Using a laser tracker for active alignment on the Large Binocular Telescope

A. Rakich*[a, b]

[a]Large Binocular Telescope Observatory, 933 N. Cherry Ave., Tucson, AZ 85733, USA;
[b]European Southern Observatory, Karl Schwarzschild Str. 2, Garching 85748, Germany.

ABSTRACT

The Large Binocular Telescope (LBT) currently achieves collimation using a combination of collimation models and closed-loop active correction schemes. Shack Hartmann wavefront sensors with off-axis guide stars are used for Gregorian modes, and a closed-loop correction scheme is used for the prime-focus cameras. While in general this combination serves to produce alignment residuals well below a good seeing limit within a few minutes of obtaining a given target field, the uniquely asymmetrical structure of the LBT is prone to producing large deflections of the telescope optics when the ambient temperature is changing unusually rapidly. These deflections are difficult to model satisfactorily, and are an ongoing source of inefficiency in telescope operations. Furthermore, none of the current approaches to telescope collimation are particularly "piston aware"; a situation that needs to be improved on now that the LBT is commencing operations with the first of its beam combining instruments, LBTI. The laser tracker is a metrology instrument capable of automatically measuring optical element positions with better than 100 micron precision within a spherical volume of 30 m radius centered on the tracker head. With the ability to directly measure optics into position to this accuracy built into the Telescope Control System (TCS), the LBT would always be starting observations from a point of near-collimation, the component telescopes would be co-pointed, and the OPD would be well within the capture range of the beam combining instrument's internal phasing systems. This paper describes first results from engineering investigations into using the laser tracker to automatically align the optics on the LBT.

Keywords: Telescope alignment, Laser tracker, collimation.

1. INTRODUCTION

The Large Binocular Telescope consists of two 8.4 m telescopes mounted on a common alt-az gimbal. The telescope has various modes of operation, including prime-focus, bent- and direct-Gregorian modes. The telescopes can feed independent instruments or their light can be combined in one of two interferometric instruments, giving an interferometric baseline of over 22 m.

The LBT puts unique demands on its open- and closed-loop active optics systems. A pair of 8 m class telescopes mounted on a common gimbal and combining images interferometricaly, the active optics system has to be "OPD aware", as is not the case in monocular telescopes, where "piston" terms can usually be disregarded. Also, with the LBT's uniquely asymmetrical structure, where each of the main optical elements is cantilevered and large telescope structural steel elements are all to one side of each of the two main optical axes, structural temperature gradients such as are commonly encountered whenever there are large swings in environmental temperature can lead to large optical displacements. These gradient terms are difficult to model, as data are relatively sparse, even when taken over several months of observing time.

Further complicating matters is the fact that when not in thermal equilibrium, the 8.4 m borosilicate primary mirrors of the two telescopes develop figure errors leading to relatively slow-changing tip/tilt, focus and low-order aberration terms.

In previous papers the author has discussed sources of error in LBT collimation models[1,2] and also the first use of the laser tracker for set-up optical alignment and elevation-induced flexure measurements on LBT optics[3]. In this paper the first steps towards integrating laser tracker measurements into the Telescope Control System (TCS) are described.

*arakich@eso.org, ph: +4989 32006168, www.eso.org

In section 2 below, the motivation for using the laser tracker as an integral component of the TCS is discussed further. In section 3 the physical and control set-up applied for the first test of automating the laser tracker for telescope alignment is described, along with ideas for permanent installation. Achieved accuracies, both from the automatic measurement and analysis approach, and from two earlier nights, where the laser tracker was operated and data reduced manually, are described in section 4, with a general discussion following.

2. MOTIVATION

Even with the improved "Range-Balanced" collimation models described in [2], it is currently possible to get errors of lateral position in LBT optics (departures from the open loop model after active optics iterations had converged) of up approximately 1.5 mm peak value in adverse conditions. While at this level serious problems such as running out of range-of-motion on mirror hexapods, which had previously plagued LBT operations, are now avoided, the extra active-optics cycles required to remove the resultant large amounts of coma, as well as the occasional need to correct pointing "manually" to bring guide stars to within the acquisition field of view of guide cameras, when these larger-than-usual errors are present, still lead to unacceptable operational inefficiencies.

The LBT active optics system currently corrects optical misalignments by detecting coma at a given field point, then rotating either the M1, M2 or both mirrors to some degree about their "pointing neutral points", thereby introducing the required corrective amount of coma. A problem arises when coma arising from a given rigid body optics motion (or a mirror figure error) is corrected by a rigid body optics motion of a different optic. For example, say the primary mirror experienced a pure lateral displacement of 1.0 mm. This would result in several thousand nm of coma and an approximately 20 arcsecond pointing change. If LBT active optics corrected all of this coma by way of a coma rotation about the pointing neutral point of M2, the pointing error from the lateral displacement would remain after coma was corrected, together with some not-insignificant amount of misalignment astigmatism (field-linear astigmatism) and focal plane tilt[4,5]. Furthermore, the uncertainty in initial optics positioning goes directly to the difficulty involved in correcting telescope differential piston errors and successfully completing an interferometric preset.

