A laser-truss based optical alignment system on LBT

Rakich, Andrew, Choi, Heejoo, Veillet, Christian, Hill, John, Bec, Matthieu, et al.

Andrew Rakich, Heejoo Choi, Christian Veillet, John M. Hill, Matthieu Bec, Yang Zhang, Trenton Brendel, Breann Sitarski, Michael Gardiner, Dae Wook Kim, Stephanie Rodriguez, "A laser-truss based optical alignment system on LBT," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 114450R (13 December 2020); doi: 10.1117/12.2558013

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

A laser-truss-based optical alignment system on LBT.

Andrew Rakich[1a], Heejoo Choi[b,c], Christian Veillet[c], John M. Hill[c], Matthieu Bec[c], Yang Zhang[c], Trenton Brendel[c], Breann Sitarski[d], Michael Gardiner[c], Dae Wook Kim[c,e], Stephanie Rodriguez[b]

a. Mersenne Optical Consulting, 41 Rimu Rd., Raumati Beach, Paraparaumu 5032 New Zealand
b. Wyant College of Optical Sciences, 1630 E University Blvd, Tucson, AZ 85721, United States
c. Large Binocular Telescope Observatory, 933 N Cherry Ave, Tucson, AZ 85721, United States
d. GMTO Corporation, 465 N Halstead St #250, Pasadena, CA 91107, United States
e. Steward Observatory, 933 N Cherry Ave, Tucson, AZ 85719, United States

ABSTRACT

Since 2017 LBTO, in partnership with GMTO, has been developing a laser-trussed based metrology system for the active alignment of telescope main optical components to each other and to instruments. The effort has addressed needs of both organizations; LBTO with the opportunity to assess the performance of a new technological approach to telescope alignment, and the GMTO with the opportunity to prototype and field-test a system that has been identified as a crucial "missing link" in the active-optics chain between open-loop modelling and wavefront-sensing for ELT-scale telescopes. Following two years of effort the positive results so far obtained have convinced LBTO, in 2019, to commence to develop an integrated operational active-optics system based on this technological approach. A team drawn from LBTO, Steward Observatory, GMTO, the Wyant College of Optical Sciences and Mersenne Optical Consulting are currently completing the first phase of this Telescope Metrology System (TMS). This paper shall describe the system in detail and report on progress, current status, and future goals.

Keywords: Telescope alignment, metrology, interferometer, active optics.

1. INTRODUCTION

The Large Binocular Telescope (LBT) comprises two 8.4 m Gregorian telescopes mounted on a common gimbal. Since first light in 2005 a steadily increasing suite of instruments and observing modes have been implemented. Today, the available modes range from monocular prime focus correctors with 8.4 m entrance pupils (LBC) to binocular interferometry, combining light over a 22.65 m baseline from the two 8.4 m Gregorian systems in the LBTI[1].

With its combination of scale and optical complexity, the LBT faces challenges unique to current optical-infrared telescopes. In some respects, LBT has more in common with the upcoming generation of Extremely Large Telescopes (ELTs). In particular, long experience shows that the combination of sheer physical scale, asymmetry and cantilevered mounting of main-optics combine to make the production of reliable open-loop models, used for positioning optics prior to running wavefront-sensor-based active optics systems, a much more challenging proposition than is the case for smaller, more symmetrical telescopes of the 8-10 m aperture class.

The Giant Magellan Telescope (GMT) is one of three ELTs currently in production[2]. This telescope has a similar (slightly larger, 25.4 m) optical baseline to the LBT and also combines Gregorian “unit telescopes” interferometrically, albeit in a different scheme that LBT. Other common features include adaptive thin-shell secondary mirrors and borosilicate 8.4 m primary mirror segments produced by the Richard F. Caris Mirror Lab.

As was reported in 2018, GMTO and LBTO have been collaborating to develop a laser truss-based metrology system which will serve their common goal of improving on open-loop modelling outcomes for primary-mirror collimation as experienced at LBT, and as predicted by modelling for GMT[3,4]. Early work reported in References 3 and 4 was focused on assessing operational viability and achievable accuracies of a laser-truss-based system in a working telescope

[1] andrew.rakich@mersenneoptical.com Ph. +64 22 4560716 www.MersenneOptical.com

Ground-based and Airborne Telescopes VIII, edited by Heather K. Marshall, Jason Spyromilio,
Tomonori Usuda, Proc. of SPIE Vol. 11445, 114450R · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2558013

environment. The laser truss metrology system, capable of measuring relative optics positions in 6-degrees of freedom, at LBT is the first of its kind to be deployed on large land-based telescopes.

Following encouraging results from the early prototyping work, LBT resolved, in 2019, to proceed with work to fully implement a laser-truss based “Telescope Metrology System” (TMS), as an integrated subsystem in the Telescope Control System. A recent paper gave a summary of technical details of the system as of mid-2020[5].

In the interests of avoiding unnecessary repetition, in this paper it will be assumed interested readers will have considered the previous work, in particular in References 3, 4 and 5, and the current paper shall focus on reporting new information. In short, the metrology system described in detail in the above references, comprises a commercially available product, Etalon Absolute Multiline Technology (EAMT) which provides a network of absolute distance measuring fibre interferometers. These are set to collimators, deployed on the primary mirror(s) of LBT, with each channel measuring distances to retroreflector targets set to other optical components on the telescope. By measuring the lengths to a minimum of three retroreflectors on a target, from a minimum of six independent launch collimators mounted on the primary mirror(s) the relative location and orientation of the target with respect to the primary mirror, referred to below as the “pose” of the target, can be determined. Position determinations can be made approximately once every 10 seconds, with resolution of the order of a few microns.

This paper will further report on progress to date. In Section 2 the outline of the plan for phased integration, with intermediate and final system architectures, will be described. In Section 3 the laser truss hardware will be discussed, with some discussion of lessons learned during prototyping and improvements made, or in the process of being made, to the system as previously reported. Section 4 will describe aspects laser-truss Kinematics. Section 5 describes a new application of the system to determining shape error of the M1. Section 6 discusses aspects of the control software. Section 7 concludes with a discussion of current status and expected progress from this point.

