PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Implementation of a laser-truss based telescope metrology system at the Large Binocular Telescope

Rodriguez, Stephanie, Rakich, Andrew, Hill, John, Kuhn, Olga, Brendel, Trenton, et al.

Stephanie Rodriguez, Andrew Rakich, John Hill, Olga Kuhn, Trenton Brendel, Christian Veillet, Dae Wook Kim, Heejoo Choi, "Implementation of a laser-truss based telescope metrology system at the Large Binocular Telescope," Proc. SPIE 11487, Optical Manufacturing and Testing XIII, 114870E (20 August 2020); doi: 10.1117/12.2576438

SPIE.

Event: SPIE Optical Engineering + Applications, 2020, Online Only

Implementation of a laser-truss based telescope metrology system at the Large Binocular Telescope

Stephanie Rodriguez,[1] Andrew Rakich,[2] John Hill,[3] Olga Kuhn,[3] Trenton Brendel,[1] Christian Veillet,[3] Dae Wook Kim,[1,3,4] and Heejoo Choi [1,3,*]

[1]Wyant College of Optical Sciences, Univ. of Arizona, 1630 E. University Blvd., Tucson, AZ 85721, USA;
[2]GMTO Corporation, 465 N Halstead St, STE 250, Pasadena, CA, 91107, USA;
[3]Large Binocular Telescope Observatory, Univ. of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA
[4]Department of Astronomy and Steward Observatory, Univ. of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA

ABSTRACT

Large ground-based telescopes are prone to perturbations caused by environmental factors that affect the mechanical structure of the telescope that can cause collimation loss and image quality degradation. The Telescope Metrology System (TMS) is a metrology method under development at the Giant Magellan Telescope (GMT) and prototyped on the Large Binocular Telescope (LBT) to monitor and maintain collimation and pointing. TMS measures the precise position and orientation of a telescope's primary mirror in relation to other telescope elements. Currently, prototyping has progressed to TMS operation at prime focus between LBT's two 8.4m primary mirrors and the Large Binocular Camera (LBC), a pair of prime focus correctors and wide-field detectors. TMS utilizes a multi-channel absolute distance measuring (ADM) interferometer to create a laser truss by determining the distance between fixed points on the primary mirror and the LBC. By performing a kinematic analysis of the ADM data, the relative position and orientation of the primary mirror and LBC can be determined. With knowledge of the position of the telescope, an optical layout model can be created using TMS data as input. This allows for iterative simulation of field aberrations and loss in image quality due to misalignment of the telescope. This will allow for collimation and pointing to be actively monitored and maintained during an observation. This paper will discuss the process of implementing TMS on LBT and the challenges that arose.

Keywords: Metrology, Telescope Alignment, Active Optics, Absolute Distance Measuring, Large Binocular Telescope

1. INTRODUCTION

1.1 Large Binocular Telescope

The Large Binocular Telescope (LBT) is located atop Mount Graham in southeastern Arizona sitting at an elevation of 3200m. It is comprised of two Gregorian telescopes on a common altitude and azimuth mount. Each telescope has an 8.4m primary mirror. This gives the telescope an 11.8m effective aperture and a 22.8m interferometric baseline. LBT is host to a suite of scientific instruments including optical wide field cameras (LBC), several spectroscopic instruments (LUCI, MODS, and PEPSI), and interferometric instruments (e.g. LBTI). To accommodate the various science instruments the telescope operates at prime focus as well as at bent and direct Gregorian modes shown in Figure 1. To engage Gregorian and bent Gregorian modes there are deployable adaptive secondary mirrors and tertiary mirrors. In total there are 12 unique focal stations on LBT [1]. Operating such a large and complex optical system at seeing limited resolution requires a sophisticated active system to compensate for environmental perturbations.

*hchoi@optics.arizona.edu

Optical Manufacturing and Testing XIII, edited by Dae Wook Kim, Rolf Rascher,
Proc. of SPIE Vol. 11487, 114870E · © 2020 SPIE · CCC code:
0277-786X/20/$21 · doi: 10.1117/12.2576438