Various new-generation telescope projects in the design or early construction stages are considering using laser trackers as a built in alignment tool available to the TCS, and integral to the basic operation of the telescope[6]. LBT engineers have been using a Tracker 3™ by Automated Precision Inc. for several years, for general engineering and alignment tasks, and, based on this experience, are interested to further investigate the application of this technology to "active" telescope alignment; that is in the alignment of optics during telescope presets. For the purposes of these tests, Spatial Analyzer™ software by New River Kinematics was employed in the control of, and subsequent data reduction of points measured by, the tracker.

Experience with the tracker at LBT, as described in [3] above, has shown that the laser tracker is capable of measuring optical component positions during telescope use with accuracies of the order of 20 microns RMS. Obviously if the laser tracker could be used to routinely position optics to this degree of accuracy, large positioning errors arising from large structural gradients would be effectively eliminated, and the problems arising from optics positioning uncertainties caused by the degeneracy of coma-corrected optics positions would be mostly mitigated.

3. INTEGRATING THE LASER TRACKER INTO THE TCS

In this section the mechanical and software setup of the laser tracker on the telescope is described in more detail. Also briefly discussed are some ideas for future improvements once this approach is taken beyond the "proof-of-concept" stage.

3.1 Hardware configuration

In figure 1 below are both a photograph and a schematic representation of the laser tracker setup employed during testing in February and April 2012. Four spherically mounted retro-reflectors "SMR"s were attached directly to the side of the primary mirror, and approximately pointed towards the laser tracker head, using adjustable corner brackets and hot-glue. We also used tethering wire on each of these as a safety precaution. Three more retro-reflectors were attached to the hexapod supporting the secondary mirror, using brackets that extended the retro-reflectors out sideways from the secondary mirror hub to locations from which they had a line-of-sight to the laser tracker. Ideally the M2 SMRs would have been directly mounted on the secondary mirror, but as the LBT secondary mirrors are thin-shells[7], and the reference body surface is not currently accessible for mounting SMRs, the best compromise currently available is to mount balls n brackets bolted onto the hexapod.

The laser tracker head is mounted on the instrument gallery as indicated in figure 1. From this location there is line-of-sight to points on the primary mirror, secondary hub (or prime-focus shell) and also the instrument rails. This last is important as current thinking is to have retro-reflectors built into reference surfaces on the interferometric instruments, and align the telescope optics to these references. While it is known that the instrument gallery itself twists and deflects with both elevation and temperature, and therefore there is some unknown deflection of the tracker itself, this effect is corrected by the measurement strategy, as described below.

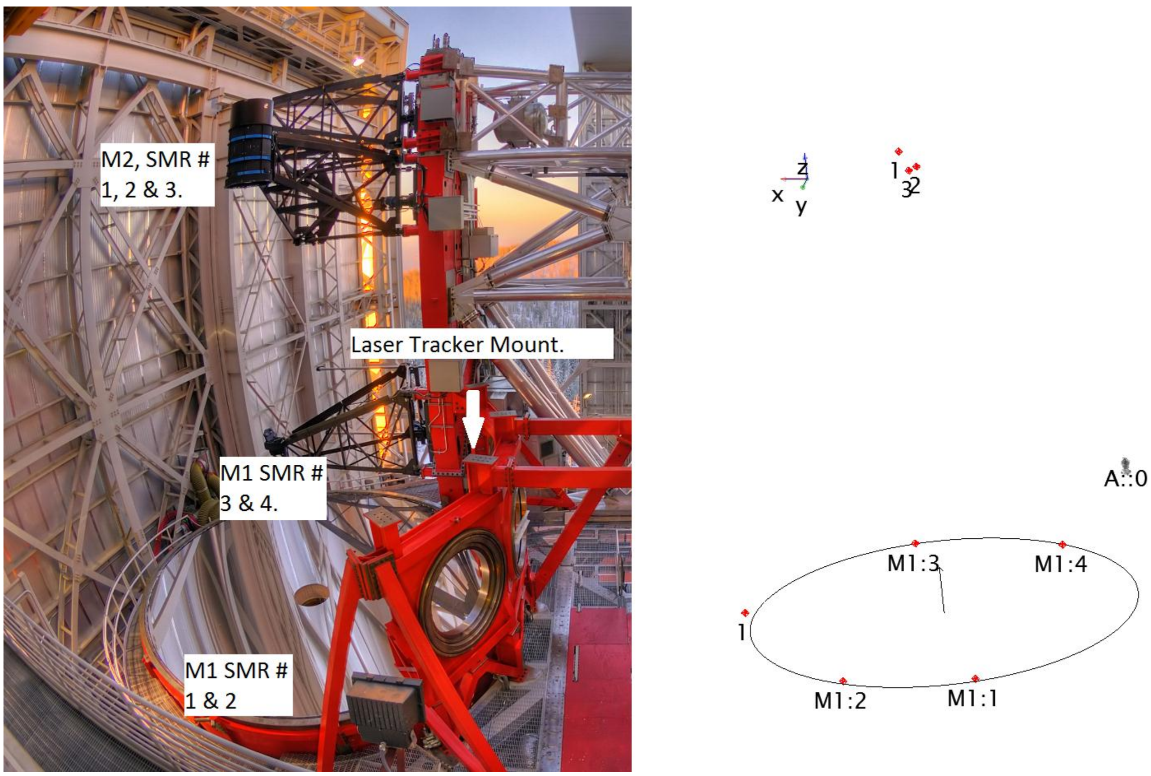

Figure 1. Illustration of component positions for the laser tracker active optics test. M1 SMRs labeled on the large circle bottom left, M2 SMRs top centre, laser tracker centre right. The reference frame for measurement is made to be congruent with the M2 hexapod coordinate system, so the final delta vector for M2 is in M2 hexapod "native" coordinates.

