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Measurement of large on-axis and off-axis mirrors using Software Configurable Optical Test System (SCOTS)

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ABSTRACT

One of the major challenges of optical fabrication is measurement of the surface when first polished out, before its figure is within the capture range of interferometry. A high dynamic range instrument with good accuracy is needed to efficiently guide the processing. Our approach is to use the Software Configurable Optical Test System (SCOTS), a deflectometry technique that uses a camera and liquid crystal display to measure the surface slope. We describe the use of SCOTS in the fabrication of a 6.5 m on-axis mirror and an 8.4 m off-axis mirror segment (Giant Magellan Telescope primary). SCOTS has the dynamic range to measure high slope errors early in the mirror figuring process, with sufficient accuracy to corroborate later interferometric measurements. Accurately measuring low order figure errors with SCOTS requires careful calibration of the system geometry. Details of the data collection and processing, and comparison to interferometry measurements are presented.

Keywords: Metrology, deflectometry, aspheric, telescope, GMT

1. INTRODUCTION

Deflectometry is an old testing technique, but it is still highly relevant for today's challenging optical metrology problems. Deflectometry is simply measurement of the lateral displacement of light coming from a surface; the test geometry converts this into a slope error, which can be interpreted as-is or integrated to obtain a surface map. All of the classical (pre-interferometry) optical testing methods are forms of deflectometry, beginning with the Foucault knife edge test and including the wire test, Ronchi test, and Hartmann test. Even as phase measuring interferometry was first appearing, the Shack-Hartmann test breathed new life into deflectometry, providing higher resolution measurements and ultimately higher accuracy as technological advances introduced digital cameras and low cost computing power. Deflectometry became a thoroughly modern technique with the advent of phase measuring deflectometry in 2004 [1]. This approach led to the development of SCOTS, which uses an LCD monitor and careful calibration of system components and geometry to allow precision metrology of optical surfaces [2], [3].

SCOTS provides several advantages over interferometry. Its high dynamic range makes it an ideal tool for in-process metrology, able to measure slopes that are too steep to be resolved by an interferometer – a common occurrence when a large optic is first polished out. Deflectometry is relatively insensitive to vibrations and turbulence, since the blurring from these effects occurs in an image plane (smoothing out fringes laterally) rather than in a pupil plane (averaging the OPD itself as the wavefront tilts or distorts), although modern instantaneous phase shifting interferometers have eliminated this advantage. The SCOTS hardware itself is inexpensive, not requiring an expensive instrument or surface-specific null optics for testing aspheres. While interferometry still has an advantage in accuracy, the difference is narrowing with improved calibration of SCOTS.

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2. SCOTS BACKGROUND

2.1 Geometry

The basic test geometry for SCOTS is shown in Figure 1. The test mirror is illuminated by the monitor, with light reflected off the mirror captured by a camera. A lens in front of the camera images the test mirror onto the detector, while a pinhole in front of the lens limits the portion of the mirror seen by the detector. For each pixel on the detector, the associated point on the mirror and monitor allow the actual surface normal on the mirror to be calculated via the law of reflection. The locations of all of the system components are measured using a laser tracker, with Sphere Mounted Retroreflectors (SMRs) positioned on the mirror, camera, and monitor. Combining the latter two with calibration yields the geometry of the pinhole and monitor pixels.

Figure 1. SCOTS test geometry.

2.2 Data collection

Spatial phase information is obtained by collecting fringe and line scan data. Sinusoidal fringes are projected on the monitor; images are captured as these are shifted in phase. This is done for both horizontal and vertical fringes (left side of the first box in Figure 2). A separate line scan process – shifting a thick line by 1 pixel between images – is done for a horizontal and vertical line (right side of the first box). The overlap between the horizontal and vertical line identifies a single pixel on the monitor that corresponds to zero phase. Without this additional information, the result of the fringe processing would give the relative arrangement of points on the monitor (equivalent to a spot diagram in a lens design program after tracing rays from the pinhole) but not their absolute coordinates. The fringe and line scan data collection is repeated for multiple mirror rotation angles and multiple cameras, if applicable. In practice, images may be averaged for each fringe phase shift and line scan pixel shift to reduce random noise.

Mapping information is obtained by collecting a fiducial image (right box in Figure 2). Targets are placed on the mirror and images captured by the camera and averaged. The target locations are measured using a laser tracker as part of the

geometry data collection (middle box). The laser tracker is also used to measure SMRs on the mirror, camera, and monitor to establish the overall system geometry.