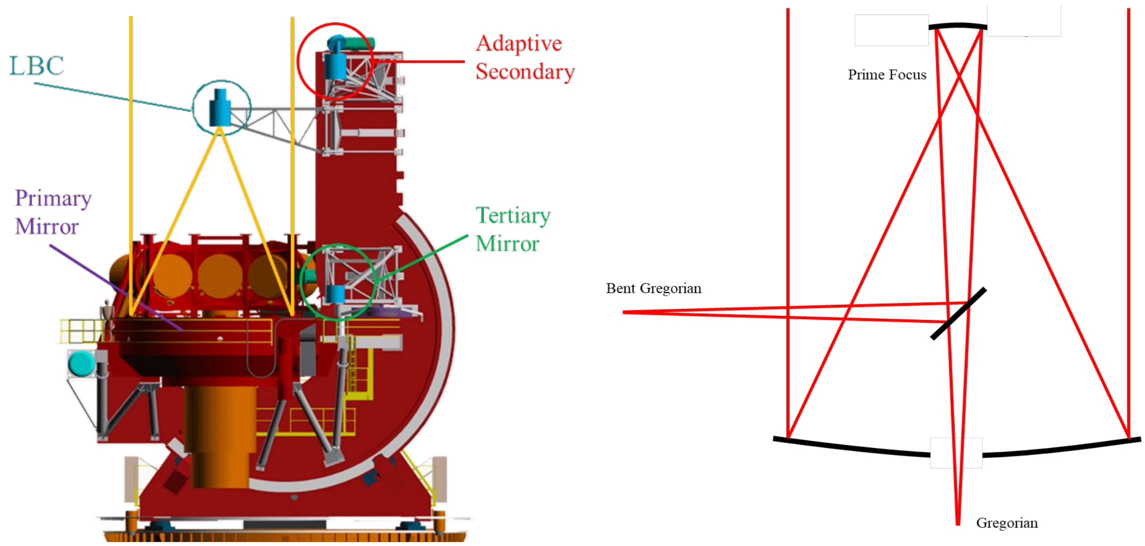

Figure 1 (left) Prime focus is engaged for use with the Large Binocular Camera (LBC). The telescope is pictured at zenith. Elevation changes occur along the c-ring structure. (right) Each mirror has three focus modes: prime focus, Gregorian, and bent Gregorian. Prime focus has a single focal station operating at F/1.142. The Gregorian and bent Gregorian operate at F/15 [2].

The Large Binocular Cameras are the prime focus instruments on LBT. Each side of the binocular houses one camera on a deployable arm. The cameras can be operated together in binocular mode, or individually in monocular mode. LBC red operates from 550nm to 1 micron. LBC blue operates from 350nm to 650nm. The combination of the two cover the optical spectral range and allow simultaneous deep imaging in two filters. They both offer wide fields of view of 23 arcmin x 25 arcmin. The focal plane is covered by four 2048x4806 pixel CCDs. Three are aligned side by side and a fourth lies above the other three and is rotated 90 degrees. The pixels are 13.5 microns and cover 0.226" on the sky.

1.2 Active optics on the Large Binocular Telescope

When operating a telescope, it is crucial to maintain collimation and pointing over an exposure. Failure to do so can cause image quality degradation via aberration and or image trailing. A well-collimated telescope will provide good image quality free from aberrations due to misalignment, although aberrations from other sources may be present. LBT is on a mechanical azimuth and altitude mount which controls gross pointing. Changes in altitude and azimuth cause changes in the gravitational effects felt by the optics, especially the primary mirror and telescope structure (swing arm). Controlled motion of the primary mirror is the main collimation control on LBT. In turn these adjustments can cause the telescope to lose pointing. LBC does not require absolute pointing at the beginning of an exposure. Therefore, these pointing changes do not strongly constrain collimation. Once the exposure begins, pointing must be maintained [3]. A balance must be met to ensure that image quality does not degrade during observation. Maintaining collimation and pointing is especially important when using a wide field instrument such as LBC.

Large ground-based telescopes are affected by various environmental factors including mechanical deflections due to gravitational forces, thermal effects, and hysteresis. Active optics are used to mitigate these environmental factors and are an essential part of any ground-based telescope. Active optics corrects larger low order aberrations (tip, tilt, coma, and astigmatism) on longer time scales. This allows the optimal dynamic range of the adaptive optics system to be conserved for smaller aberrations that occur over very short time scales.

LBC uses extra-focal pupil imaging to measure the wavefront, along with control loops to drive the prime focus active optics. The extra-focal images are produced by movement of the primary mirror along the optical axis. These images are used to collimate the telescope and determine how best to correct aberrations [4]. The primary control algorithm for collimation of LBC is the Focal Plane Image Analysis (FPIA), which uses a geometric approach to analyze low order aberrations. When the telescope is perfectly collimated the extra-focal image is non-aberrated and looks like then entrance pupil of the telescope. The size, centration of the central obscuration, ellipticity, and ratio of central obscuration size to outer diameter of the extra-focal image can determine focus, coma, astigmatism, and spherical aberration respectively [5].

Once the aberrations are known the proper corrections to the primary mirror position and shape can be made to improve collimation.

The extra-focal pupil technique is useful for achieving collimation at the beginning of acquiring a new field. However, once an exposure has begun the telescope cannot be defocused to obtain the extra-focal pupil images for analysis. Since FPIA is the main active control method for observation with LBC LBT is left in a vulnerable position. Currently a series of look up tables are used to position the primary mirror while at various elevations and under given environmental conditions. These look up tables provide gross correction, but struggle to achieve and maintain good image quality in adverse thermal conditions. These could be refined with the help of the metrology described in this paper. Therefore, in the case of the LBCs another technique must be developed to help ensure that collimation can be maintained over an exposure while still achieving proper pointing.

2. TELESCOPE METROLOGY SYSTEM OVERVIEW

2.1 Telescope Metrology System background

The Telescope Metrology System (TMS) measures the precise position and orientation of a telescope's primary mirror in relation to other optical elements. This allows for collimation and pointing to be monitored and maintained during observation without the need for wavefront sensing or image analysis. This is of particular interest with regards to the use of prime focus on LBT since wavefront-sensing means are unavailable for use with LBC while an exposure is underway.

The Telescope Metrology System is an ongoing development program, developed by staff at the Giant Magellan Telescope (GMT) [6]. Since 2017 there has been a mutually beneficial collaboration between LBT and GMT in the technical development of a TMS. TMS was installed on LBT to act as a testbed for the planned GMT metrology method. LBT's 8.4m primary mirrors are approximately the same size as each of the seven segmented mirrors on GMT [7]. This allows GMT to develop and characterize the system, while also adding an element to LBT's active optics system. The prototyping of TMS on LBT is a three-phase process. The first phase, acquiring a working TMS for use at prime focus, is covered in the scope of this paper. The next two phase are outside the scope of this paper and involve the use of TMS at bent Gregorian and in interferometric observation.