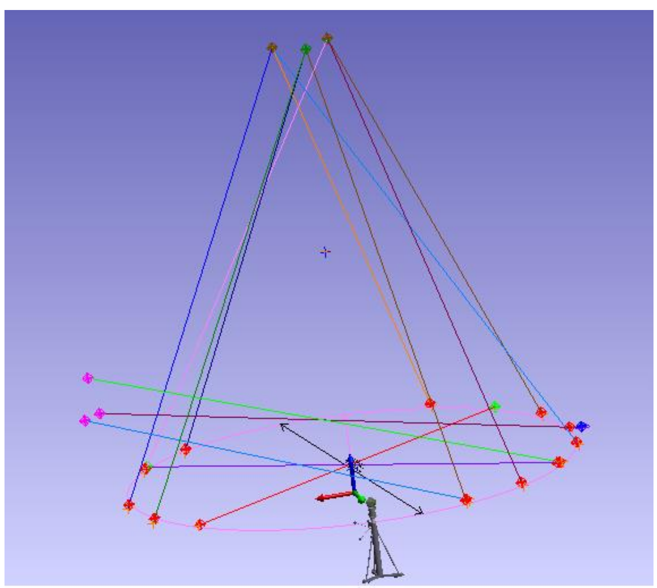

Figure 1 Laser Tracker Survey of TMS launch collimator positions around the edge of the primary mirror on the Right hand LBT mirror (lower) and target points on the prime focus camera (upper three points). The survey is required to establish the base geometry for kinematics equations.

2. Plan for the phased integration of a laser truss based TMS

In transitioning from the “concept testing” and prototyping phase as described in References (3) and (4) to implementing the metrology system as an integrated part of the Telescope Control System, an emphasis must be placed not only on accuracy, but also on reliability. Failure modes must be investigated thoroughly, and error handling automated as much as possible, to ensure smooth operation.

To this end, the TMS team at LBT took the prototype system as it existed in Q3 2018, which had been set up for Gregorian prototyping, and reset it to the single-sided Prime Focus mode. This represents the simplest possible configuration of the TMS: 9 metrology channels measure from the right-hand side, or “DX”, primary mirror to three retroreflectors on the prime focus camera. With this system the detailed implementation required to deliver a robust metrology subsystem, suitable for observatory operations, is being developed.

Various features of the system have been or are being actively refined at this stage. These include:

- Upgrading collimator optics and mounts.
- Implementing Inverse Kinematics pose calculations.
- Implementing software error handling.
- Developing robust and reliable software interaction with the metrology system and telescope.
- Implementing OPD corrections to vacuum length.
- Correcting for borosilicate mirror thermal expansion.

These aspects of development will be discussed in more detail in subsequent sections.

Once the single-sided Prime Focus system is proven on sky, experience with the prototype (see Reference 4) shows that setting up the expanded system for binocular operations will be a relatively small step. Following commissioning it expected that the system will go immediately into regular use in support of binocular Prime Focus operations on the telescope.

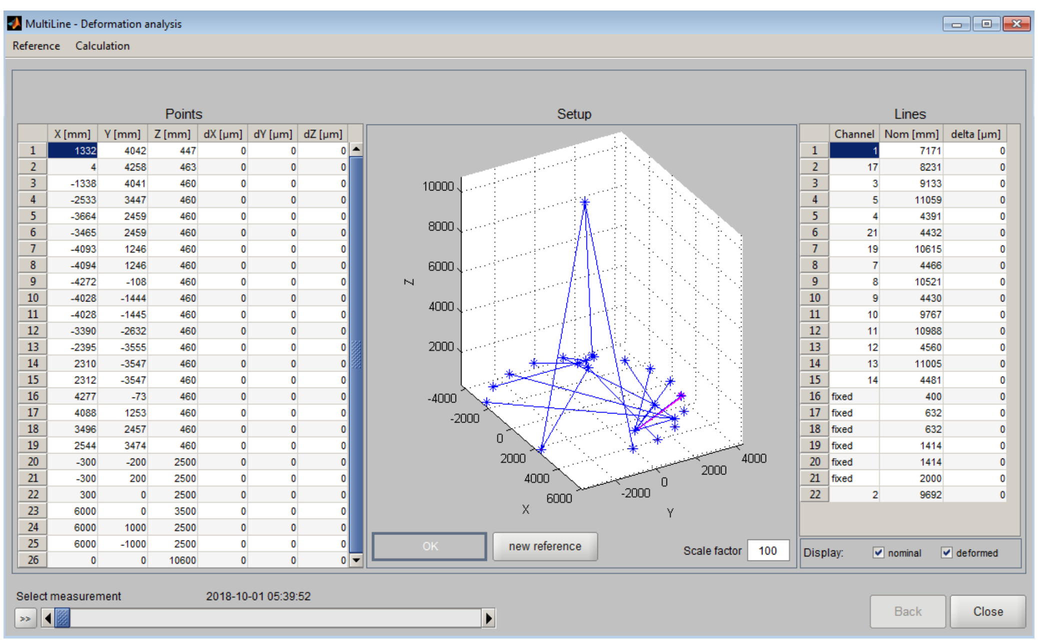

Figure 2 First laser metrology truss set to measure folded Gregorian optics (M1, M2 and M3) to an instrument rotator.

Subsequent to the binocular Prime Focus truss becoming operational, development will begin on supporting Gregorian operations. During prototyping, a truss was set up on one side of the telescope to measure the primary, secondary and tertiary mirrors with respect to a rotator (Figure 2). Initial results indicated good performance with some problems associated with collimator mounts and truss geometry. To progress with this development, a fiber switch has been procured which will allow quick switching between sets of 12 fibers. This will allow for the permanent configuration for both Prime Focus and Gregorian modes with an optical switch selecting the desired observing mode. The development of the Gregorian system can therefore take place without disturbing the operational enhancements provided by the system to the Prime Focus mode.

3. Laser-Truss hardware and lessons-learned.

With some years of experience of the EAMT system on LBT there are various learned lessons, and these are discussed in this section.

1) Collimator type.

Achromatic fiber collimators are highly desirable when working with the EAMT system. This is because, while the metrology waveband (1532 +/- 70 nm) can be corrected with a suitable monochromat collimator, the alignment of the system over long distances requires that the same collimator also be well-corrected for the visible wavelength of the alignment laser (633 nm). Initial alignment at LBT was very difficult for channels at approximately 10 m ranges, as the alignment laser was spread to approximately 300 mm diameter. Subsequently one of the authors designed an achromatic collimator and Etalon AG. arranged production. The achromatic collimators have proven to be effective and this problem is now effectively solved.

