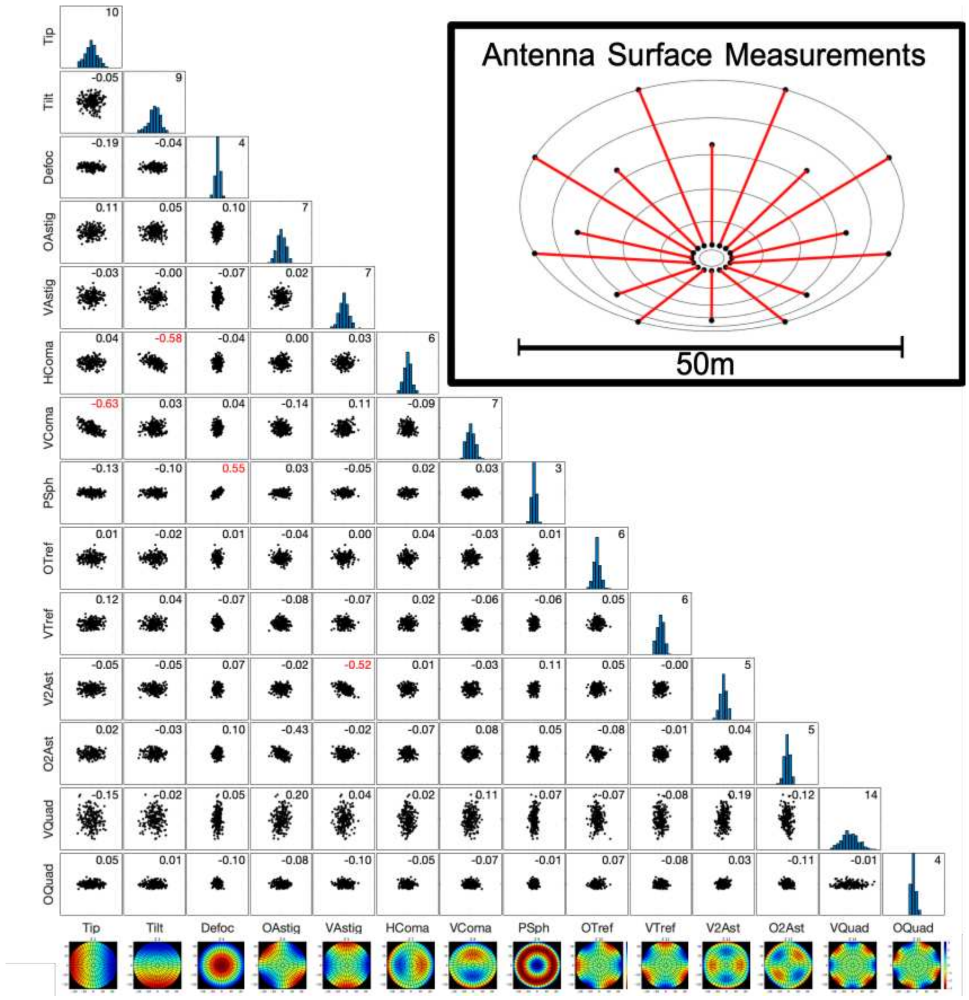

Figure 3 - A corner plot showing the results of Monte Carlo simulation of the experiment to determine 14 Zernike coefficients, Z_2-Z_{15} in our nomenclature. The inset panel shows the 16 point-to-point measurement locations adopted for the simulation. The Monte Carlo simulation assumed nominal relative measurement errors of 5×10^{-7}. The diagonal across the figure shows histograms of the errors for coefficient, with the standard deviation of the error presented in the upper right corner of the plot in units of microns. The off-diagonal figures show the correlated errors from the simulation for each parameter pair. Here the number in the upper right corner of the figure is the correlation coefficient between parameters. Four cases of values in excess of 0.5 are highlighted in red. All windows are scaled to show errors in the range from -50 to +50 microns.