2.2 Overview and system requirements

The Telescope Metrology System uses changes in distance from points around the primary mirror to retroreflectors on the prime focus instrument to calculate the precise position and orientation of the elements in relation to one another. Using a multichannel absolute distance measure interferometer, a laser truss is created between collimators positioned around the primary mirror and retroreflectors on LBC. If LBC is taken to be fixed the changes in lengths of the legs of the laser truss can be used to determine the relative movement of the primary mirror in 6 degrees of freedom: lateral x, y, z movement and rotational Rx, Ry, and Rz movement. Knowledge of the precise position of the primary mirror can be a valuable tool in an active optics control system.

TMS operates without the need for wavefront sensing elements and without adding any additional optical elements in the telescope's optical path [7]. The measurement channel hardware is comprised of fiber routed to the telescope, collimators around the primary mirror, and retroreflectors mounted on LBC and other parts of the mechanical structure of the telescope. All hardware elements are attached to mechanical structures, to passively monitor the position of the optical elements. Collimators are mounted around the primary mirror and aligned to retroreflectors on LBC to create the laser truss as shown in Figure 2.

The legs of the laser truss are measurement arms of the TMS system. To measure the distance between the collimator and retroreflector, TMS utilizes an Etalon Absolute Multiline Technology (EAMT). The EAMT is an absolute distance measuring interferometer that uses a dynamic frequency scanning technique capable of measuring multiple channels with micron level accuracy. When airpaths are adequately temperature-sensed and corrected for variation in refractive index of air, the EAMT has a measurement uncertainty of 0.5 microns per meter and can measure distances up to 20m. The EAMT uses fiber tip Fizeau interferometry [8]. This allows the measurement channels to remain simple. The channels consist of a telecom fiber coupled to a collimator that launches the beam to a retroreflector. The ability to simultaneously measure many channels is especially useful for TMS, as the kinematic analysis requires a minimum of 6 channels to calculate the relative position and orientation of the primary mirror and LBC. This also allows for redundant laser truss channels and additional channels needed to measure the diameter of the primary mirror and for use at Gregorian and bent Gregorian focus in the next phases of the project.

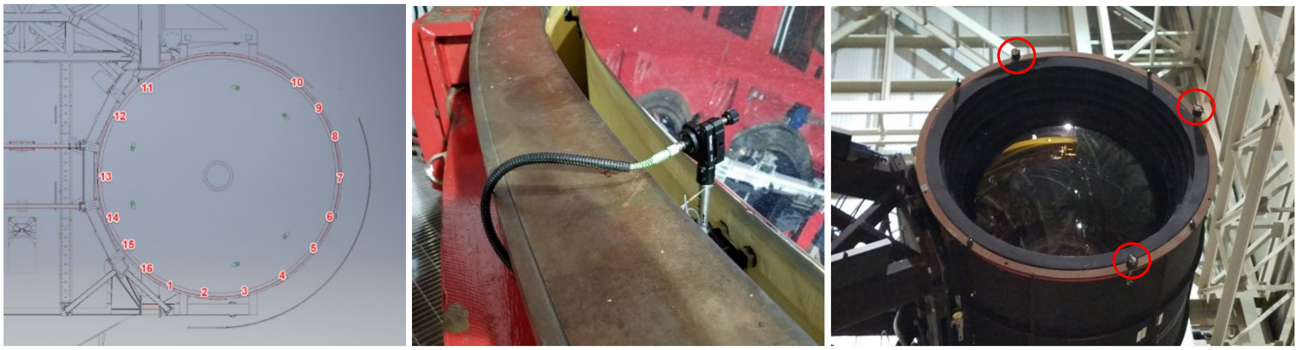

Figure 2 Primary mirror cell positions around the primary mirror (left). There are a total of 16 collimator mounts attached directly to the primary mirror using silicone sealant and Invar base to prevent damage to the primary mirror due to thermal expansion. The collimator mounts are then magnetically coupled to the mirror bases (center). There are 9 collimators aligned to retroreflectors on LBC. Three retroreflectors are installed on the outer rim of the LBC (right, red circles).

The primary mirrors have 6 degrees of freedom for lateral x, y, and z motion and rotational Rx, Ry, and Rz motion. Primary mirror motion is induced by movement of the hexapod hardpoints. Each hardpoint is housed in a cylinder with a diameter of 6mm and a height of 6mm. The range of motion of the hardpoints define the range of motion of the primary mirror. Lateral motion in the x and y direction has a range of ±2.0 mm while the z direction (along the mirror axis direction) has a range of ±2.6 mm. Rotational motion in Rx, Ry, and Rz has a range of ±100 arcsec.

The primary mirror also has an array of actuators that can induce 56 Zernike polynomial terms onto the surface of the mirror that may be used in conjunction with hardpoint motion. The actuators can be used to compensate for mirror bending due to thermal and gravitational effects, as well as alignment aberrations. LBC is deployed on a swing arm at prime focus, and although it can change position due to mechanical deflections of the swing arm, it is considered a fixed element.

A kinematic analysis is performed to translate laser truss leg measurements from the EAMT into position and orientation information for the relative position and orientation, or "pose" of the LBC correctors to the primary mirror. The kinematic analysis is based on the mechanical principle of a Stewart-Gough hexapod platform, in which the desired motion of a platform relative to its base is induced by controlled changes in the length of the legs of the platform. The TMS requires known changes in leg length to determine the motion of the system elements. This is accomplished through an inverse kinematic technique described later, giving the precise position and orientation of the primary mirror.