2) Collimator diameter.

The original prototype utilized two types of collimator, one giving a 3 mm and one giving a 7 mm diameter beam. The advantages inherent in the bigger collimator are now clear. Comparing the larger diameter beam collimator to the smaller, there is approximately a 40% improvement in beam-walk tolerance (effectively the allowable radial offset of the center of the metrology beam from the retroreflector vertex). This is approximately the inverse of the beam diameter ratio, but the detail of what causes beam walk limits is complicated and we cannot infer a general rule without more data.

Another advantage with the larger beam collimators is that the system generally receives higher contrast interference signals, improving overall robustness. The TMS system at LBT is moving to standardize on the larger diameter collimators going forward.

3) Multi-core mono-mode fibers.

Laser light for each of the EAMT metrology channels is conducted to the associated collimator-retroreflector pair by a mono-mode fiber. The original fiber run during prototyping involved running 28 fibers over 30 m from the EAMT unit to the telescope. This was a manageable but not trivial task. An alternative solution is to run multi-core mono-mode fibers. Etalon AG supplied 12-core fibers, which allow a single fiber to carry 12 channels from the Etalon unit to the telescope, and then be split to individual fibers with a Patch Panel box.

In the current implementation there is a problem with a faulty Patch Panel box and the team are currently working to replace it.

4) Collimator alignment stability.

In general, the alignment of the collimators has remained good over long periods of time. As an indication, maintenance alignment might be limited to several collimators a year. Some specific problems have been identified, first on the Gregorian truss, in which, due to geometric constraints the fiber tails from the collimators, mounted on the mirrors, make physical contact with the mirror flange while still close to the collimator. Under these circumstances it seems that the resultant “fiber rub” can cause misalignment and mechanically induce path length changes. In some cases, in particular with the Gregorian truss, the geometrical constraints are hard to avoid with the current collimator mounts, and so alternatives are being investigated. A promising alternative involves attaching a small 90 degree prism at the exit aperture of the collimator, allowing the fiber tails to run tangentially to the mirror.

5) Temperature telemetry

The EAMT unit supplied Etalon AG. requires input from three wireless temperature sensors. The OPD of the airpath varies with temperature, pressure, humidity and CO2 content, with the temperature contribution dominating. The provided wireless sensors must be relatively close to the base unit and so are not suitable for measuring air temperature in close proximity to the metrology channels. Fortunately, the LBT has suitable air temperature telemetry both near the primary mirror and at various locations on the telescope, which provide suitable inputs for temperature induced OPD correction.

Utilizing this telemetry requires that we get raw measurement data from the EAMT unit and do our own path length "vacuum" correction. As this approach is not compatible with the vendor supplied Kinematics software, using our own telemetry requires also that we develop our own kinematics solutions. Fortunately, this is not too taxing a task, and is described in the next section.

In summary, and with the exception of temperature telemetry, the above-mentioned changes are iterative in nature. Overall, we have concluded that the hardware has proven to be robust and suitable for the application, and we expect improvements as the upgrades described here are implemented.

4. Truss-kinematics

Motivated both by the temperature telemetry issue and the desire for system flexibility, the TMS team have implemented their own Inverse Kinematics solutions. The adopted Inverse Kinematics mathematical formulation can be applied to the determination of relative position and orientation between any pair of objects when the metrology truss meets the minimum requirements for channel number and geometry.

The desired flexibility primarily relates to the need to smoothly handle "dropped channels"; the EAMT supplied software stops working when a channel signal is returned with a bad value, as happens occasionally. Long term experience suggests that with the current hardware and geometry, dropped channels occur in < 1% of measurements. Although dropped channels occur infrequently, when they do occur it is desirable to continue to extract measurements from the remaining channels. In general, this situation has arisen in particular channels that were already near a limit in their alignment, becoming misaligned beyond a practical limit as gravity and/or temperature changes perturb optics positions.

Once a truss has been set up and collimators aligned to retroreflectors, the base geometry is surveyed with a laser tracker, with results such as in Figure 1, Figure 3 and Table 1 below.

Table 1 Laser tracker survey of points indicated in Figure 1. In this table collimator launch points and retroreflector vertex positions are defined, and corresponding channels are identified.

Mirror cell	x [mm]	y[mm]	z[mm]		Etalon ch
3L FT coll	-1317.72693	4073.221343	478.3960714	lbc y +	17
3R FT coll	-1369.632618	4003.112898	525.4651162	lbti y-	3
4 FT coll	-2530.74617	3452.605338	477.3280014	lbc x-	4
5L FT2 coll	-3485.486146	2496.874102	550.0683182	d x+	6
5R FT coll	-3525.783906	2422.763811	530.9197916	lbti z+	5
6R FT coll	-4104.920518	1197.552266	496.8522194	lbc x+	23
7L FT coll	-4263.454922	-71.8568032	523.1772366	lbti y+	7
8R FT coll	-4004.947692	-1473.938276	489.9075038	lbc x-	8
10R FT coll	-2323.274906	-3570.040383	476.2105284	lbc x+	10
11R FT coll	2437.351132	-3497.896332	406.2160532	lbc y+	11
12 FT coll	3421.568493	-2581.142437	396.9313372	lbc x-	15
13 FT coll	4290.203535	-86.2900738	397.6248842	lbc x+	13
14 FT coll	4095.908115	1209.555036	368.4380744	lbc y+	14
15 FT coll	3484.229582	2450.402465	509.3050266	d x-	16
LBC X+ retro	537.6053002	-3.034919	8693.517182		
LBC X- retro	-521.5278368	-2.1489416	8694.67146		
LBC Y+ retro	7.3354946	526.9748668	8694.067169		

The mathematical development is given in Reference 5, Section 4. In February of 2020, the current working truss geometry was set and surveyed, and the Inverse Kinematics solutions tested.