Figure 2. SCOTS data collection flow.

2.3 Data processing

As with data collection, processing consists of phase calculation, mapping, and geometry (Figure 3). The system geometry is obtained by combining laser tracker measurements of the current test configuration with calibration data for the monitor and pinhole. The geometry data is used by the mapping and phase processes.

Figure 3. SCOTS data processing flow. Orange boxes indicate input data.

Mapping is critical to remove the effect of distortion introduced by the SCOTS camera lens and any auxiliary optics, as well as keystone that is introduced by the camera being slightly off-axis. The fiducials are located in the image and their centroids calculated. These are compared to the fiducial locations measured by the laser tracker, and orthogonal mapping polynomials (S & T polynomials [4], [5]) are used for the fit. These polynomials are applied to the regular grid of camera pixels to obtain an irregular grid of distortion-corrected points on the mirror. The mirror prescription is used to calculate the surface sag and ideal surface normal at each mirror point.

Phase is obtained by feeding the fringe data to a phase shifting algorithm. We do a sinusoidal fit to the data, but a standard phase-shifting interferometry algorithm might also be used. A modulation map is also obtained; this and an intensity map are used to mask out data with low modulation or low signal. The masked phase data is processed by a phase unwrapping algorithm to give relative offsets between the points. Line scan data is processed to find the pixel with zero phase. The resulting phase map is combined with the pixel geometry to yield the points on the monitor (spot diagram).

Actual surface normals are calculated via geometry between the actual (distortion-corrected) mirror points, the pinhole, and the monitor points. Subtracting the actual normals from the ideal normals yields a slope error map. After interpolating this onto a regular grid, the slope is integrated (based on Southwell [6]) to obtain the surface map.

3. 6.5 M ON-AXIS MIRROR SCOTS TEST

3.1 Test hardware and model.

A photograph of the hardware used to test a 6.5 m mirror is shown in Figure 4. The source is a 30" LCD monitor, shown face down on the left. Two cameras on adjustable mounts are in the center, with four SMRs mounted around the lens barrel on each camera. The structure on the right is a hexapod for the interferometry system. A 4D interferometer illuminates a refractive Offner null corrector (the gold cylinders); below that (not visible) is a reference CGH that can be inserted into the beam for calibration of the null corrector. Since the interferometry and SCOTS hardware both need to be centered at the axis of the test mirror, the test hardware sits on a carriage that rolls along two large mechanical beams, allowing easy switching between the two tests.

Figure 4. SCOTS hardware for 6.5 m mirror testing. Monitor is at the left; cameras are in the center. On the right is an Offner null corrector mounted on a hexapod. The entire assembly rides on a carriage to switch between tests.

The ZEMAX layout and spot diagram are shown in Figure 5. The two (green and blue) spot diagrams correspond to the two cameras (ray tracing from their pinholes). A smaller monitor would have sufficed, but we reused the 30" LCD and basic mounting structure that was available from the test setup for the 4.2 m Daniel K. Inouye Solar Telescope (DKIST) primary [7].

Figure 5. SCOTS geometry and beam footprint (image of pinholes for two cameras) on monitor for 6.5 m mirror test.

3.2 Calibration

Since ultimately we need to know the location of the camera pinhole(s) and monitor pixels relative to their SMRs, calibration of these components is essential. To avoid changes between calibration and operation, we calibrate them in the same configuration as the test. For both DKIST and the 6.5 m mirror, the monitor and camera are facing downward. This eliminated use of a Coordinate Measuring Machine (CMM) as an option, so the calibration was done using a Point Source Microscope (PSM) with SMRs attached to it. As the PSM was moved and focused on different objects (edges of the pinholes, pixels on the monitor, SMRs on both subassemblies), the PSM location was measured using a laser tracker. The PSM itself was calibrated by focusing on an SMR, with this SMR then related to the PSM's SMRs.

Specific calibrations performed for the 6.5 m SCOTS hardware were the camera pinhole and monitor pixels. For each camera, several points around the periphery of its pinhole were measured; a fit to these yielded the center of the pinhole, which was related to the camera's SMRs. The PSM was focused on specific pixels on the monitor. These were related to the monitor's SMRs. Measuring the monitor pixels also yields the actual pixel spacing and the orientation of the rows and columns relative to the SMRs.