3. CONFIGURING TMS ON LBT

The first step in configuring TMS on LBT is to determine the available channels of the EAMT on the telescope. The signal strength of each channel was probed at every connection point along the fiber. This process helps determine where the signal is lost along the fiber route. The return signal strength from the EAMT software was used to establish the status of the channel. Noise on the channel can give return strength up to 4-5%, which will still produce distance data causing noise error in the TMS kinematic analysis calculations. Therefore, a signal strength of greater than 10% is preferred to produce an accurate measurement and to minimize noise error.

A minimum of 11 channels are needed for TMS operation at prime focus (9 for LBC and 2 for primary mirror diameter). There are currently fifteen available channels on the mirror cell with enough return signal to make a measurement. Fortunately, that is enough channels to deploy TMS in monocular configuration.

With knowledge of operational channels, a configuration of the laser truss is built. Collimators around the primary mirror cell are aligned to retroreflectors on the LBC as shown in Figure 3. Three collimators are aligned to each of the three LBC retroreflectors. This provides a "redundant truss" as in principle six channels to three retroreflectors is the minimum requirement, but redundancy is deemed useful for system stability and error checking. The optimal separation of collimators around the mirror cell per retroreflector is 120 degrees. An attempt was made to approach this optimal positioning as the mirror cell position and available channels allowed. Two channels measure the diameter of the primary mirror separated by approximately 90 degrees. Although this is not used in the pose calculations it can be used to monitor and compensate for thermal expansion of the primary mirror.

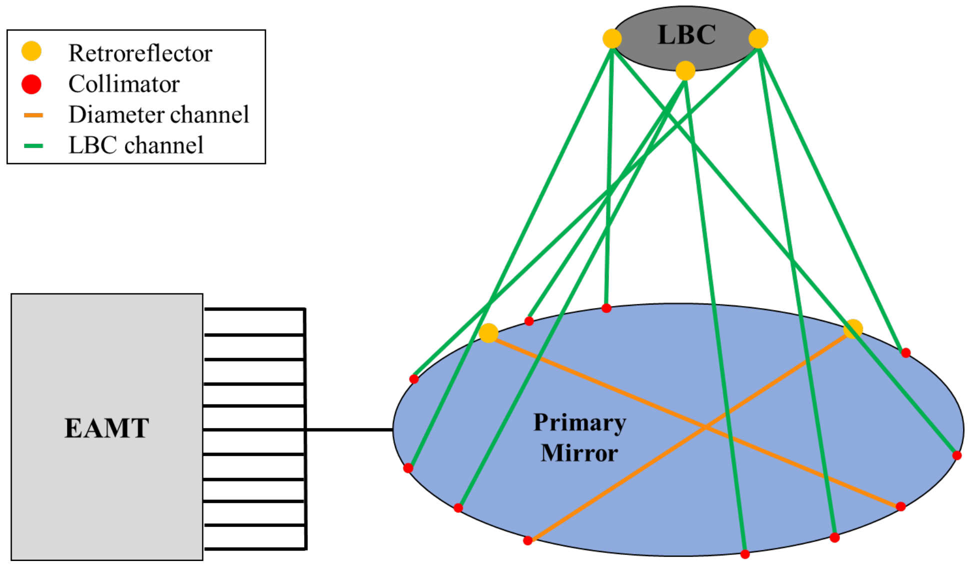

Figure 3 Collimator and retroreflector scheme on TMS. Fiber channels are routed from the EAM to the collimators around the primary mirror. The collimators are aligned to three retroreflectors on LBC to create the laser truss. Two retroreflectors on the primary mirror are used to monitor the diameter of the mirror.

An aspect of the kinematic analysis requires the positions of the retroreflectors and collimators to be defined in a reference frame. A laser tracker survey is performed to determine the location of the collimators and retroreflectors in space. The distance measuring accuracy of the laser tracker is ± 25 microns with resolution of 0.1 microns, which is sufficient for the planned use. The acquired points can be extrapolated in CAD software to create shapes, filtering out noisy points. The laser tracker survey defines the origin of the reference frame to be at the vertex of the primary mirror.

4. DATA PROCESSING: KINEMATIC ANALYSIS

With TMS functionality restored the distance data is converted into position and orientation of the primary mirror (pose). This is done using an inverse kinematic technique that will be described in Section 4.2. The pose data can then be used to maintain the optics pose and to recover the stored baseline pose.

4.1 Input data and data pipeline

Multiple applications must be used to complete the simulation process. First channel length data must be collected from the EAMT software. The EAMT collects interferometric data from each of the channels, producing an OPD. It then corrects the OPD to a vacuum length using the Ciddor equation [9] together with temperature, pressure, and humidity data collected from its sensors. This data is then loaded into MATLAB to perform the kinematic analysis. The kinematic analysis returns data in the form of a matrix containing x, y, and z positions and Rx, Ry, and Rz rotations for each pose of the primary mirror. A summary of the data flow is shown in Figure 4.

