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A new test for optical surfaces

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Off-the-shelf components can measure precision astronomical mirrors and solar-energy collectors as accurately as interferometric methods but much more cheaply.

For an optical system to produce the best possible images, the optical surfaces of the mirrors and lenses must be polished to the correct shape to within a fraction of the wavelength of light (in most cases, this means a few tens of nanometers). Interferometry is usually used to inspect the mirror or lens and ensure that the correct shape has been achieved. However, the equipment is expensive and these tests are sensitive to alignment and environmental disturbances.

We have developed a test system based on readily available consumer electronics that measures the slope of rays reflected from optical surfaces. It rivals interferometry in sensitivity to surface errors, yet is much less expensive. We call our system, whose performance is entirely software controlled, a software-configurable optical test system (SCOTS). We have used it to measure large precision mirrors—such as the Giant Magellan Telescope's (GMT) primary mirrors—and solar-energy concentrators/collectors. It is functionally similar to interferometry, but directly measures slopes rather than surface heights. This approach can be more efficient and reliable for lens systems, and thus SCOTS is also a promising tool for evaluation of lenses. In its simplest configuration, only a laptop computer with a built-in camera is required. The laptop's LCD screen illuminates the surface and the camera detects reflected images that the computer then uses to calculate optical-surface gradients.

SCOTS uses the same basic test geometry as phase-measuring or fringe-reflection deflectometry.[1,2] It can be better understood as doing a traditional Hartmann test[3] with the light going through the system in reverse: see Figure 1(a) and (b). The CCD camera works as the point source and the screen has the function of the detector in a Hartmann test. Figure 1(b) shows schematically how the surface slope is measured and calculated. The computer or TV monitor is set up with its screen near the center of curvature and facing the mirror under test. If a single pixel is lit up on the otherwise dark screen, the image of the mirror, which is captured by the camera's CCD detector, will show a

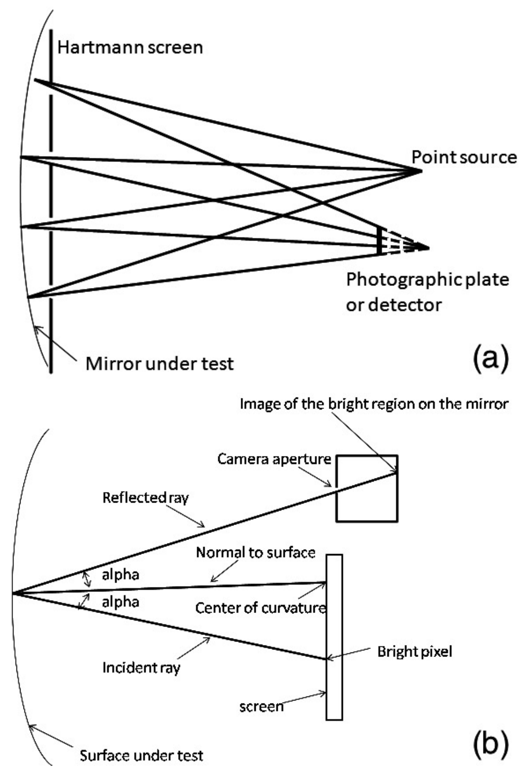
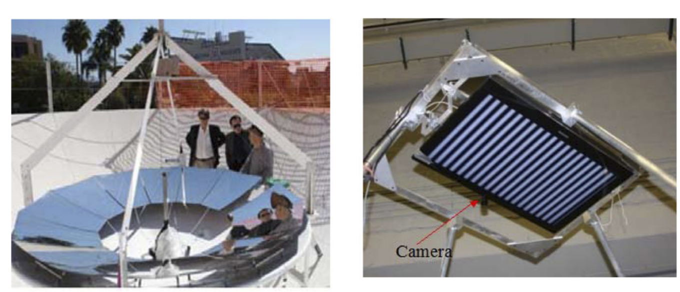


Figure 1. *Comparison of the test geometry for (a) a Hartmann test and (b) our software-configurable optical test system (SCOTS). Alpha: Angle of incidence/reflection.*



(a) (b)

Figure 2. *(a) A segmented 3m, f/0.5 (focal ratio) paraboloidal solar concentrator built at the University of Arizona. (b) Hardware setup of SCOTS located near the center of curvature of the solar concentrator.*