3.2 Measurement and software configuration

One obvious pre-requisite for the successful use of the laser tracker to preset optics during normal operations is the requirement that measurement, analysis and the subsequent communication of commands to the telescope hexapods be automated. To this end we utilized a high-level programming facility within the Spatial Analyzer™ software. With a "Measurement Plan" program we could automate the measurement of points, error checking and recovery, perform the two separate coordinate transforms required and subsequently write an ASCII file to a directory on the TCS computer network containing a vector of M2 hexapod position commands.

Figure 2 is a flow chart summarizing the program. Altogether a little over 200 lines of code were required to fully automate the laser tracker active optics and data reduction. The program was tested and refined in weeks leading up to the on-sky test, using seven SMRs set on two platforms, with the platforms both being adjustable in translation and rotation. By the time it was first tried on the telescope the program had proven itself capable of running to completion, with working error recovery routines in the case of failed measurements on any points, and with a “graceful exit” in the case of unrecoverable measurement failure.

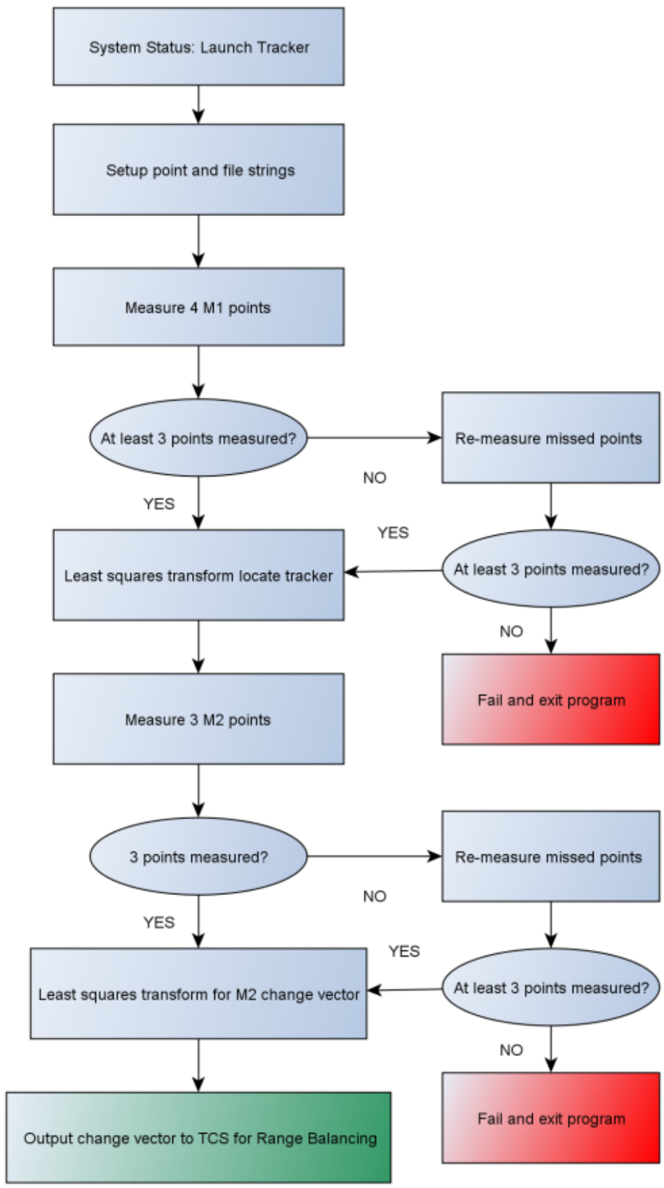

Figure 2. Flow-chart illustrating basic features of the laser tracker control program. If insufficient measurements are obtained for either of the two transforms, the system exits and the telescope begins active optics using look-up table positions for the mirrors.