Noise in the distance measurements from the EAMT can cause errors in the pose calculation. When a beam is broken the EAMT still returns a distance value, though the value is either very large or small. A "sanity check" step determines if the value given by the EAMT is valid for use in the calculation. A check is performed in MATLAB to ensure that the distance reading from the EAMT is valid. Since the range of the motion is known to be on the order of millimeters any large change in laser truss leg length would be impossible and must be rejected. If the leg length changes by greater than 1 % (10 cm on LBC test) of the original distance given by the laser tracker survey that data is deemed invalid. This check is performed for every set of laser truss leg length data given by the EAMT. Three retroreflectors on LBC comprise one end of the laser truss. A minimum of six laser truss legs in various configurations are needed to perform the kinematic analysis. There can be two channels per LBC retroreflector or there can be three, two and one channels on each of the three LBC retroreflectors. If a channel measurement is deemed "bad" it must be removed from the kinematic analysis and the Jacobian matrix must be updated before the pose can be calculated. If an insufficient number of channels are available to make a calculation the data set is discarded, and the next set of data is analyzed. Therefore, it is still possible to calculate the pose if channels are lost, whether due to misalignment, beams moving out of lateral range of retroreflector, or damage to the fiber channel. The redundancy in the number of channels ensures that a pose calculation can be made despite noise or collimator misalignment.

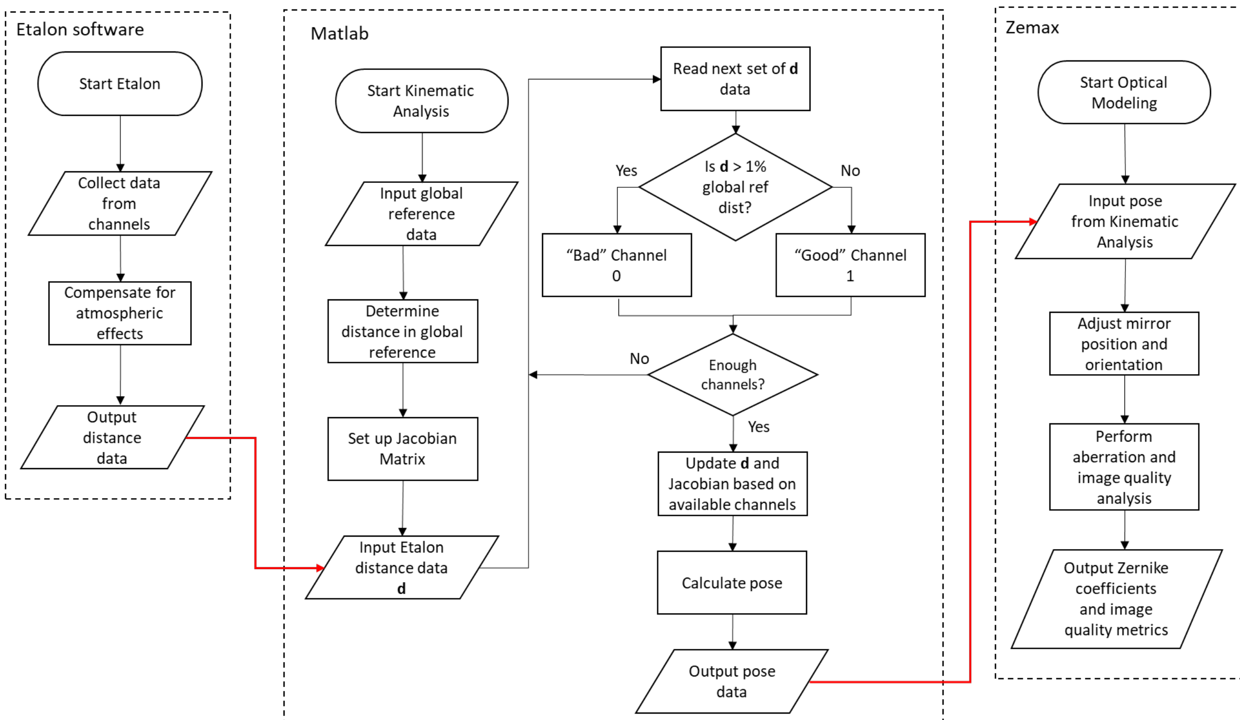

Figure 4 Data pipeline from the Etalon Absolute Multiline Technology to kinematic analysis performed in MATLAB to image quality and aberration analysis in Zemax OpticStudio. Currently the process is modular, with each program working independently. The red arrows indicate a transfer of data from one program to the next, which is performed manually.

4.2 Hexapod inverse kinematics

The kinematic analysis is based on the principles of a Stewart-Gough platform in which a platform and base are connected by six legs at three points on the platform and six points on the base, creating a hexapod geometry as shown in Figure 5. A Stewart-Gough platform is a mechanical system which uses actuators to drive changes in the length of the legs inducing a change the position of the platform. For the TMS, the legs of the platform are the channels of the EAMT constituting the laser truss between the primary mirror and the LBC. In a traditional Stewart-Gough platform forward kinematics are used to map desired changes in position and orientation of the platform to changes in leg length. In the case of TMS on LBT, the leg length is known, and the position and orientation of the primary mirror must be determined. This is accomplished using an inverse kinematic technique, which produces a Jacobian sensitivity matrix for relating leg-length changes to modal pose changes, then uses the Moore-Penrose pseudoinverse of this matrix to calculate modal pose changes from a vector of leg-length changes [10].

The Jacobian matrix is the foundation of the kinematic analysis technique and must be defined first. The Jacobian matrix defines sensitivity of position and orientation changes in the platform (pose) relative to the base to changes in truss leg length. When the Jacobian is multiplied by the changes in pose and orientation the change length of the legs of the platform is defined by

$$ {}^{l}SC_x \hat{x} = \Delta l \qquad (1) $$

where ${}^{l}SC_x$ is the Jacobian matrix, $\hat{x}$ is the pose matrix, and Δl is the change in leg length corresponding to the desired change in pose. This is a simple linear algebra equation that is the basis for the kinematic analysis of a Stewart-Gough platform.