3.3 Measurement Concept for the Primary Reflector Shape

The first goal of LASERS is to measure the shape of the primary mirror and, using the active surface, remove deformations that are due to thermal gradients within the antenna structure. Our study of the shapes of these deformations indicates that they may mainly be removed with measurement of coefficients of 15 Zernike polynomials, and so a real-time system needs to be able to determine the contribution of each polynomial coefficient with a minimum amount of crosstalk with the other coefficients.

Ideally, measurements of reflector surface shape using laser ranging techniques would align the measurement with the optical axis of the parabola or with the normal to the reflector surface. However, there is no ideal place on the LMT structure to accomplish this requirement. From the point of view of realizing a useful system, therefore, we have studied the use of a position near the vertex of the parabola atop one of the stiffest structural elements in the antenna backup structure. The main problem with this approach is that the distance between the vertex and a point on the surface is only sensitive to a component of the antenna deformation along the antenna optical axis. Consequently, the measuring device must be more accurate than the formal requirement for measuring surface deformation errors.

To demonstrate the possibility of this approach, we consider a set of 16 radial measurements between points on the LMT surface. Figure 3 (inset) illustrates the arrangement of the distance measurements. In this example, the surface is modeled considering only deformations along the optical axis. Sixteen distance measurements are made between points on the surface of the primary mirror, and these measurements are used to solve for the coefficients of 14 low order Zernike polynomials that describe these surface errors. We note that the polynomials selected for the fit exclude the constant Zernike term (Z_1), which cannot be found through measurement of relative positions on the parabola.

Figure 3 shows results of a Monte Carlo simulation of the measurement process. Each Monte Carlo trial uses a set of sixteen measurements with random errors to estimate 14 Zernike polynomial coefficients. Random errors are based on the relative distance uncertainty of the AMT system ($\delta L/L = 5 \times 10^{-7}$). The figure shows a "corner plot" of the errors in the simulations to establish the accuracy of the measurement of the coefficients and the extent to which errors in coefficient measurements are correlated with one another. The histograms along the diagonal of the plot show that the Z_2-Z_{15} terms can be estimated with errors of only a few microns. The off-diagonal plots of correlations between errors show that, while correlations do exist, they are not at a level that compromises the parameter estimations.

The performance of the primary surface measurement system can be further quantified by using the Monte Carlo simulation to compute residual surface errors that would be expected in the map after the Zernike terms are removed. These residual surface errors are used to compute the antenna beam pattern to determine the impact of the residual errors on the antenna performance. Figure 4 shows an example of the calculation for a single Monte Carlo trial.

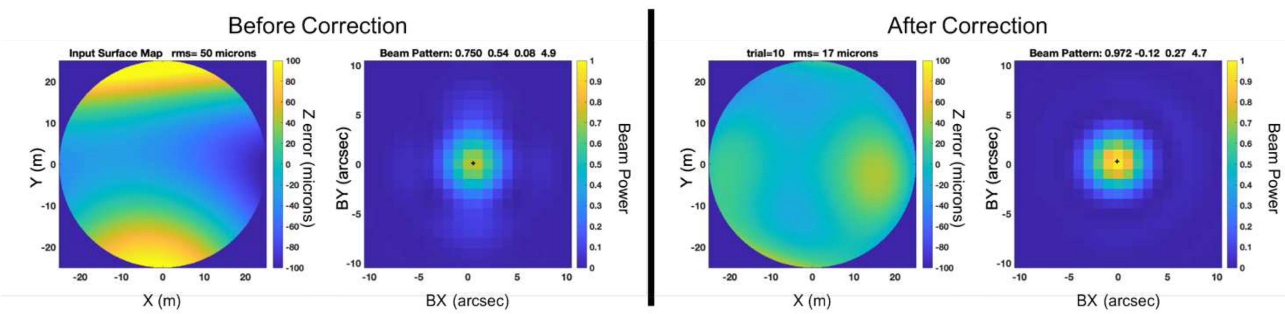

Figure 4. Example of beam pattern calculation for a single Monte Carlo trial of the primary surface measurement system. The left two panels show the surface error map that was input to the Monte Carlo trials and resulting beam pattern at 1.1 mm wavelength. The right two panels show the same results from a single Monte Carlo trial after correction. Beam patterns are fit to determine peak gain, pointing offset, and half power beam width of the main beam. The black cross marks the peak position of the main beam.