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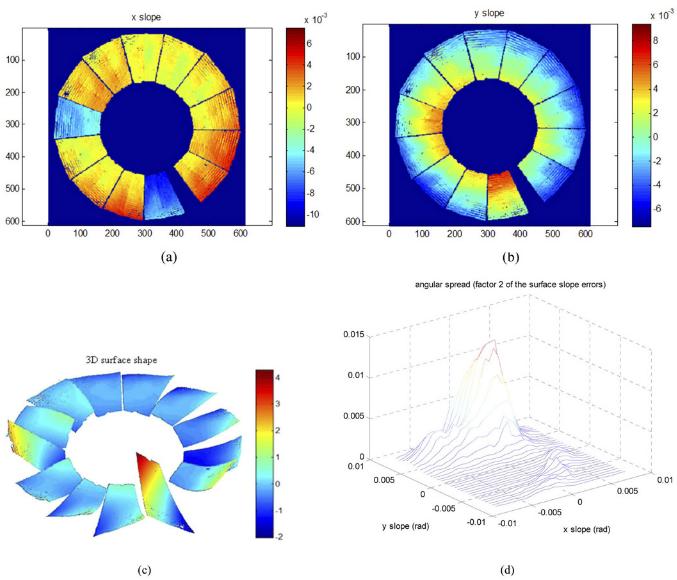

Figure 3. *(a) and (b) x- and yslope errors, respectively, for the segmented solar concentrator measured with SCOTS (color scale in milliradians). (c) 3D surface shape after removing overall paraboloidal shape (color scale in mm). (d) Light angular spread of solar concentrator (in radians).*

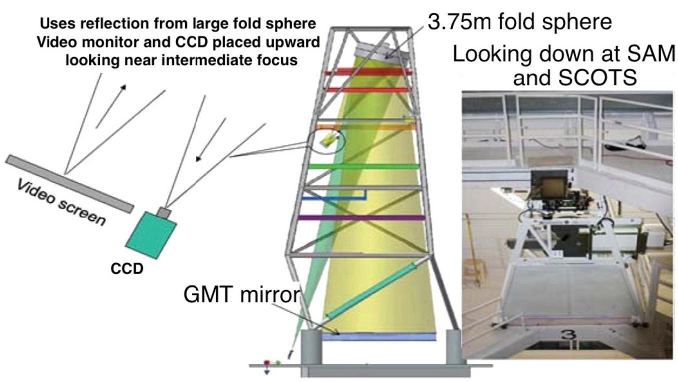

Figure 4. *Test setup for the Giant Magellan Telescope's (GMT) mirror, where the optical bench for the SCOTS test is located below the screen and camera. SAM: Self-aligned mirror.*

bright region corresponding to the area on the mirror where the angle of incidence from the bright pixel on the screen is equal to the angle of reflection back to the camera. The angular bisector of the incident and reflected rays is normal to the surface at the bright point. The surface slopes at the bright points can be calculated based on triangulation using the coordinates of the lit screen pixel, the camera aperture, and the reflection of the illuminated pixel. The surface shape can then be obtained by integrating the surface slopes.

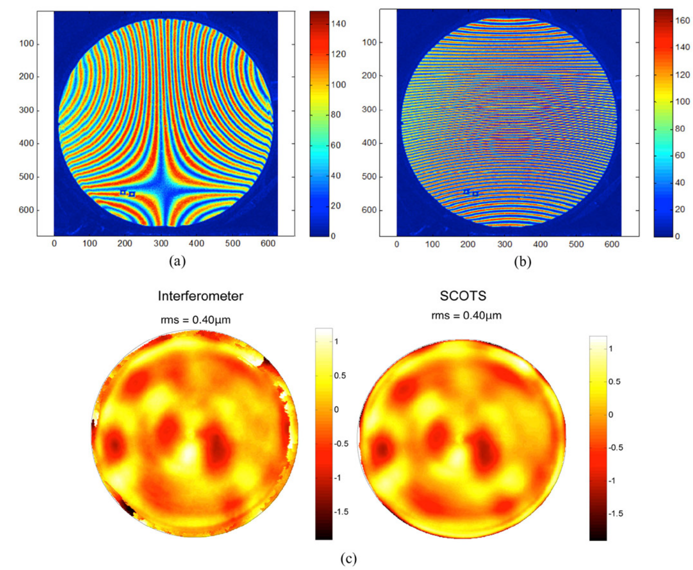

Figure 5. *Images of phase-shifted (a) x- and (b) y-sinusoidal fringes at the GMT mirror. (c) GMT surface data measured interferometrically (left) and by SCOTS (right). The circle represents the 8.4m clear aperture and the color-bar units are μm.*

Two complementary methods are employed in SCOTS for data collection and reduction. One is a brute-force line-scanning and centroiding method, which we developed based on the concept of the reverse-Hartmann test.[4] We illuminate the test surface with horizontal and vertical lines and reduce the collected data by centroiding on the intersections of the lines. The other method employs the more common phase-shifting approach, in which the test surface is illuminated with sinusoidal fringes. We calculate the slopes from the phase of the fringes. We compared both methods[4] and concluded that practical considerations may favor one method over the other.