Additional calibration of the monitor was done for DKIST [7], [8]. The thickness of the glass was measured at multiple pixels by focusing on both the active area of the pixel and the glass surface at that location. The average glass thickness was calculated, and this was input into a ZEMAX model that was used for the DKIST processing. The shape of the monitor was also measured by focusing on a grid of pixels. For DKIST the shape was found to be cylindrical, which was modeled as a toroid in the ZEMAX ray trace. For the 6.5 m calibration, pixels were measured over a smaller region of interest. Combined with a different (now kinematic) mounting interface, the result was that no obvious low order shape was found. Analysis for DKIST had shown that the effect of the glass thickness was dominated by power (400 nm), and the monitor bending dominated by power (200 nm) and astigmatism (72 nm). Due to various factors, ZEMAX was

already used as part of the DKIST processing, and adding this additional information came at no penalty. However, ZEMAX was linked to our Matlab processing through Dynamic Data Exchange (DDE), which proved to be unstable and resulted in the need to restart Matlab after each ZEMAX processing step. To eliminate this instability, and because the power error was not significant enough for the 6.5 m test and the monitor shape not as large or obvious as on DKIST, we chose not to use ZEMAX as part of the processing and did not include these other effects. In the future, now that a reliable API interface between Matlab and ZEMAX exists, we may add these features back.

3.3 Other improvements on DKIST

The SCOTS test on DKIST included two other enhancements from earlier tests: multiple cameras and rotation of the test mirror. Adding a second camera enables an easy check of SCOTS repeatability as well as an additional set of measurements to average. The large polishing machine at the College of Optical Sciences sits below a large test tower, so all metrology is in situ and does not require any mirror handling for testing. Having the test above the table enables rotating the mirror during testing, which allows some SCOTS errors (notably distortion residual) to be reduced by averaging measurements taken at different mirror angles. Mirror rotation also facilitates establishment of the mirror location by the laser tracker.

3.4 Coma issue on DKIST

One issue that demonstrates the sensitivity of SCOTS to calibration errors emerged during the DKIST primary fabrication. Due to delays in the complex interferometry system (which used a fold sphere to reduce astigmatism, similarly to the GMT test configuration that will be shown in section 4.1), most of the figuring was guided by SCOTS testing. When the interferometry system became operational, initial measurements showed a 500 nm difference in coma between interferometry and SCOTS. Coma in this test indicated an error in the primary mirror vertex location, and 500 nm was enough to place it outside the vertex specification.

Investigation revealed a systematic error due to lateral chromatic aberration (lateral color) in the SCOTS lens. Red pixels on the monitor were used to generate the fringe data. The fiducials consisted of white paper targets with a black area in the middle (Figure 6, Top Center) that was located and centroided in the fiducial image. (Within the black area was a black ring that the SMR sat on for laser tracker measurement of the fiducial position, as shown in the Bottom Center image.) Due to the limited intensity of the monitor, the black areas would not be visible if the monitor were used for illumination, so room lights were used instead. A simple commercial off the shelf (COTS) doublet was used to focus the mirror onto the sensor. Figure 6 (left) shows the spot diagram for F-d-C wavelengths in the lens design, which shows obvious lateral color between the blue, green, and red wavelengths. At the edge of the field, the difference in centroid between the spectrum of a red phosphor and the spectrum of typical fluorescent lights proved to be 0.2 pixels, or 0.5 mm on the mirror. This corresponded to a 500 nm error in coma for SCOTS.

To eliminate this error, the incoherent fiducials were replaced by coherent fiducials (Figure 6, Right). A hole in the center of the fiducial enabled red light from the monitor to reflect off the mirror, giving high signal. For adequate image sampling, the center hole was too large to accept an SMR without contacting the glass, so a center plug was made using a concentric punch to provide a seat for the SMR. After switching to these fiducials, the vertex location predicted by SCOTS came into agreement with the interferometry, and the mirror was refigured slightly to eliminate the error in the vertex location.

Figure 6. (Left) Spot diagram for DKIST SCOTS lens showing lateral color. (Middle, Top) Incoherent fiducial. (Middle, Bottom) SMR seated on incoherent fiducial. (Right, Top) Coherent fiducial as used for camera image. (Right, Bottom) Coherent fiducial with insert for SMR registration.