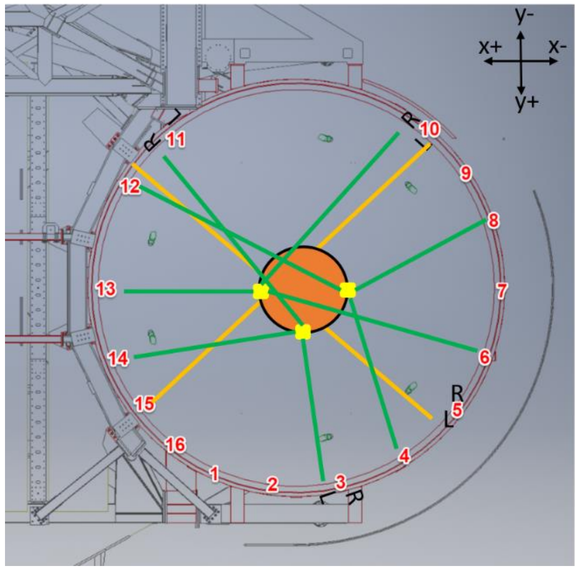

Figure 3. Channel paths connecting points indicated in Figure 1. In this table collimator launch points and retroreflector vertex positions are defined, and corresponding channels shown. The nine channels labeled "LBC" in Table 1 connect the outer disk (M1 edge) to inner disc (Prime focus camera) in this top-view schematic.

The current working truss has nine channels, three to each of three retroreflectors on the target prime focus camera. This set-up gives a three-channel redundancy; as many as three channels can fail (as long as all retroreflectors see at least one channel, and at least two retroreflectors see at least two channels); a minimum of six working channels are required to provide a pose solution for six degrees of freedom (translation and rotation). This redundancy improves system robustness and also accuracy, reducing errors in pose calculation arising from noise in individual channel measurements.

The truss kinematics solutions were qualified by entering a range of commands on each axis, from large mm scale measurements down to the encoder bit-limit for the M1 position actuator. Figures 4-6 give indicative examples of results, in this case for M1 position actuation along the x-axis.

Crosstalk in the measurement was also investigated, with similarly positive results. Only very small residuals of crosstalk were discovered, which do not limit the systems ability to converge. Figure 7 shows a typical example of crosstalk residuals; here measurement crosstalk into the y-axis is shown as the x-axis is actuated as in figure 4.

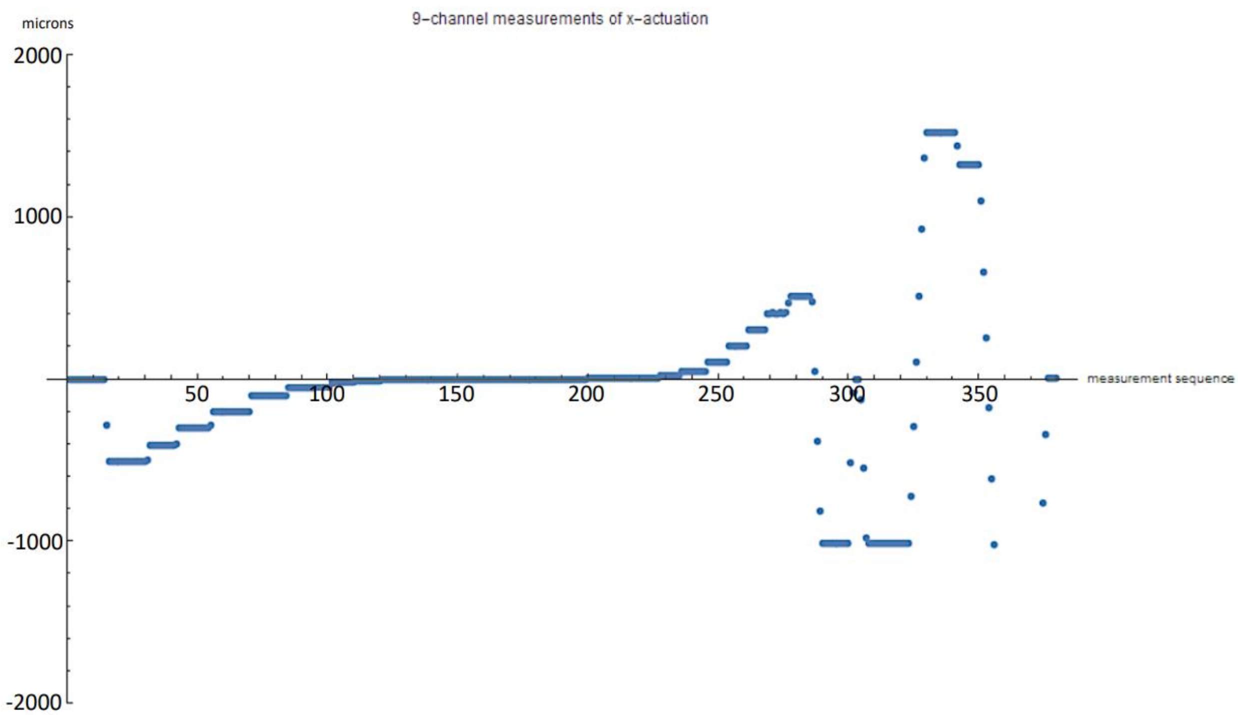

Figure 4. The primary mirror was sent to x-positions in the range of +/- 1.5 mm, as the metrology truss measured position. In this case all nine channels were used. The vertical axis represents measured x-position of the mirror and the horizontal plot indicates time-sequential order of measurement. The greatest errors were less than 1% of the commanded position.