The Jacobian is formed using the global reference data obtained during the laser tracker survey taken while the telescope was collimated at zenith. First the laser truss legs must be established. The legs of the laser truss are defined as vector l_i

between retroreflector points c_i and the collimator points b_i as determined by the laser tracker survey. Then to simplify the calculation the unit vector of l_i is used where $\widehat{e_\iota}$ is the unit vector of the i^th leg of the truss.

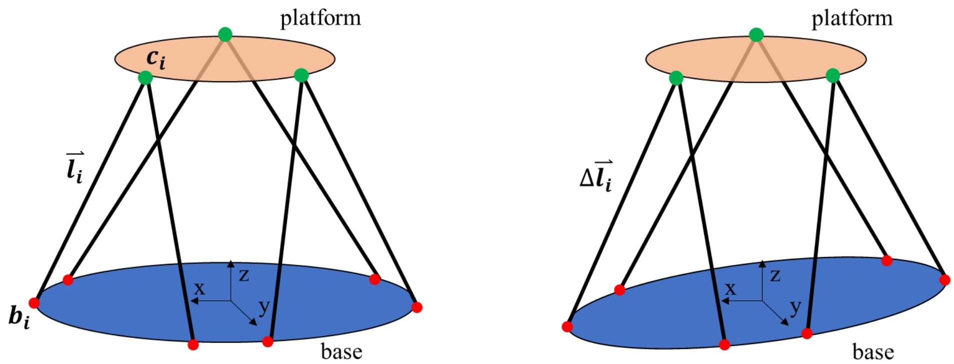

Figure 5 The Stewart-Gough platform in its initial position consists of a platform held parallel to a base supported by legs of length l (left). Changes in leg length Δl are made to move the platform to a desired position and orientation relative to the stationary base (right).

The Jacobian matrix ${}^{l}SC_x$ is created by cross multiplying the position of the retroreflectors c_i with the unit vector $\widehat{e_\iota}$ for the i^th leg of the truss and then taking the transpose. This defines the sensitivities to rotation of the primary mirror around its x, y, and z axis with origin at the vertex of the primary mirror. The sensitivities to translation are the transpose of the unit vector of the i^th leg of the truss and make up the last column of the matrix.

$$ {}^{l}SC_x = \begin{vmatrix} (c_1 \times \widehat{e_1})^T & \widehat{e_1}^T \\ \vdots & \vdots \\ (c_n \times \widehat{e_n})^T & \widehat{e_n}^T \end{vmatrix} \tag{2}$$

The Jacobian is an n×6 matrix that defines the system sensitivity to the six degrees of freedom in rotation and translation.

When using forward kinematics, the Jacobian is multiplied by the desired position and orientation to determine the changes in leg length needed to achieve the desired pose.

$$ \left(\begin{pmatrix} {}^{1}SC_1 & \cdots & {}^{1}SC_m \\ \vdots & \ddots & \vdots \\ {}^{n}SC_1 & \cdots & {}^{n}SC_m \end{pmatrix} \right) \begin{pmatrix} \theta_x \\ \theta_y \\ \theta_z \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \Delta l_1 \\ \vdots \\ \Delta l_n \end{pmatrix} \tag{3}$$

To map changes in laser truss leg length to changes in position and orientation the inverse of the Jacobian matrix ${}^{x}SC_l$ must be used. This is the inverse kinematic technique. The inverse Jacobian can then be used to determine the pose for any given data set of laser truss leg lengths using a simple matrix multiplication.

$$ \hat{x} = \left({}^{l}SC_x \right)^{-1} \widehat{\Delta l} \tag{4}$$

where $\hat{x}$ is the pose matrix defining the position and orientation of the primary mirror and $\widehat{\Delta l}$ is the change laser truss leg length as reported by the EAMT. Note that the over-determined system described above in general produce a matrix that is non-invertible, but in such cases the pseudoinverse provides the optimum solution.

It is important to note that the technique described above differs from that used in reference 7, in which case the EAMT system software was used to give point deflections of each retroreflector. The new technique has several advantages over what has been done previously, allowing dynamic channel deletion and the use of telescope temperature telemetry.

4.3 Validation of TMS using known movement

To validate the TMS, the telescope control system (TCS) was used to induce known primary mirror movement. The telescope motions were then compared to the pose data from the TMS.

The test was performed in stable environmental conditions, at zenith under a closed dome. Keeping the telescope at zenith, ensures that there are no varying deflections in mirror position due to gravitational effects. Performing the test under a close dome minimizes the amount of errors due to environmental fluctuations such as rapid changes in ambient temperature humidity, and pressure. Each of the six degrees of freedom of movement of the primary mirror were individually tested. The primary mirror was moved incrementally over the full range of motion or until the beams of the laser truss were broken which is over the normal telescope operation mode. The results of the induced rotational and lateral motion compared to the measured motion are shown in Figure 6.