3.5 Results for 6.5 m mirror

Figure 7 shows testing results for a 6.5 m mirror. Good agreement is shown between SCOTS (left) and interferometry (right). While there are small errors in low order Zernike terms (the terms most affected by errors in geometry and calibration), agreement is excellent when these are removed. The bottom half of the figure has 22 Zernikes removed, to approximate the available bending modes for this particular mirror. Over the required clear aperture, the SCOTS and interferometry RMS errors are 31 and 32 nm, respectively, and there is good agreement between the features in the two maps.

SCOTS can also be used to obtain the mirror radius of curvature and vertex location. The primary measurement tool for the radius was interferometry, where the reference CGH location was measured relative to the mirror and that spacing compared to the nominal radius. The average error found with this method was -0.375 mm. A redundant measurement was performed by measuring two orthogonal diameters across the mirror using a laser tracker in its more accurate interferometric (IFM) mode, with an SMR carefully stepped across the mirror. The result of that measurement was an error of -0.328 mm. With SCOTS, the power Zernike (Z4) is used to calculate the radius via a ZEMAX model, giving an error estimate of -0.115 mm. While the difference between the other methods and SCOTS is ~0.25 mm, this is well within specification, and less than the variation we saw in measurements due to thermal behavior in our shop. Including the screen thickness and bending in a more complex processing model may reduce this difference.

The mirror vertex location was found using interferometry, involving a complex process. The interferometer was aligned to the mirror, for four different mirror rotation angles. At each angle, the CGH vertex location was measured using a laser tracker, with a significant number of measurements averaged to accurately obtain the tilt of the CGH over a relatively small lever arm. As a redundant check, a spot focused at the vertex of the mirror by a small pattern at the center of the CGH was tracked with a camera mounted in the mirror's center hole during the primary test. The result of these measurements was an average error of -1.13 mm. With SCOTS, the vertex error is obtained simply by combining the measured coma with a ZEMAX model. Its result of -1.25 mm was within the uncertainty of the measurements obtained using interferometry, and the directions were consistent.

Figure 7. Comparison of SCOTS (left) and Interferometry (right) results for a 6.5 m mirror. Top row is with only power and coma (interferometry alignment terms) removed; bottom row has 22 Zernikes removed to approximate bending modes available for the mirror.

4. 8.4 M OFF-AXIS MIRROR SCOTS TEST

A photograph of the Giant Magellan Telescope (GMT) primary segment #2 (S2), situated under the test tower at the Richard F. Caris Mirror Lab (RFCML), is shown in Figure 8. Unlike at the College of Optical Sciences, this facility has a large optical generator on one side of the tower and a polishing machine on the other, so mirrors can be moved to test from either machine. Consequently, the mirror cannot be easily rotated during testing, and this is not an option anyway for the off-axis configuration used to test these segments.

Figure 8. GMT segment 2 under the test tower.

4.1 Geometry and test hardware

The test configuration and resulting spot diagram for GMT off-axis segment testing is shown in Figure 9. To reduce the huge amount of astigmatism that results when testing the GMT segment at its center of curvature, a 3.8 m large fold sphere (LFS) is mounted at the top of the test tower. The principal test (interferometry) hardware is located near the origin of the rays shown in the figure.

Figure 9. SCOTS geometry and beam footprint (image of camera pinhole) on monitor for off-axis GMT 8.4 m segment test.

DKIST had a similar test configuration for interferometry, albeit at half scale. SCOTS was mounted at the center of curvature of the mirror, above the smaller fold sphere used at Optical Sciences, with the fold sphere moved out of the way for SCOTS testing. The DKIST test was effectively an on-axis test of an off-axis mirror. However, the LFS at the RFCML is mounted at the top of the test tower, which is 25 m tall and was built before SCOTS was invented. Consequently, the SCOTS test for the GMT segments must be mounted in front of the interferometry, facing upward and imaged through the LFS. The resulting spot diagram, shown in the right of Figure 9, is highly distorted and resembles a fish. Rotating the mirror, if it were practical during testing, would destroy the astigmatism compensation performed by the LFS and create a significantly larger spot diagram, requiring a much larger monitor.

Figure 10 shows photographs of the GMT SCOTS hardware. The hardware is mounted on a tray (left) that slides in front of the interferometric test. The camera is located in a well, which made it impractical to mount SMRs around its barrel as was done for DKIST and the 6.5 m project since the laser tracker could not view them. Instead, the SMRs are mounted at the top of the camera subassembly (right). The picture shows a PSM mounted to a CMM (which was essentially used as a translation stage with encoder), with the PSM focused at the center of an SMR. The camera is mounted to manual translation stages above a rotation stage, with the translation stages used to align the pinhole to the rotation axis. The rotation stage allows measurements to be taken at different camera angles, to average errors introduced by the lenses.