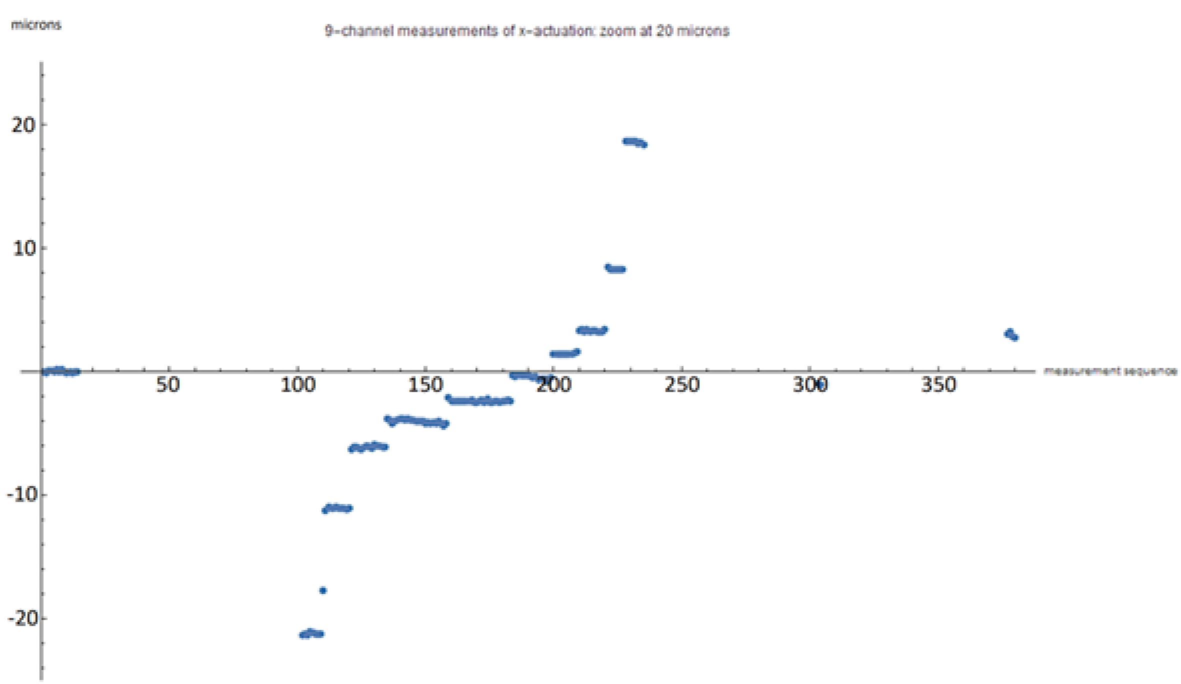

Figure 5. Zooming the y-scale from 2.5 mm to 25 microns shows the small-step resolution at a very reliable 2 microns. Each point is a single measurement at approximately a 7 second measurement interval. Looking at the point grouping the indication is that this is the actuator bit-resolution limit, not a measurement resolution limit.

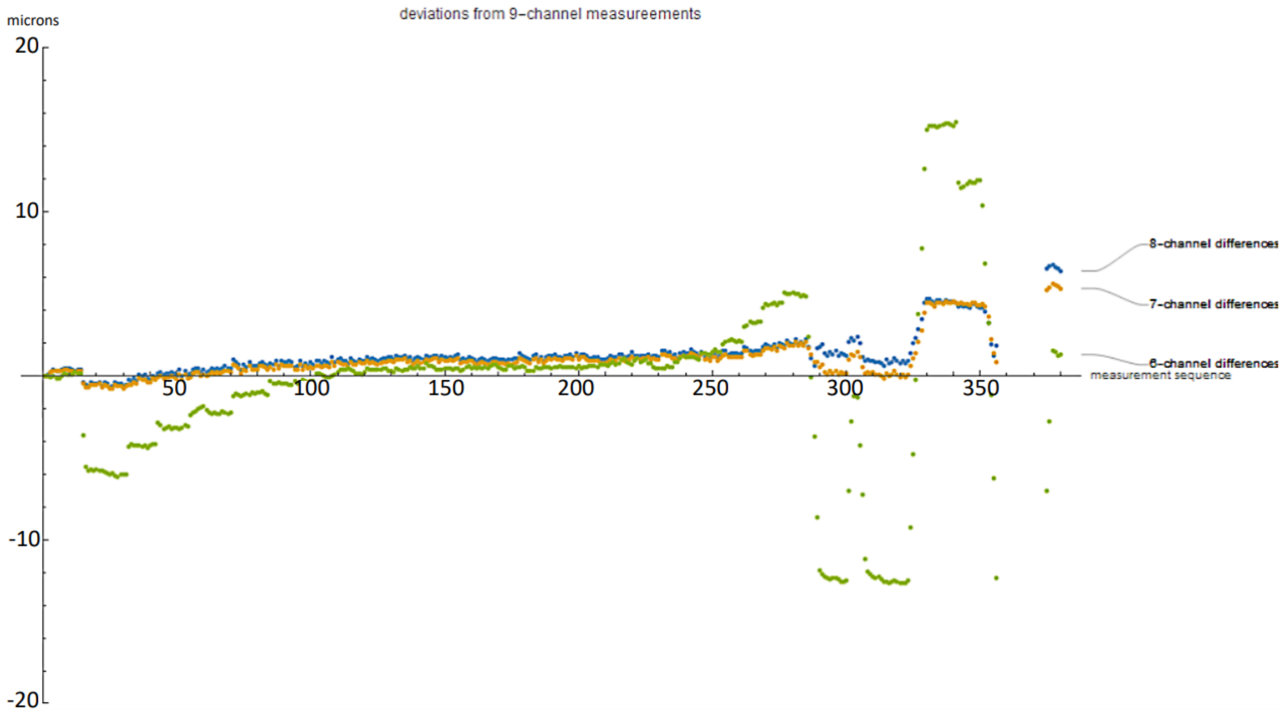

Figure 6. Investigating deviations in results between 8, 7 and 6 channel measurements we found clear degradation with reducing number of channels, but the errors were still less than 2% of commanded value at worst, with the 6-channel measurements. Note that the "large" 20 micron excursions at around measurement sequence number 300 occurred when the mirror was driven 1500 microns, so these differences are relatively small compared to commanded position.