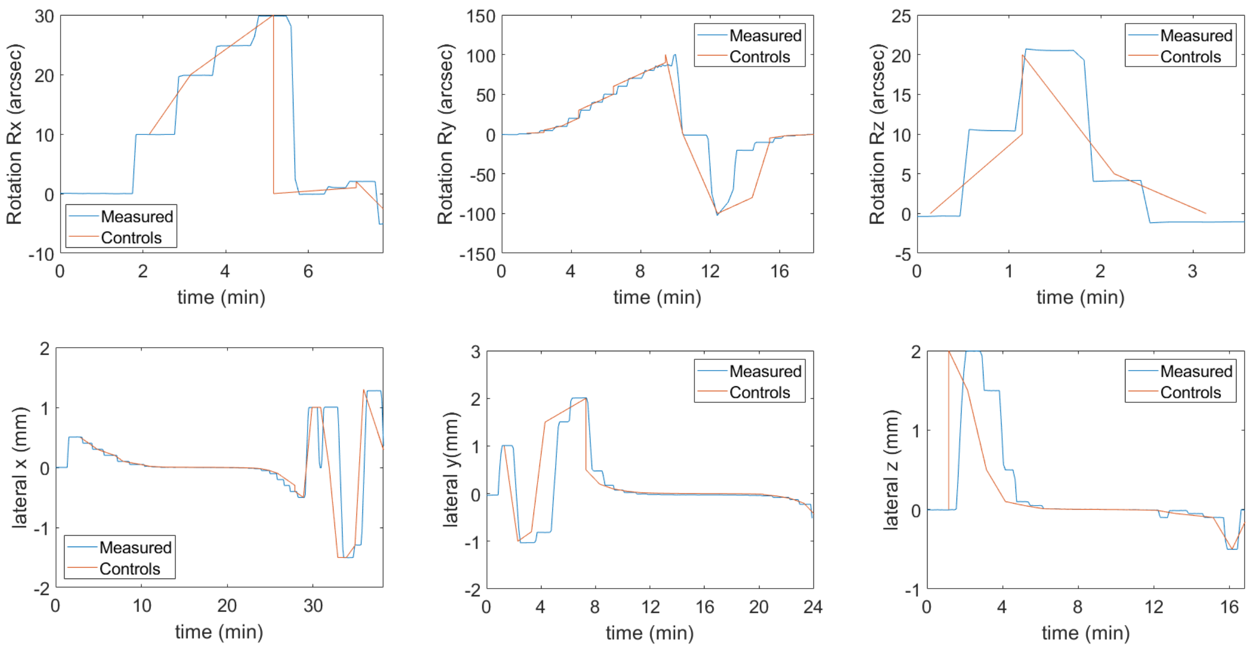

Figure 6 TMS data for Rx, Ry, and Rz rotational (top) and x, y, and z lateral motion (bottom). In all plots the red line represents the induced motion of the primary mirror and the blue line corresponds to the measured change in position and orientation. For all controlled steps in motion TMS determined the corresponding pose, although there is some delay due to different sampling times between TCS and TMS.

The calculated pose showed a maximum deviation from TCS controls for the given set of data of 1.7µm for lateral motion and 0.1 arcsec for rotational motion. These are within the expected range or deviation, and account for a very small percentage of the commanded motions. These deviations cannot be attributed to error in pose calculation alone. There are other sources of error that contribute to deviations from TCS controls. Data is only compared to TCS controls at periods when the primary mirror is stationary. The data was taken with relatively short periods of rest at each step in the motion, which could cause oscillation in the primary mirror position as it stops and starts motion. It is also possible that there is hysteresis in the mechanisms that control primary mirror movement. If TCS is not accurately driving the primary mirror position this will compound the error between TCS control inputs and TMS pose data. Fortunately, the error is also relatively small compared to the requirements of telescope alignment. The system's ability to contribute to telescope alignment has been validated [7]. It is reasonable to expect that the small percent of error in pose calculation will not greatly impact system performance.

5. DATA PROCESSING: OPTICAL MODELING

5.1 Optical-modeling using TMS data

Once the validity of the pose of the TMS data was verified it could then be used to perform aberration and image analysis using an optical model. This allows for a wide variety of simulation and analysis to be performed using measured telescope position and orientation. An optical model of the LBT in prime focus mode, including the optical elements of the LBC are modeled. The goal of optical modeling is to determine how misalignment of the telescope affects the star image. The optical elements are assumed to maintain their shape, though in reality, the optics will endure bending, mechanical strain, and thermal expansion. Such considerations are outside the current scope of this project but are being be considered in ongoing development of the metrology methodology using mechanical simulation analysis.

The pose data from TMS is input into the optical model. Pose is given as lateral x, y, and z displacement and Rx, Ry, and Rz rotational displacement. At each pose of the primary mirror system performance is analyzed. The effect of system misalignment propagates through the system and is examined at the image plane. When using TMS data from on-sky observation, the image simulation using the optical model can provide the expected image quality for all fields and guide the pointing and collimation procedure.

5.2 Aberration and image quality analysis

Performing aberration analysis can help determine what aberrations are caused purely by optical misalignment, making it possible to disentangle misalignment aberrations from aberrations caused by other factors. This information can be used to determine what kind of corrections to primary mirror position need to be made to improve image quality. Using a TMS data set taken over induced Rx motion the Zernike coefficients for first order coma are shown in Figure 7. Coma was observed for both the on-axis and off-axis field. Z7 is oriented parallel to the increase in field angle and the field dependence is seen. Z7 shifts in magnitude at an off-axis field position. Z8 is oriented perpendicular to the field and therefore it does not have field dependence in that direction.