Figure 10. SCOTS hardware for GMT. (Left) SCOTS tray mounted in test tower. (Right) Close up of camera subassembly during calibration. PSM is focused on an SMR.

4.2 Differences from on-axis SCOTS test

Imaging through the large fold sphere complicates the processing. In particular, to obtain the actual slope errors on the mirror, we do a complex ray trace of all the points using ZEMAX. The LFS figure itself must also be considered during final figuring. The LFS is measured at its center of curvature using an interferometer, with fiducials on the LFS used to register its map to the principal test map. For SCOTS, since the test is non-null with the beam taking dramatically

different paths to/from the test mirror, different morphing is required for each path. This was fully implemented on GMT segment #1 (S1), but has not yet been applied to S2. This will be included when S2 is closer to completion.

Camera rotation was implemented as an upgrade last year. The camera was tilted manually during S1 testing to average out certain errors from the lens, but this introduced large uncertainty into the position of the pinhole which is a likely source of the large errors seen in low order Zernikes for S1 SCOTS testing. Camera rotation was tested using S1 last year, and data has been collected for S2 but not yet fully debugged. Use of this data will be necessary to reduce errors from the SCOTS lens as S2 nears completion.

Line scanning data collection and processing were never used on S1. While it has been implemented in the data collection GUI, it has not been applied in the processing. Instead, the spot diagram is compared to an ideal spot diagram generated for the current test configuration using ZEMAX, with the offset between them used to properly position the measured monitor spots. The line scan has been implemented in the code used at Optical Sciences, and we are in the process of switching GMT to use that code for improved commonality and easier maintainability between projects.

One significant difference is that room lights have been used for GMT SCOTS data collection, up until this conference. The available fiducials were incoherent fiducials similar in construction to the ones used initially for DKIST. Since the low orders measured for GMT S1 had significantly higher errors than expected, they were subtracted from S1 measurements and were not a high priority for S2, so we stuck with the existing hardware and process. However, now that we are attempting to improve the low order agreement between SCOTS and interferometry on GMT, this has proven to be a limiting factor, as will be seen in section 4.4.

4.3 GMT ray tracing

The ZEMAX model used for GMT is shown in Figure 11. The mirror segment is modeled using an in-house DLL used to define off-axis segments without requiring complex tilt/decenter arrangements. The system is ray traced in double pass through the LFS. There are tilts for the LFS and the monitor. The second pass through the LFS propagates to its center of curvature (CoC) and back, to allow optimization of the CoC location.

Figure 11. Detailed ZEMAX model for GMT SCOTS ray tracing. (Lower, Left) Merit Function contains global XYZ targets for measured components. (Lower, Right) Pinhole, pixels, and ray tracing geometry are separated into different configurations.

Multiple configurations are used to define and optimize the locations of the measured hardware elements. Four configurations define pixels, while one defines the pinhole and two others are used for ray tracing. The merit function contains the global coordinates of the object surface for the pinhole and pixels, as well as the global coordinates of the LFS CoC. These values are read in for each test using the current measured geometry. The prescription is optimized to force the prescription to match the test.

A macro performs the essential ray tracing, outputting ray data for use in calculating the actual surface normals in Matlab. Matlab outputs mirror points and monitor (spot diagram) points, which are read into ZEMAX. Dividing by the stop radius converts mirror points to pupil coordinates. The field is modeled using object height and rectangular normalization. One configuration is reserved for the field center; this is used to get the global coordinate of the field center as well as to trace rays for field coordinates of (1, 0) and (0, 1) to calculate the coordinate axes on the object. Each monitor point is then subtracted from the origin, and a dot product is taken with these axes to obtain the field coordinates. Robust ray aiming in ZEMAX allows ray tracing specific object points to specific points on the mirror through the LFS. The stop is shifted by the mirror sag at each mirror point (with a pickup used to maintain the mirror location), since each mirror point is on the mirror surface, not in a plane at the vertex of the mirror.