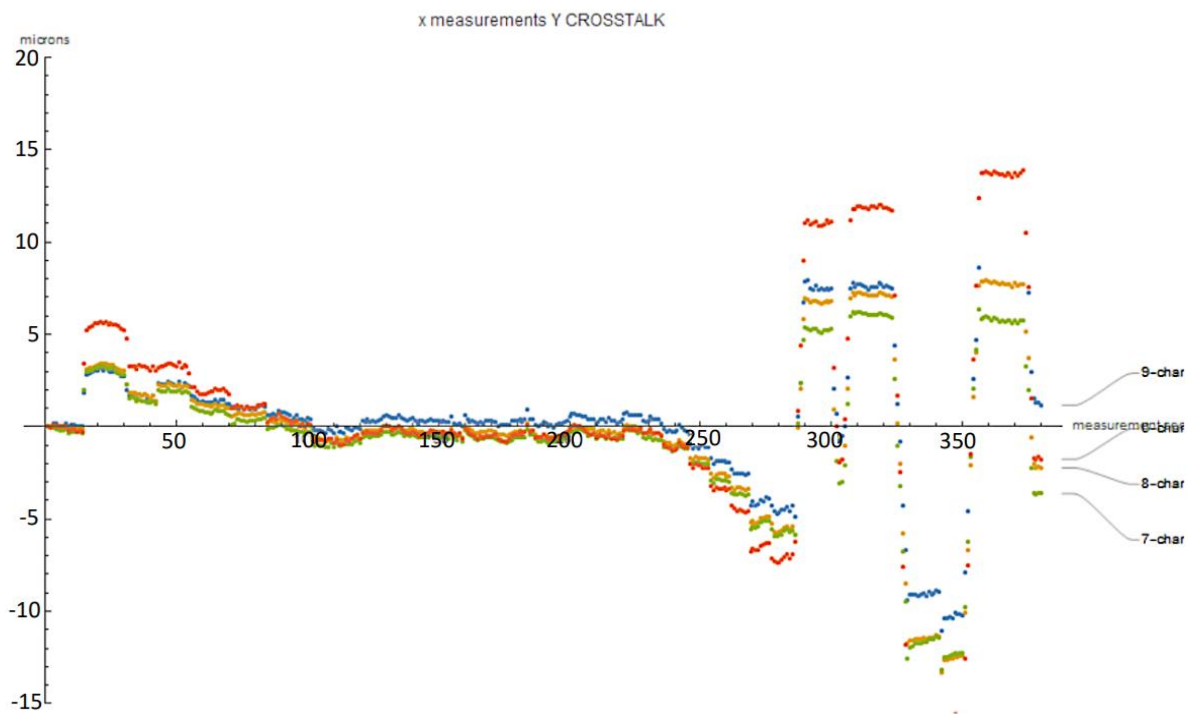

Figure 7. Crosstalk proved to be small too. Here for example is shown crosstalk into the Y-axis.

5. M1 shape determination

When the mirror shape becomes astigmatic, this affects the lengths measured by collimators, placed at different azimuthal locations around the primary mirror edge in differing amounts. These are shown in Figure 8. An investigation is underway into how accurately this shape can be determined by investigating differences in length measurements, and into what, if any, impact astigmatic shape change has on the accuracy of mirror pose determination.

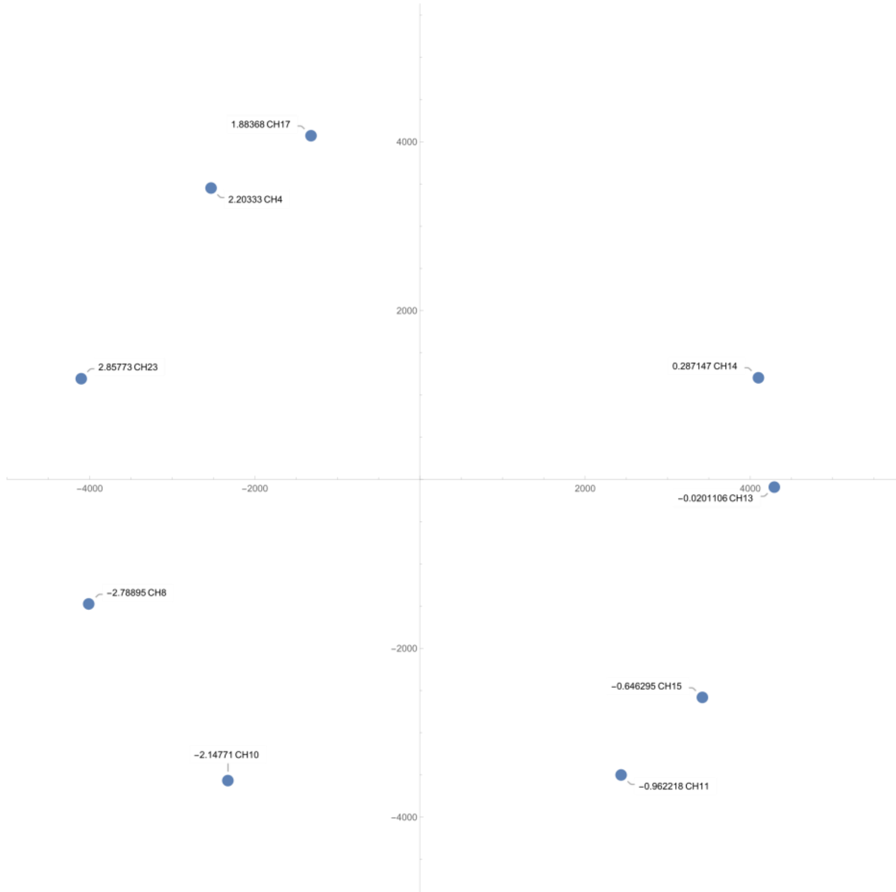

Figure 8. Azimuthal mapping of metrology channels for the current laser truss. Numerical values at each labeled channel are clocking angles in radians. The X- and Y-axes serve to indicate the position of each channel with respect to the center of the mirror surface in millimeters.

In one test, a series of astigmatic errors in Z5 and Z6 were driven into the primary mirror shape using the mirror shape force actuators, while the metrology system was running.

Noll-Zernike RMS Astigmatism values of +/- 5000, 3000 and 1000 nm were driven into the mirror. Such shape changes lead to peak surface deformations in the direction of the mirror surface normal, at the edge of +/- 14.7, 8.8 and 2.9 microns respectively. At this level, as we have seen in the previous section, we should be able to extract reliable length data and fit astigmatic shape.

As discussed in Reference 5, each channel is defined by a unit vector in the channel direction. By calculating the surface normal vector at the surface position corresponding to a collimator position on the mirror, we can find the expected change in corresponding lengths for a given commanded Zernike astigmatism by finding the projection of the surface change vector onto the measurement channel vector. Conversely, by back-projecting length changes onto the surface normal vector we can determine local shape change at each azimuthal position, and fit to a function of the form $A\,Sin(2\theta + B)$ to these data.

When this was done, we found 5000 nm shapes were recovered with RMS errors of 8%, 3000 nm shapes were recovered with RMS errors of 15% and 1000 nm shapes were recovered with RMS errors of 30%. A representative fit result is shown in Figure 9.

This represents the first time that distance measuring lasers have been used to measure telescope mirror shape and the results are certainly interesting. In the case of GMT off-axis segments there is a pure degeneracy between shape and position, and it will be interesting to investigate further how breaking that degeneracy with the already-planned laser truss channels on the GMT TMS might be useful in the overall control strategy.