The program is run from a “base file” in which the positions of the seven SMRs were measured at some time when the telescope was collimated using the active optics system. The program then re-measures the same targets at some subsequent preset and determines how the position of the secondary mirror relative to the primary has changed. The

Cartesian reference frame for the measurement is chosen to near-exactly match the frame for the M2 hexapod.
As outlined in figure 2, the basic steps in the program are as follows:

1) Check to see if tracker is connected, and if not, connect.
2) Create strings to use for point names and file names.
3) Create counters used in point naming.
4) Point the tracker at the four M1 points, and measure each point, writing each new measurement to a particular directory. If a point is missed, two more attempts are made to acquire the point before moving on to the next one.
5) Check to ensure that at least 3 points were measured. If less than three points are measured, try to measure missed points again. If at the end of this, less than three points measured, the laser tracker component of the preset has failed, and the telescope begins active optics from collimation model optics positions.
6) With at least three measured M1 points, and using Spatial Analyzer's "Locate Instrument/Transform To Part" function, obtain a transform that places the measured SMR points as close as possible to the corresponding points from the base file, minimizing any residuals in a least squares sense. This transform effectively means that subsequent measurements of the secondary mirror will give only the deflection of the secondary relative to the primary, even if both the tracker head and the primary mirror have themselves moved.
7) Measure secondary mirror points (only three points during this step, four would have been preferred) and carry out similar error checking to steps (4) and (5).
8) Determine a transform that places the measured M2 points on top of the baseline M2 points, minimizing residuals in a least squares sense.
9) Write this vector to an ASCII file in a directory available to the TCS. This vector is exactly the commanded change required to place the M2 back in the same relative position to M1 as in the base file.

One further step is required in practice. Step (6) means that the change in optics positions from those in the base file is assumed to be entirely due to the secondary mirror. In fact both mirrors have probably moved. It would be possible, with an unfortunate combination of initial positions and primary mirror position changes, for the program described above to command M2 to a position outside of the range of available motion of its hexapod.

One strategy to prevent this outcome is to use the algorithm described in reference [2], "Range balancing", to redistribute the consumption of hexapod range on the two mirrors in an optimum way, using coma-free pointing rotations of the two mirrors as a single rigid body. This delivers a collimated telescope but would in general introduce some pointing and OPD error, which would be proportional to how much the primary mirror had actually deflected.

3.3 Future configurations

If the laser tracker is to be used as a permanent component of the TCS, various points have to be considered. For example, the tracker head should be housed in a permanent enclosure, with a shutter. A shutter and light-tight enclosure is necessary as the laser tracker uses two lasers, one infra-red and one red, which both need to be left on all night, creating an obvious stray light problem. This would also be useful environmental protection for the tracker head, and could also mitigate any potential thermal control issues.

SMRs are not necessary for these measurements, standard retro-reflectors could be used just as well, because the absolute position measurement features enabled by an SMR are not required of the relative measurements made here. That is, once the baseline retro-reflector positions have been measured on the optics positions determined by closed-loop active optics, subsequent measurements do not rely on the accurate "re-placement" of the retro-reflectors, as they stay attached to their respective optics. That is, we do not require the properties of an SMR that make it expensive; the precise location of the vertex of the retro-reflector at the centre of a well-made sphere, for these relative position measurements.

If SMRs are used, they could be anodized black on the external spherical surface, and stray light should not be an issue from the corner reflectors (which by their nature return stray light on its original path). However, shuttered housings for the SMRs or standard retro-reflectors, semi-permanently attached to M1 and M2 (where possible), would be desirable to protect the reflective surfaces of the retro-reflectors from environmental contamination.

The location of best mounting positions for M2 SMRs still requires some thought. Ideally the SMRs would be contacted directly to the sides of the reference body. This may be possible with some re-engineering of the M2 hubs. If this is not possible, then mounting the retro-reflectors directly on the M2 hexapod should be possible, with optical windows inserted into the sidewalls of the M2 hub to maintain the dust protection of the hub walls. In this case calibration of mechanical deflections between the hexapod and the optical surface of M2 would be necessary.

4. FIRST ON-SKY RESULTS

4.1 LBC results

The first test of the laser tracker on-sky was done in fact with the left-hand-side, blue-channel, prime-focus camera (LBCB). For a first test this was easier to implement than the subsequent tests on the Gregorian system, as the mounting of SMRs on the LBCB hub was less complicated than mounting SMRs on or near the thin shell adaptive secondary mirror proved to be.

The LBCB test proceeded as follows. First the telescope was collimated at a field at 84 degrees elevation (near zenith), and the SMR positions were recorded with the laser tracker. The telescope was then preset to a number of different elevations and the active optics system was iterated on the target fields until it converged. Once collimation was achieved the laser tracker was manually pointed to seven SMR targets, four on the primary mirror and three on the prime-focus hub and these points were recorded. In post-analysis, the measured points were transformed such that the measured primary mirror points overlaid the initial high-elevation measurement of primary mirror points in a least-squares best-fit minimizing position error. Then an assumption was made that the rotation of the M1 relative to the hub was a coma-free rotation, so rotations were disregarded and translations corresponding to the required coma-free translation component for the given measured rotation component, assumed to be coma free, were subtracted from measured translations. The resultant translation errors in hub position relative to M1are therefore indicative of the coma and focus errors that would occur if the laser tracker had been used to preset the telescope optics positions.