For each mirror point and corresponding monitor point (more than two million sets), after determining the ZEMAX pupil and field coordinates, a ray is traced to the LFS and its global coordinates there written to a file. A ray is also traced to the LFS for the same mirror point from the pinhole configuration. We found that there is a significant time penalty in switching between configurations in ZEMAX, so the monitor and pinhole ray traces are performed in separate loops, each reading completely through the input file. The resulting processing takes 1.75 hours; with the monitor and pinhole ray traces in the same loop, we estimated that processing would have taken 5–7 days. After processing in ZEMAX, the LFS ray coordinates are read back into Matlab and combined with the corresponding mirror point and the pinhole location to calculate the actual surface normals at each point.

4.4 Results for 8.4 m GMT S2 mirror

Figure 12 shows the latest complete results (4 June 2018) for S2. These maps have 12 Zernikes removed, a significant improvement over S1 which had 21 Zernike gradients removed in slope space and was never able to obtain reasonable agreement with interferometry for low orders. The RMS is slightly higher for SCOTS (left), a result of missing data in the interferometry (right). SCOTS is invaluable for measuring steep areas not yet observable with interferometry. Also note the double set of LFS fiducials in the SCOTS map, a result of the different beam paths taken to/from the LFS.

Figure 12. Comparison of SCOTS (left) and Interferometry (right) results for GMT segment 2 (in process results from 6/4/18) after removing first 12 Zernikes.

The low order Zernikes (ZEMAX standard – Noll set) removed from the previous maps are shown in Table 1. The interferometry map was corrected for the LFS figure, as well as force and temperature compensation for the polishing cell. The most significant corrections (> 100 nm) were for power (Z4) and astigmatism (Z6). Since power and astigmatism are the most sensitive terms to calibration/geometry errors in SCOTS, and SCOTS had no compensations applied (and data was taken earlier in the day than interferometry, so any compensations may have been different from what was applied to interferometry), it is not surprising to have differences in these terms. However, three of the terms have a higher than anticipated difference: Z8 (coma), Z11 (spherical), and Z12 (higher order – ρ^4 – astigmatism). Simulating this level of Z12 suggested that stretching of the fish-shaped spot diagram would result in this type of error, reminiscent of the radial scaling we saw on DKIST due to lateral color in its lens coupled with using room lights to illuminate the fiducials.

On 11 June, a SCOTS measurement was taken after the latest polishing run, and additional fiducial measurements were taken with illumination provided by the red pixels on the monitor. The fiducial image was processed outside our normal routines (using a circle finding routine in Matlab, something used for the 6.5 m SCOTS processing). When this data was incorporated into the latest processing, the magnitude of Z8, Z11, and Z12 dropped significantly, to the values shown in the last column of Table 1. This suggests that these somewhat large differences in the Zernikes were due to lateral color in the GMT SCOTS lens, and future testing should be performed using red pixels to illuminate the fiducials with the processing altered accordingly.

Table 1. Low order comparison for preceding GMT test results (4 June 2018). Zernikes are the ZEMAX Standard (Noll) set.

The 11 June data, which was taken after a subsequent polishing run, used red light for fiducial illumination.

Zernike	4 June SCOTS (nm)	4 June Interferometry (nm)	11 June SCOTS (nm)
Z4	-260	795	-1358
Z5	53	-113	-365
Z6	-269	-549	-770
Z7	188	253	391
Z8	-537	43	-147
Z9	-117	-98	126
Z10	-186	-130	27
Z11	-235	-30	-39
Z12	-245	-27	-92

5. FUTURE DEVELOPMENT

Detailed error analysis has been performed for DKIST and earlier projects, including some initial work for GMT S1. The numerical results of this work have been published [8] or discussed in internal project documents. However, little of the detailed methodology of the modeling has been described. We plan to perform error analysis for GMT and our next 6.5 m project (for Telescopio San Pedro Mártir [9]), applying knowledge gained on recent projects and fully documenting the models and results. This process will provide a roadmap for making further improvements in the low order accuracy of SCOTS.

6. SUMMARY

We have implemented SCOTS, with improvements based on past experience, on both a 6.5 m primary mirror and the GMT off-axis segment #2. ZEMAX was used to ray trace the complex GMT test configuration. SCOTS and interferometry show excellent agreement for the 6.5 m mirror test. For GMT they show excellent agreement with low orders removed. The most significant differences in the lowest 12 terms were recently found to be a result of lateral color in the SCOTS lens and will be eliminated by using red light in future SCOTS tests.

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