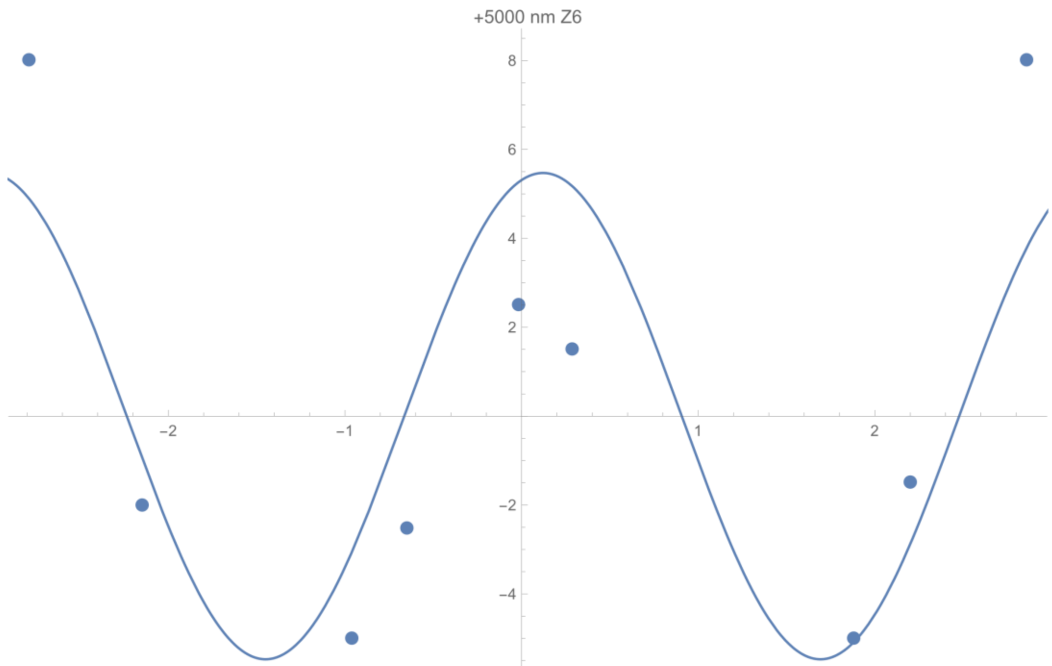

Figure 9. A representative fit of measured channel length changes back-projected to surface normal changes at various azimuth points, to an astigmatic shape change, as measured in the edge-zone of the mirror.

6. Software.

The EAMT unit comes with its native, Windows-based software. This is still used for turning the system on, running diagnostics, setting lasers, alignment etc. The Windows-based software also comes with a TCP/IP interface. Various command handles can be sent to the TCP server, which then commands the EAMT unit to perform the corresponding operations and then sends back a reply with the intended results. Currently we use the TCP server interface to retrieve raw channel length measurements, which are then processed further as detailed in the following paragraphs.

The LBTO software group has developed an experimental code to get measurements, manage the various subtleties of the interaction of such a metrology system with a real telescope, and send pose-corrections to the primary mirror. The primary features of this experimental code include:

- Saving a set of “reference poses” whenever the system completes an active optics cycle.

- Dynamically allowing for commanded changes in the relative position of the M1 and corrector, occurring due to say, on-sky active optics, look-up table commands, filter-focus offsets etc.

- Checking the status of the primary mirror and pausing if it is moving.

- Filtering received measurement data and rejecting spurious measurements

- Managing "dropped channels" and reconfiguring the Kinematics calculation to match the profile of available channels.

The central part of the experimental code is focused on transforming the raw channel length measurements from the EAMT TCP server to a final "change of pose" vector, which when adjusted for various telescope instruments offsets, is then sent to the telescope control system (TCS) as the final correction vector.

Figure 10 provides an overview of the major steps involved in transforming the raw TMS channel length received over the EAMT TCP server to the change of pose vector. The resulting change of pose vector is essentially a preliminary TMS correction vector. We first compute a pose from the raw length received, and then we subtract it the most recent reference pose (e.g., one made from the last active optics cycle) to reach the change of pose vector. This change of pose vector is then further processed to combine with various other terms such as the prime focus camera guiding corrections, PSF instrument offsets, as well as the primary mirror bending terms, etc. to reach the final corrections to be sent to the TCS system.

The first step shown in Figure 10 uses LBT's weather telemetry data to compute a vacuum corrected channel length vector. The primary equations involved in the calculation are from Reference 6. We then perform a sanity check on the corrected length to reject unreasonable results (e.g., length data that differ from a standard reference by a large margin, or cases where too many channels have failed to provide valid results etc.). If the sanity check results in a valid length vector, we then move on to the most important phase to calculate the pose from the corrected length. Otherwise, if the sanity check results in a failed length vector, then we give up TMS correction within the current cycle.

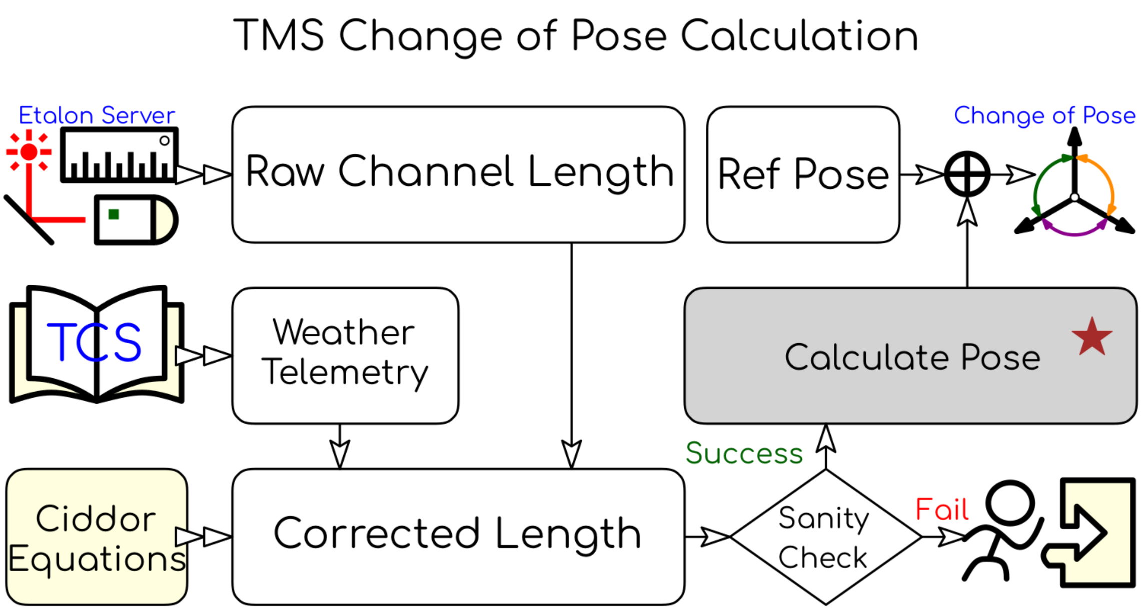

Figure 10. Overview of the major steps transforming raw TMS channel length to a preliminary correction vector (i.e., the "change of pose" vector). The shaded and starred box "Calculate Pose" is expanded and explained in detail in the text.