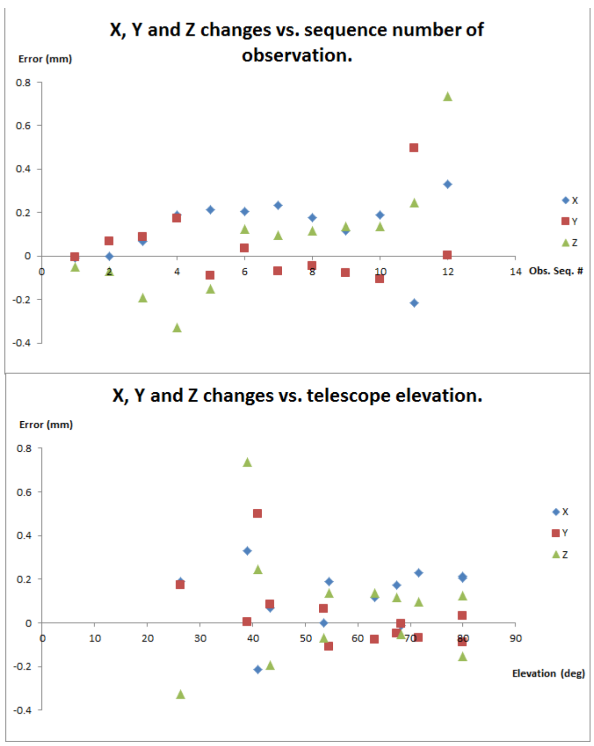

Figure 3. Representative differences in X, Y and Z between the expected primary mirror position, and the position actually measured by the laser tracker after closed-loop active optics had converged (in prime-focus mode). The top plot shows these against order-of-observation, the lower plot shows the same errors vs. target elevation. Clearly the "order-of-observation" plot shows some systematic drift in error.

The results in figure 3 indicate that there was a systematic measurement drift occurring in time, but not in elevation. On the night the data was taken the ambient air temperature in the enclosure had been relatively stable, but the ventilation system on the primary mirror had been first cooling, then warming, the primary mirror, which is made of borosilicate glass. Previous investigations[8] have shown that the borosilicate primary mirror will experience large changes in focus, spherical aberration, pointing and coma under these conditions. Both the magnitude and timescale (and sign, at least in the case of the Z error) of these errors are consistent with previous measurements made of thermally induced aberrations in the primary mirror.

This gives a clear indication of the potential of the laser tracker to measure optics positions, the "noise" in the data in the top part of figure 3 is ~ 20 microns RMS once the slowly changing measurement drift is removed with appropriate fitted polynomials. However, these results do point out a particular limitation of the laser tracker measurements for active optics; the laser tracker is seemingly well able to position optics, but is blind to optical figure error.

4.2 First results with the Gregorian configuration

In February 2012 the first tests were made with the left channel Gregorian telescope. The SMRs were mounted on M1 and M2 as described above. In these tests, the telescope was initially collimated at a high elevation, then the laser tracker was used to measure and record the positions of M1 and M2 for the collimated telescope. After this, active presets were made to fields at a number of elevations, in general changing smoothly from high elevation points to low elevation points, and the active optics system was run until it converged. The laser tracker then measured the resultant optics positions. In post-analysis all points were transformed such that the M1 points exactly overlaid the baseline M1 points, and changes in X, Y, Z, Rx and Ry were recorded. All laser tracker pointing and data reduction was performed manually at this stage. The results are shown in figures 4 and 5 below.

These initial results are encouraging, though as seen in figure 4 there was some indication of hysteresis and/or measurement drift on the +/- 150 micron level, with one sudden jump, and also a pronounced and quite linear elevation effect, particularly in the Y, Rx and Z components.

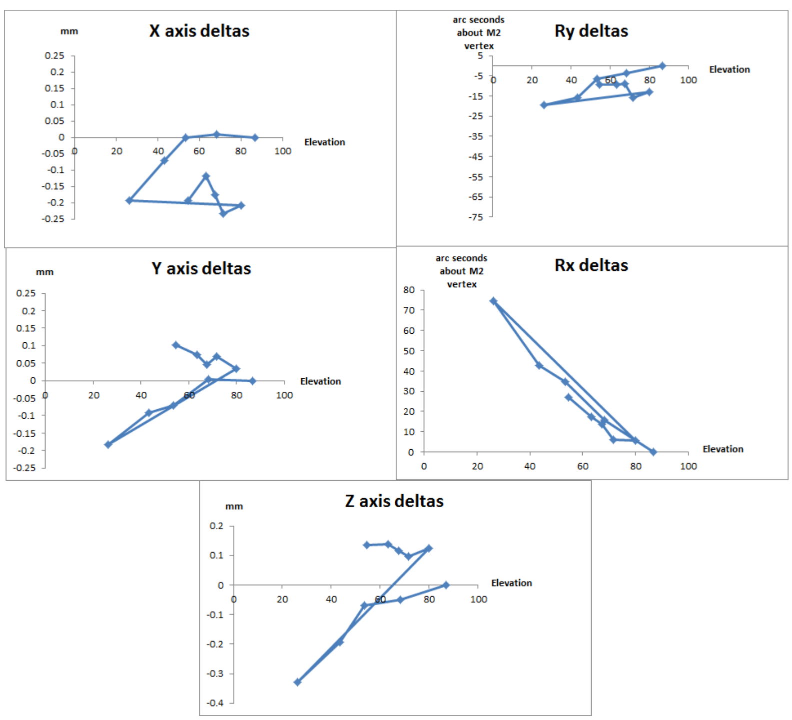

Figure 4. Plotted here are M2 hexapod position vector components, { X, Y, Z, Rx, Ry}, that would reposition the M2 to exactly the same position and orientation that it originally had to M1 when the system was initially collimated at high elevation, vs. elevation. There is some evidence of hysteresis or measurement drift, particularly in the Y and Z axes, and also a sudden jump in the Y, Rx and Z axes, corresponding to an elevation change of ~ 25 degrees to 80 degrees. The solid lines connecting points give an idea of the order of observation.