Beam pattern results for a series of 200 Monte Carlo trials are illustrated in Figure 5. In addition to the loss of gain due to random residual surface errors, there are two other effects which affect the antenna's performance. First the beam peak position moves on the sky compared to the antenna axis by small amounts characterized by a pointing error of approximately 0.3 arcsec. The second error is that, because the beam peak moves, a detector monitoring the on-axis position will see a decreased signal. For this set of trials, it is found that the median observed gain is approximately 6% below the optimum value.

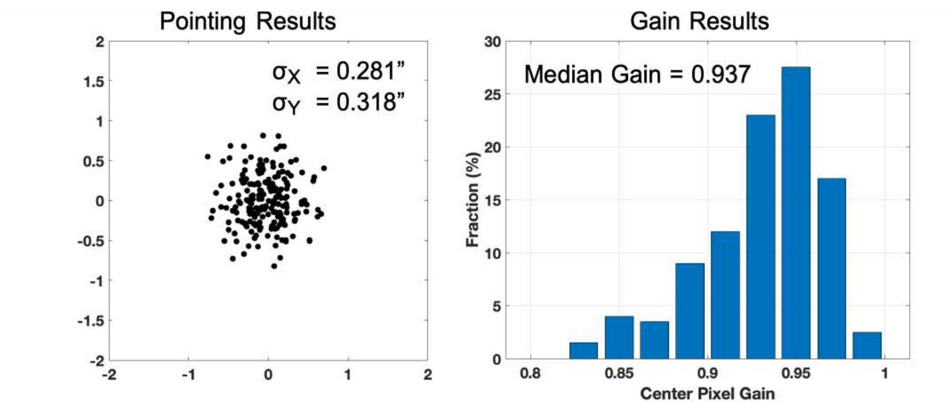

Figure 5. Analysis of beam patterns computed from Monte Carlo trials of the recovery of the reflector surface shape. The left panel shows the location of the peak of the antenna power pattern. The right panel shows a histogram of the values of the power pattern along the antenna axis - uncorrected for the residual pointing offset.