The shaded and starred box in Figure 10 is the most important step in the whole process. Ideally given a vacuum corrected TMS channel length vector v, we calculate the pose $p(v) = J^{-1}.v$ where J^{-1} is the pseudo-inverse of the sensitivity matrix derived from the truss geometry, and v is a vector of measured lengths. The rows of the Jacobian matrix are constructed in the same channel order as in the length vector v. The main complication arises when, due to missed or rejected channels, the length vector v is incomplete.

As described, we currently have a total of nine channels setup to the prime focus camera, and we can afford to lose at most three channels, as long as no retroreflectors lose all of their channels, and at least two retroreflectors see at least two channels. We use the notation v_c to denote a length vector v with missing channel set c, where c is the set of any valid channel combinations that we can afford to lose. The pose for the v_c is thus defined as: $p(v_c) = J_c^{-1}.v_c$, where J_c is the Jacobian matrix of the truss geometry with the same missing channel information as v_c.

The pose for a length vector with missing channels will be different than a complete one, e.g., $p(v) \neq p(v_c)$. In the ideal case, the change of pose will be the same, i.e., given two length vectors v and u, $p(v) - p(u) = p(v_c) - p(u_c)$. However in reality, residual errors exist that make the previous relation invalid, especially when vectors v and u are produced at significantly different times.

Currently in our calculations, we have adopted a scheme that tries to correct such residual errors. Specifically given v_c, we calculate its "corrected pose" as: $p(v_c) - p(u_c) + p(u)$, where u is a most recent measured length vector that predates v that has full channel information. The term "$p(u) - p(u_c)$" is referred to as the "pose correction term".

The primary objective of this pose calculation scheme with missing channels is to ensure that the system produces sensible pose data at each measurement cycle, even in the occasional case where we do not receive the full nine channels information. Some subtleties occur to do with jumps in the pose calculations depending on the profile of available channels. In one experiment we have conducted that simulates a real scenario where channels only occasionally drop, this error correction scheme worked well. In this experiment, we specified two fixed channels to be dropped at 5% and 2% probabilities and kept the system running for over ten hours. In another experiment, we stress tested the system where we always drop two random channels at each measurement and kept the system running for one and half hours. The results of this stress test experiment were more "noisy", in that there are more jumps in the corrections computed out of the resulting seven random channels setup with our error correction pose calculation. This aspect of the control software is a recent development and constitutes a work in progress at this stage. We plan to investigate more into the theoretical underpinnings of truss geometry and the change of pose with respect to incomplete channel information.

Another aspect of practical software development concerns the "sanity check" box in Figure 10. We discovered that, in reality, a simple threshold-based sanity check may not be robust enough to filter all physically unreasonable inputs. A more intelligent and sophisticated checking should be developed, and we are currently in the process to study and develop a scheme.

We are currently close to being able to deploy the software for regular routine use on the LBT with the prime focus camera, pending some requirements review and on-sky commissioning. Future software work will likely focus on restructuring the infrastructure and redesigning the whole system to become more robust and user-friendly, as well as easy to extend and maintain.

7. Current status and future work.

Currently the TMS team are working to produce an integrated hardware and software metrology package to support LBC operations. The system has so far proved itself in passive tests, where it runs in parallel to science observations but does not send the corrections it determines. The next milestone will be to complete an on-sky commissioning phase during telescope engineering time on sky.

The technical proposal for this commissioning period is currently in production.

Key benchmarks the TMS will be required to meet prior to being delivered to the telescope are:

- Reliability. An agreed set of standards for reliability of operations are in development.
- Error Handling (actually, part of reliability). The system must, at worst, not degrade the current alignment performance achieved by the LBC. In cases where it is not able to operate a "seamless exit" must be demonstrated.
- Accuracy. A set of IQ statistics shall be produced demonstrating that the system improves on the image quality delivered by the current Active Optics system ("Focal Plane Image Analysis"). A basic requirement, that the system is capable of routinely correcting for deterministic test perturbations, has already been delivered by the system
- Operability. The system must not significantly complicate, or otherwise add to the workload, of the telescope operators.

Assuming success in the commissioning stage, the anticipated release of "TMS v.1." will be in Q1 2021. At this time development work will proceed to both monitor/refine and improve the deployed system and to develop a system capable of supporting Gregorian operations. To this end a fibre switch has been purchased. This will allow quick optical switching between deployed fibres currently supporting prime focus metrology and to-be-deployed set of fibres required for Gregorian-telescope trusses.

8. References

[1] Rothberg, B. et Al., "Current Status of the Facility Instrumentation Suite at The Large Binocular Telescope Observatory", Proc. SPIE 10702, Ground-based and Airborne Instrumentation for Astronomy VII; 1070205 (2018)

[2] Fanson, J. et Al., "Overview and status of the Giant Magellan Telescope project", Proc. SPIE 10700, Ground-based and Airborne Telescopes VII: 1070012 (2018)

[3] Rakich, A, Leveque, S., Guisard, S., Dettman, L., "A 3-D metrology system for the GMT", Proc. SPIE 9906, Ground-based and Airborne Telescopes VI; 990614 (2016)

[4] Rakich, A., Schurter, P., Conan, R., Hill, J., Gardiner, M., Bec, M., Kuhn, O. "Prototyping the GMT telescope metrology system on LBT," Proc. SPIE, 10700 (2018).

[5] Rodriguez, S. L., Rakich, A., Choi, H., Veillet, C., Hill, J. M., Bec, M. D., Zhang, Y., Gardiner, M., Kim, D.W., "A laser-truss based optical alignment system on LBT," Proc. SPIE 11445 (2020).

[6] Ciddor, P. E., "Refractive index of air: new equations for the visible and near infrared," Applied Optics, Vol 35, No 9 (March 1996).