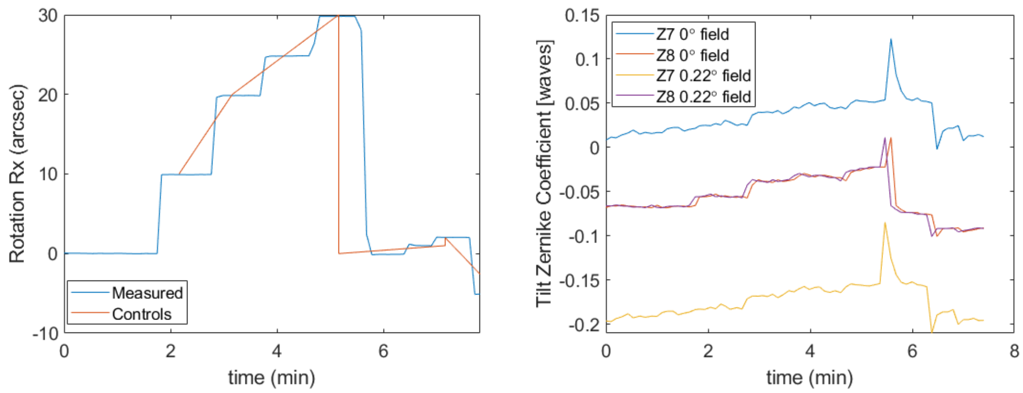

Figure 7 Aberration analysis for induced Rx motion. The first order coma Zernike terms are shown for on-axis and off-axis fields (right) for the Rx motion of the primary mirror (left).

When an optical system is decentered or tilted it becomes non-rotationally symmetric. A viable tool when analyzing a non-rotationally symmetric optical system is a spot diagram. In a more practical sense, when viewing star images, the spot size and shape produced in the optical model can indicate misalignment patterns like those observed with FPIA. The change in RMS spot size due to lateral x decenter is shown in Figure 8. Spot size analysis only shows changes in magnitude, not sign. Using TMS data the sign ambiguity of the change in spot size can be resolved.

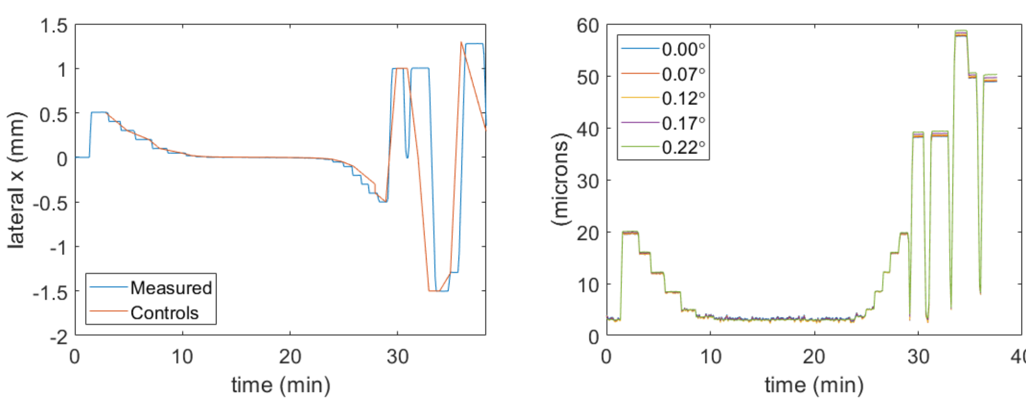

Figure 8 The effect of lateral x decenter (left) on the image RMS spot size (right). Using TMS pose data the spot size is determined across several fields and is found to correlate well to the induced lateral motion.

6. CONCLUSION AND FUTURE WORK

Functionality of TMS was achieved at prime focus in monocular mode. The position and orientation of the primary mirror and LBC was successfully determined using an inverse kinematic analysis of noise-filtered EAMT distance data. TMS pose data was integrated into an optical model. The optical model was used to iteratively perform image quality and aberration analysis.

The proposed metrology technique has been verified by using controlled movements of the primary mirror. Next, the system will be used to passively monitor primary mirror position during on-sky observation and the results correlated to image quality data from FPIA.

The next step in the prototyping process is preparing TMS for binocular use at prime focus. Fortunately, the process for deploying TMS on the SX side of the telescope is identical to the process for the DX side. The same kinematic analysis can be used with modifications to the Jacobian based on the difference between the collimator and retroreflector positions on the SX and DX sides.

7. REFERENCES

[1] Ashby, D. S., Biddick, C., and Hill, J. M., "Active optics control development at the LBT," Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91452S (22 July 2014).

[2] Hill, J. M., "The Large Binocular Telescope," Applied Optics 49(16), D115-D122 (2010).

[3] Terret, D., *Active Optics and Pointing on LBT,* LBT internal document, 2006.

[4] Hill, J.M,. Ragazzoni, R., Baruffolo, A., Biddick, C.J., Kuhn, O.P., Diolaiti, E., Thompson, D., and Rakich, A., "Prime focus active optics with the Large Binocular Telescope," Proc. SPIE 7012, Ground-based and Airborne Telescopes II, 70121M (10 July 2008).

[5] Wilson, R., Reflecting Telscope Optics II, Springer, 1999.

[6] Rakich, A., Dettmann, L., Leveque, S., and Guisard, S., "A 3D metrology system for the GMT," *Proceedings of SPIE,* vol. 9906, no. SPIE Astronomical Telescopes + Instrumentation, 2016.

[7] Rakich, A., Schurter, P., Conan, R., Hill, J.M., Gardiner, M., Bec, M., and Kuhn, O., "Prototyping the GMT telescope metrology system on LBT," Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 107001S (10 July 2018).

[8] Dale, J., Hughes, B., Lancaster, A.J., Lewis, A.J., Reichold, A.J., and Warden, M.S., "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), 24869-24893 (2014) .

[9] Ciddor P. E., "Refractive index of air: new equations for the visible and near infrared," Applied Optics 35(9), 1566-1573 (1996).

[10] Ashby, D. S., Biddick, C., and Hill, J. M., "Active optics control development at the LBT," Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91452S (22 July 2014).