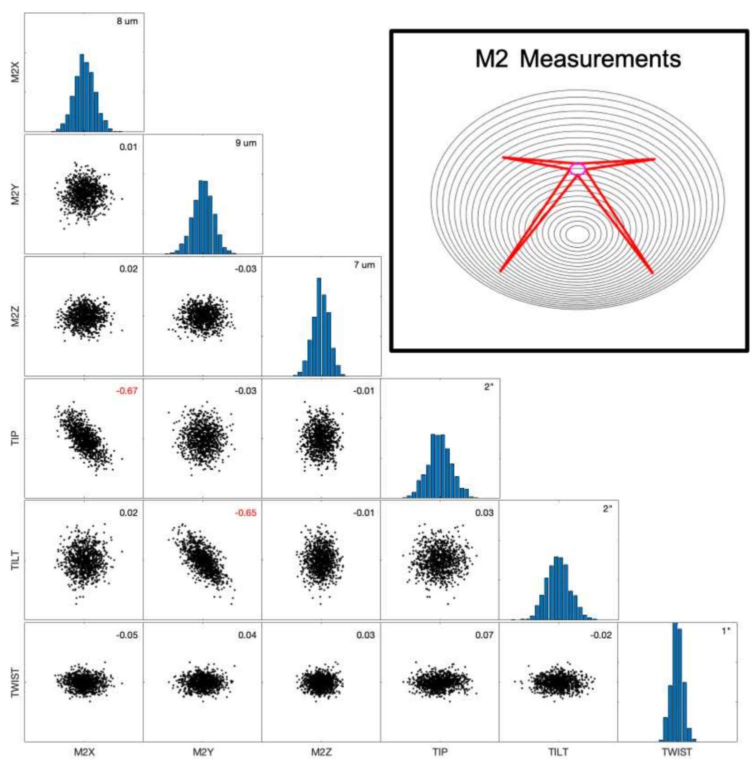

Figure 6. A corner plot showing the results of Monte Carlo simulations of the measurement of all six degrees of freedom in the secondary mirror position with respect to the primary mirror. The measurement approach is shown in the figure inset. Eight point-to-point measurements between locations on the LMT surface and positions at the edge of the secondary mirror. Beams originate at the primary surface near the base of the tetrapod legs. Passive retroreflectors are then placed on the secondary. The system of 8 measurements is used to solve for the six degrees of freedom that are required to locate the secondary mirror in space relative to the surface reference points. We note that translational motions are determined to the 10-micron RMS level. Rotations are measured to the level of ~2 arcseconds RMS.

3.4 Measurement Concept for Secondary Position

The concept of secondary (M2) position measurement with laser ranging devices follows basic ideas presented in previous work[8,9,10]. Figure 6 illustrates our concept for determination of the position of the secondary mirror with respect to the primary. A set of eight point-to-point measurements are made between a location at the base of each tetrapod leg and points attached to the LMT secondary mirror. The points on the secondary mirror can be simple retroreflector targets, which simplifies the implementation of the system. The total of eight measurements is used to determine the secondary location and orientation in space with respect to the reference points on the surface. Thus, we have 8 measurements and 6 degrees of freedom (three translational and three rotational) to be constrained.

We have carried out a Monte Carlo simulation of the measurement process using the nominal relative distance errors of the system. Errors of several microns are found for the translational degrees of freedom; errors on the determination of the rotational angles are at the arcsecond level. Given the simulated results, one can compute the expected antenna properties that would result. Z errors in the secondary position at the level of 11 microns RMS have no effect on the antenna gain, and so the impact on performance is mainly through pointing effects. The X-Y translation errors at the level of 8 microns lead to pointing errors of 0.07 arcsec. The X-Y tilt errors of 2 arcsec lead to 0.16 arcsec pointing errors. If all errors are combined the final RMS pointing error (due to this term in the pointing error budget) would be 0.25 arcsec. An antenna pointing error of this amount means that the beam peak is not on the source and the received power is reduced by 0.5%

4. LABORATORY TESTING OF THE ABSOLUTE MULTILINE TECHNOLOGY INSTRUMENT

We have recently acquired an AMT device and begun testing in the INAOE Aspheric Surfaces Laboratory. This testing phase of the development program allows our metrology team to gain experience with the setup and alignment of the AMT instrument. It has also provided the opportunity to integrate the device with our operational telescope system control software to permit an easy integration of the system upon arrival at the telescope. Figure 7 shows an initial result of monitoring distances under temperature-controlled laboratory conditions. Two channels of the device were arranged to measure distance along the lab floor at a range of 20.6m. The figure shows results of a long monitoring run which indicates a diurnal change of about 20 microns in the length between the stations. The diurnal change shown has been repeated over many days, and we believe, based on experience doing metrology within the lab, that this is likely to be a real effect. The 10-micron bar corresponds to the nominal 5×10^{-7} relative accuracy specification. Our next set of experiments will test the system under outdoor conditions, culminating with testing at the 4600m telescope site.