In figure 5, where the data points are plotted against order of observation rather than elevation, it is clear that there is some slowly changing drift, but also that there is a sudden large jump in the Y, Rx and Z data points (but not in the X or Ry points) from the 4th to the fifth point, corresponding to a sudden and large change in elevation.

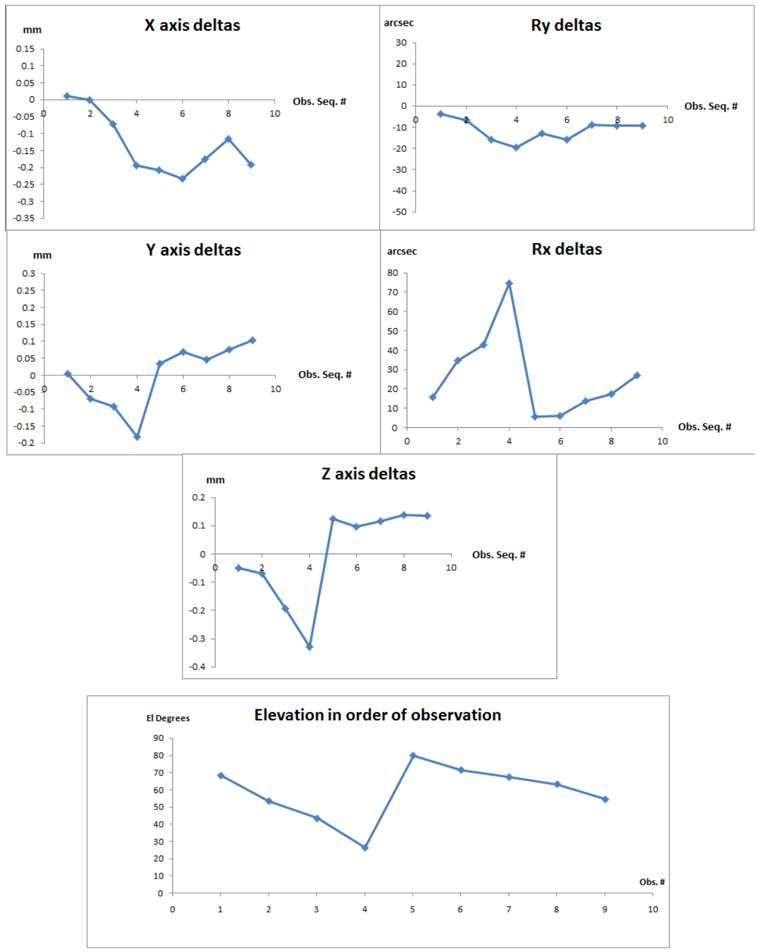

Figure 5. Plotted here are the same axis-error data as in figure 4, but this time vs. order of observation. Obviously the sudden jumps in Y, Rx and Z are related to a jump in elevation, (as shown also by the linearity for these errors in figure 4), but also there is some small drift at about the same level shown with the LBC data in figure 3.

This is data is consistent with the slow changing drift observed in the LBC data in figure 3, together with a new effect with elevation in the Gregorian measurements, which was not present in the prime-focus camera data.

4.3 First results with the Gregorian configuration and automated laser tracker

In April 2012 the "semi-automated" laser tracker presetting of telescope optics was tested during the half-night of technical time then available. "Semi-automated" because the Range Balancing routine described above had been imperfectly modified to use the laser tracker input vectors as starting points, and as a result, hexapod changes were sent by hand and the telescope hexapods were not range-balanced. Because of the resultant need to manually input hexapod commands, only seven useful datapoints were obtained in the 1.5 hour observation window allowed by weather. However, these data do present further useful insight.

Firstly, the laser tracker control program was tested by collimating the telescope, measuring "nominal" points for M1 and M2, then clearing the hexapod positions requested by the active optics system (i.e. returning to the open-loop collimation model hexapod positions, a change of ~ 1.0 mm in translation of the M2 vertex, together with some rotation), and running the program on the newly updated baseline file. The laser tracker completed its measurements and analysis and produced a change vector for M2 in a little under 40 seconds.

The values from this change vector were manually entered as offsets into the control GUI for the M2 hexapod, and active optics was re-run (on the same field, at the same altitude). For the first iteration, the active change vector for the M2 hexapod, {X, Y, Z, Rx, Ry}, was (-0.020 mm, -0.022 mm, -0.005 mm, 2.1”, -2.25”), showing that the laser tracker had repositioned the M2 to within the noise level of the active optics system.