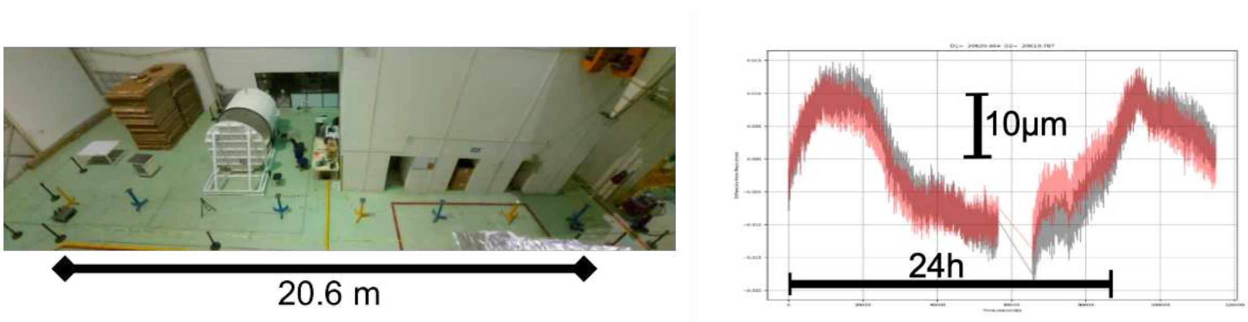

Figure 7. Laboratory testing of the AMT instrument in the INAOE Aspheric Surfaces Laboratory. Two channels of the AMT instrument were set up in the temperature-controlled laboratory at a distance of 20.6m, as illustrated in the left panel of this figure. Measurements for the two channels (Gray and Pink) were recorded during a period of over 24 hours in the test and are shown in the right panel. The measurements show a diurnal variation in the distance between the two stations, which we attribute to an actual relative movement within the building. The 10-micron bar corresponds to the nominal 5×10^{-7} relative accuracy of the instrument.

5. LASERS CAVEATS AND COMMISSIONING

The calculation of expected results based on real time measurements presented in this paper contains a number of simplifications. In addition, there are important real-world effects to consider about the measurements as we continue to develop LASERS. In this section, we will consider some of these effects and summarize our thinking about how they will be dealt with in the final system.

5.1 Precise knowledge of location of the beams on the structure

The LASERS beams measure the distance between two points on the structure with a precision of microns. However, the actual location of the collimator and retroreflector are not that well known. As a first step, the actual locations of beams on the surface will be measured using photogrammetry or laser trackers. However, these techniques do not provide enough accuracy to predict lengths between structural points to the micron level.

To deal with this uncertainty, we expect to pursue a calibration approach to determine the relationship between LASERS measurements and the set of deformations being measured. The approach will be to measure the shape of the surface by some other means while the LASERS system is on and measuring distances between points. This may be done using metrology techniques or through the use of astronomical observations to estimate surface shape (out-of-focus holography[5,6]) or best secondary position. Another approach is to use the secondary mirror positioner to input small changes in the mirror orientation, or the active primary surface to intentionally distort the surface in known ways. Changes in the measured distances that result from these known position changes should then allow the system to be calibrated.

5.2 Three-dimensional motion of points on the surface

LASERS measurements of the shape of the primary surface, described in section 3.3, assumed that a point on the surface only moved up and down along the optical (z) axis of the parabola. However, finite element models of the structure show that translations of the points in the x-y plane will also occur. Motions in this orthogonal direction will also lead to changes in the distance between points on the surface, and so these motions must be accounted for in the analysis. We note that this also pertains to measurements of the position of the secondary mirror since measurements are made with respect to the reflector surface.

The technique outlined in section 3.3 made use of Zernike polynomials as a way to interpolate a surface shape between measurement points. In the actual system, with three dimensional motions, our approach will be to use a more realistic model of the surface. We have explored the use of finite element models of the LMT to provide the necessary information needed to derive surface shape from a set of distance measurements. We find that specific thermal gradients in the structure produce distinctive patterns of surface deformation which can be recognized with a set of distance measurements similar to the simple model illustrated in Figure 3. Therefore, our implementation plan is expected to make use of the finite element modeling to provide a basis set of functional forms to be derived from the LASERS measurements.

5.3 Environmental effects on the measurement

The accuracy of the LASERS distance measurements will be fundamentally limited by knowledge of the index of refraction of the air along the line of sight. The index of refraction is most sensitive to the temperature, and so estimation of the air temperature along the line of sight is critical. Our system will provide measurements of the air temperature at each end of the beam and make use of the average value to determine the index of refraction. However, the outdoor air temperature above the reflector surface may be quite complex. For example, measurements of the antenna surface temperature under solar illumination show that the surface panels are heated to temperatures that are 40 ºC above the ambient air temperature. Therefore, beams along the surface will likely be affected by turbulence during daytime operation. Study of the actual performance of the system under these conditions is a high priority for initial site testing of the instrument.

5.4 Wind loading of the structure

Wind loads on antennas can be important sources of deformation. Winds are variable on short time scales, and when the LMT was designed, it was anticipated that there would be no possibility for real time measurement of the structure to allow for correction of wind deformations. Consequently, the original design emphasized stiffness against wind loads to keep the error contributions due to wind as low as possible.

With LASERS in operation, it is clear that the system will be sensitive to wind deformations of the structure. One may consider a "quasi-static" component of the wind, representing the average wind speed and direction over time as well as a component that fluctuates with time. The latter will lead to an extra source of noise in the LASERS measurements as the structure flexes in response to the changing load. However, we note that averaging measurements over time may permit the "quasi-static" component to be measured and compensated.

6. CONCLUSION

We look forward to working towards one of the original LMT design goals, which called for use of active measurement systems and the active antenna surface to achieve stable performance under a wide range of environmental conditions. The LASERS project provides a path to measure important properties of the LMT structure in real time. The successful realization of this system will provide a path forward for structural measurement and control in the large radio telescopes of the future.

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REFERENCES

[1] Schloerb, P., Aretxaga, I., Chavez, M., Gutermuth, R., Heyer, M., Hughes, D. H., Narayanan, G., Pope, A., Souccar, K., Wilson, G., and Yun, M. (2019). A Decade of US Community Access to the Large Millimeter Telescope Alfonso Serrano. In Bulletin of the American Astronomical Society, volume 51, page 148.

[2] Hughes, D. H., Schloerb, F. P., Aretxaga, I., Castillo-Dominguez, E., Chavez Dagostino, M. C., Colon, E., Erickson, N., Rodriguez, D. F., Gale, D. M., Gomez-Ruiz, A., Rebollar, J. L. H., Heyer, M., Lowenthal, J., Montana, A., Nolasco, M. E. M., Narayanan, G., Pope, A., Rodriguez-Montoya, I., Sanchez-Arguelles, D., Smith, D., Souccar, K., de la Rosa Becerra, M. V., Wilson, G. W., and Yun, M. S. (2020). The Large Millimeter Telescope (LMT) Alfonso Serrano: current status and telescope performance. In Marshall, H. K., Spyromilio, J., and Usuda, T., editors, Ground-based and Airborne Telescopes VIII, volume 11445, pages 447 – 468. International Society for Optics and Photonics, SPIE.

[3] Greve, A. and Bremer, M. (2010). Thermal Design and Thermal Behavior of Radio Telescopes and their Enclosures. Springer, Berlin.

[4] Schloerb, F. P., Sanchez, D., Narayanan, G., Erickson, N., Souccar, K., Wilson, G., Gale, D., Hughes, D. H., and Smith, D. (2016). Calibration and operation of the active surface of the Large Millimeter Telescope. In Hall, H. J., Gilmozzi, R., and Marshall, H. K., editors, Ground-based and Airborne Telescopes VI, volume 9906 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 99066C.

[5] Nikolic, B., Hills, R. E., and Richer, J. S. (2007a). Measurement of antenna surfaces from in- and out-of-focus beam maps using astronomical sources. A&A, 465(2):679–683.