The baseline file obtained at the start of the night was used for the subsequent seven “laser tracker active presets”. The time-to-complete for these presets varied between 36 s and 45 s. There some small variation in time given that after slewing to each point the tracker has to acquire the new target, typically taking between 0 and 2 seconds to do this. In no case during this particular test did the track “miss” a point and have to attempt to re-measure. Therefore, even allowing for time for the hexapod to move, it is still reasonable to expect from this that a typical laser tracker active preset could be completed in approximately the same time as one cycle of the Shack Hartmann active optics system.

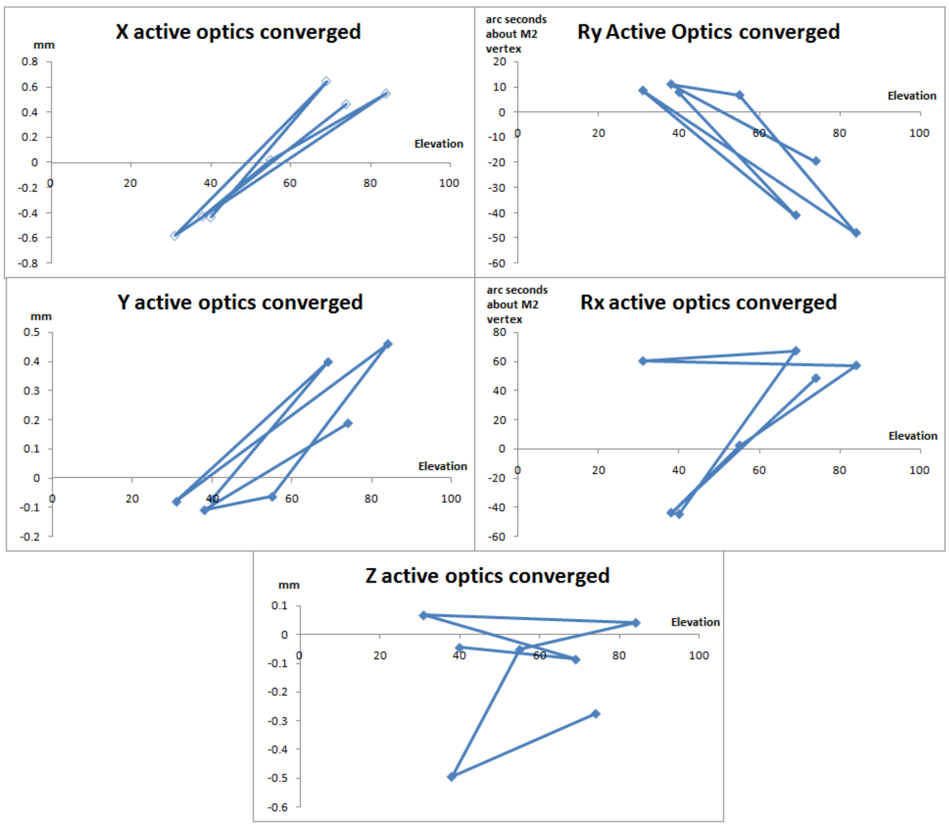

Figure 6. . At first glance is a clear difference between these plots of hexapod error vs. elevation, to those in figure 4. In fact, the observations were carried out differently, in the earlier case elevation was changed gradually between observations, with one exception; here elevation oscillated high-low between observations, as can be seen also in the next figure.

For these measurements the telescope was sent in track presets to alternately high and low elevations. Once tracking was achieved the Measurement Plan program was run, and values from the resultant M2 change vector manually input to the M2 hexapod via the GUI. Then a second preset, this time an “active” preset was sent to the same target and the active optics system was run until it converged and the resultant total change requested in M2 position by this system was recorded. These are the data presented in figures 6 and 7.

At first glance there is a striking difference between the results in figure 6 and those of the corresponding figure 4 from the earlier Gregorian data set. In fact, there was a significant jump in Y, Rx and Z between the fourth and fifth observations from the initial Gregorian data set, which corresponded to the only large change in elevation between consecutive points in that data set. Here now we are getting the jumps also in X and Ry, and also the magnitude of the jumps has increased. Note also that there is no evidence of these jumps in the LBC data.