[6] Nikolic, B., Prestage, R. M., Balser, D. S., Chandler, C. J., and Hills, R. E. (2007b). Out-of-focus holography at the Green Bank Telescope. A&A, 465(2):685–693

[7] Schloerb, F. P., Souccar, K., Chavez Dagostino, M. C., Rodriguez, D. F., Gale, D. M., Gomez-Ruiz, A., Huerta, A. L., Hughes, D. H., Sanchez-Arguelles, D. O., and Wilson, G. W. (2020). Moving towards daytime observing at the Large Millimeter Telescope. In Marshall, H. K., Spyromilio, J., and Usuda, T., editors, Ground-based and Airborne Telescopes VIII, volume 11445, pages 1031–1046. International Society for Optics and Photonics, SPIE

[8] Rakich, A., Choi, H., Veillet, C., Hill, J. M., Bec, M., Zhang, Y., Brendel, T., Sitarski, B., Gardiner, M., Kim, D.W., and Rodriguez, S. (2020). A laser-truss based optical alignment system on LBT. In Marshall, H. K., Spyromilio, J., and Usuda, T., editors, Ground-based and Airborne Telescopes VIII, volume 11445, pages 127 – 139. International Society for Optics and Photonics, SPIE.

[9] Rakich, A., Dettmann, L., Leveque, S., and Guisard, S. (2016). A 3D metrology system for the GMT. In Hall, H. J., Gilmozzi, R., and Marshall, H. K., editors, Ground-based and Airborne Telescopes VI, volume 9906 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 990614.

[10] Rakich, A., Schurter, P., Conan, R., Hill, J. M., Gardiner, M., Bec, M., and Kuhn, O. (2018). Prototyping the GMT telescope metrology system on LBT. In Marshall, H. K. and Spyromilio J., editors, Ground-based and Airborne Telescopes VII, volume 10700 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, page 107001S

[11] Dale, J., Hughes, B., Lancaster, A. J., Lewis, A. J., Reichold, A. J. H., and Warden, M. S. (2014). Multi-channel absolute distance measurement system with sub ppm-accuracy and 20 m range using frequency scanning interferometry and gas absorption cells. Optics Express, 22(20):24869

[12] Gale, D.M., Schloerb, F.P., León Huerta, A., Lucero Álvarez, M., Cabrera Cuevas, L., Tecuapetla Sosa, E., Castro Santos, D., Tzile Torres, C., Hernández Rios, E., "Photogrammetry mapping and alignment of the LMT 50-meter primary reflector," Proc. SPIE 10706, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, 1070646 (2018)

[13] Holst, C. and Kuhlmann, H. (2014). Aiming at self-calibration of terrestrial laser scanners using only one single object and one single scan. Journal of Applied Geodesy, 8(4):295–310.

[14] Holst, C., Schunck, D., Nothnagel, A., Haas, R., Wennerback, L., Olofsson, H., Hammargren, R., and Kuhlmann, H. (2017). Terrestrial Laser Scanner Two-Face Measurements for Analyzing the Elevation-Dependent Deformation of the Onsala Space Observatory 20-m Radio Telescope's Main Reflector in a Bundle Adjustment. Sensors, 17(8):1833

[15] Lockman, F., Salas, P., and Seymour, A. (2020). LASSI — Real Time Surface Adjustment of the Green Bank Telescope. In American Astronomical Society Meeting Abstracts #236, volume 236 of American Astronomical Society Meeting Abstracts, page 142.01

[16] Salas, P., Marganian, P., Brandt, J., Shelton, J., Sharp, N., Egan, D., Sizemore, N. D., Beaudet, C., Jensen, L., Bloss, M., Seymour, A., Schwab, F. R., and Lockman, F. J. (2020). The laser antenna surface scanning instrument. In

Marshall, H. K., Spyromilio, J., and Usuda, T., editors, Ground-based and Airborne Telescopes VIII, volume 11445, pages 1123 – 1128. International Society for Optics and Photonics, SPIE.

[17] Salas, P., Marganian, P., Seymour, A., Brandt, J., Egan, D., Jensen, L., Sizemore, N., Bloss, M., Beaudet, C., Schwab, F., and Lockman, F. (2020). LASSI: keeping the Green Bank Telescope in shape. In American Astronomical Society Meeting Abstracts #235, volume 235 of American Astronomical Society Meeting Abstracts, page 175.16