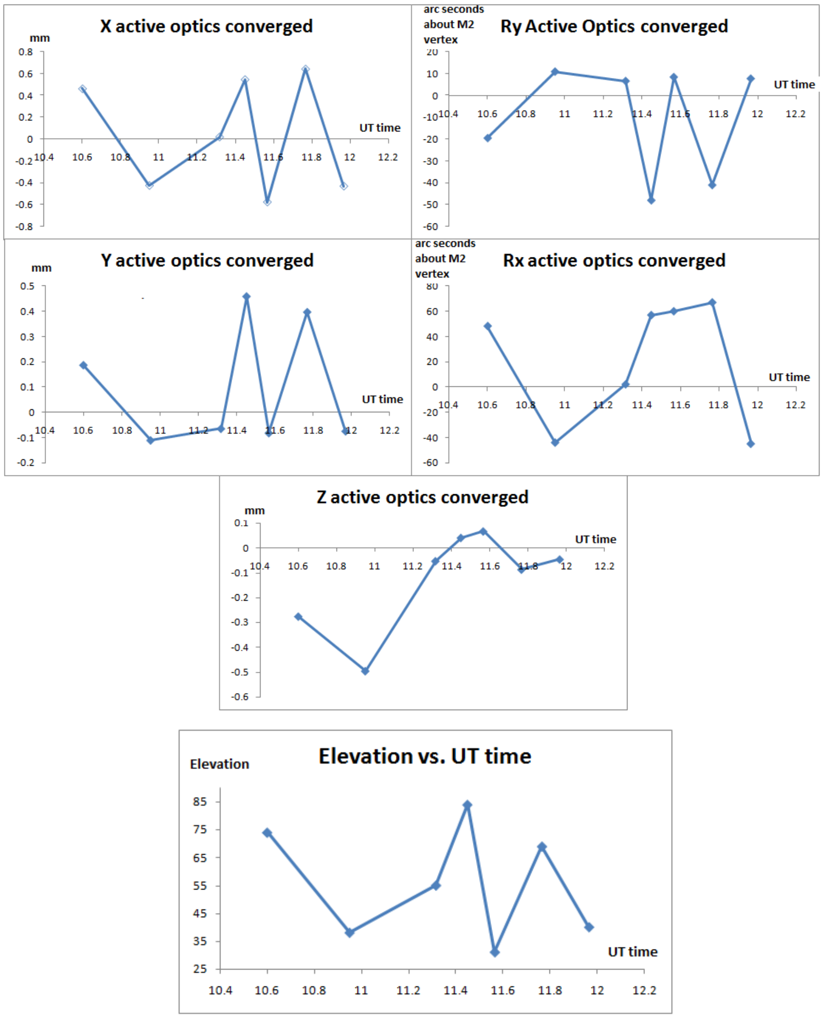

Figure 7. It is clear that in most cases the errors in hexapod position are closely correlated to elevation. In fact there is also a gradual drift, of similar magnitude to that seen on the prime-focus camera as shown in figure 3.

5. DISCUSSION

While initial tests with the laser tracker have not been an instant "success", there are a number of interesting observations to be made from this data.

First, looking at the LBC data, it seems clear that the laser tracker is capable of very accurate positioning of optics, but also that it is limited in not being able to measure mirror figure errors, and these figure errors have already been shown to be large when the borosilicate mirrors are not in thermal equilibrium. Interestingly, in the LBC data there is no strong evidence of systematic jumps with elevation. Again, with the Gregorian case, when we positioned the optics using the Shack Hartmann active optics system until converged, then measured mirror positions, cleared active position commands and used the laser tracker to re-position the optics to the measured positions immediately, the resultant errors were within the noise of the active optics system. In this case there was no significant change in elevation or primary mirror thermal figure over the time taken.

However, in general in the Gregorian tests we did see what looked like at least two separate causes of hexapod position errors. This was seen by a slowly changing measurement drift, of the order of that observed with the LBC data, and another error component with strong dependence on elevation.

One big difference between the physical setup for measuring the Gregorian M2 position and the prime-focus camera is that in the latter case, the SMRs were mounted directly onto the prime-focus camera exterior, which is unlikely to experience much relative movement to the prime-focus camera's optical components. On the other hand, in the case of the Gregorian M2, the SMRs were mounted on brackets that were bolted to the M2 hexapod, and that extended several hundred millimeters from the mounting flanges.

Also, between the hexapod and the secondary mirror surface there are two stages of mechanical de-coupling; through an electronics box and a cold plate. From modeling it was expected that there should be some deflection between the secondary mirror surface and the hexapod of the order of several hundred microns, and it was expected that this deflection should be free of hysteresis.

The difference between the two sets of Gregorian data presented here; the data in figures 4 and 5 compared to those of figures 6 and 7, argue that the brackets holding the SMRs are at least contributing some effect, as the removal and reinstallation of these brackets is the only thing that has changed with the hardware setup between the two sets of measurements, and in the first set there was no strong X, Ry component to the hexapod position errors, whereas in the second data set there was.

In conclusion it would seem that the laser tracker has a very real possibility of leading to big improvements in telescope efficiency: firstly, by positioning optics quickly, reliably and accurately, and secondly, in doing so and thereby removing position error contributions to wavefront error, in allowing a more accurate modeling of the thermal figure errors of the primary mirror, a task that up until now has been largely neglected.

It should be noted too, that the good results suggested by this work could in principle be directly improved on by adding more laser trackers to the system, thus reducing "shot noise". That is, if the ~ 20 microns RMS errors found here, or some scaled-up error on longer path measurements, say on one of the Extremely Large Telescope projects currently in the works, was deemed to be undesirably large, then in principle this error could be reduced by a factor of $\frac{1}{\sqrt{N}}$ where N is the number of laser trackers used to measure the same point.

A number of telescope projects currently under development have been investigating the use of a laser tracker for telescope alignment; these first results from the LBT strongly suggest that these investigations are on the right track.

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