We developed SCOTS as a low-cost, fast method for measuring the surfaces of relatively low-accuracy, large-scale solar reflectors (see Figure 2). We measured the slope data and surface shape for a fully segmented solar concentrator after removing the overall paraboloidal shape (see Figure 3). We found that two of the segments—the one at the bottom and another in the left-hand corner in Figure 3(a), (b), and (c)—are substantially out of alignment with the others, while at the same time the higher spatial-frequency errors caused by the molding process are clearly visible. The net performance of the solar concentrator

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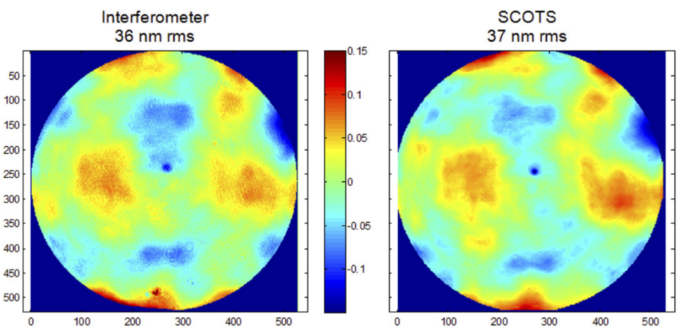

Figure 6. Comparison of 3.75m fold-sphere figure measured by interferometer and SCOTS. The low-order alignment terms and astigmatism, coma, trefoil, and primary spherical aberration have been removed from this data (color scale in μm).

is described by its light angular spread (twice the surface-slope errors) at the focal plane: see Figure 3(d). As such, SCOTS can very efficiently test and guide production and alignment of large solar concentrators.

We successfully applied SCOTS to a large optics project,[5] the GMT, where there was difficulty getting good interferometric data at the edge of the steeply aspheric 8.4m-diameter off-axis primary-mirror segment, which was being polished. The interferometric GMT test used a set of null optics that included a 3.75m tilted sphere, a 1m sphere, a computer-generated hologram, and an instantaneous phase-shifting interferometer.[5] All interferometric null-test optics, except for the 3.75m sphere, were mounted on an optical bench. For the SCOTS test, we placed the LCD-monitor screen and CCD camera above the optical bench and only used the 3.75m tilted sphere as part of the test (see Figure 4). In this configuration, the SCOTS test was nonnull and used an area of approximately 180mm in diameter on the screen to completely cover the mirror with fringes.

We displayed sinusoidal fringes in the x and y directions on the screen and recorded the corresponding images of the GMT mirror: see Figure 5(a) and (b), respectively. One can observe the slope errors at the edge of the mirror, particularly at 3 and 9 o'clock. Using SCOTS to measure the GMT surface, we removed the first 24 low-order Zernike terms to better illustrate the high degree of correspondence between the SCOTS and interferometric test data (where there is good data from both measurements): see Figure 5(c). The interferometric test has trouble getting good data outside 90% of the mirror aperture because of the steep slopes at the mirror's edge. Over the central 90% of the aperture, where both methods obtained good data, the SCOTS and interferometric data compared well. We are now using SCOTS as a major source of data for shaping the GMT's primary mirror.

To further quantify the accuracy of SCOTS, we also used measured the 3.75m fold sphere that is used for the GMT's optical null test. Figure 6 shows a comparison between the SCOTS and the interferometric test after removal of the low-order terms of astigmatism, coma, trefoil, and primary spherical aberration. The spatial resolution is similar and the magnitudes of the features measured are virtually identical in height and shape. Only 16 measurements were taken and averaged for the SCOTS data, while 80 interferograms were averaged. There are still random components left in the SCOTS data and additional data sets would further improve the test accuracy. Current measurement results of the low-order terms show them matched to ∼20nm rms between SCOTS and interferometric test. Based on analysis now underway, we believe that a careful calibration of the SCOTS test geometry can improve the test accuracy to the 1nm rms level for both low-order and higher-spatial-frequency data.

In summary, we have developed a low-cost, flexible, high-dynamic-range test that can rapidly, robustly, and accurately measure large, highly aspherical shapes such as solar collectors and astronomical optics. We have shown that the test can achieve measurement accuracy comparable with interferometric testing and has great potential for nonnull testing. We are now further developing SCOTS to measure lens systems with the idea that specifying lens systems in terms of slopes rather than heights more nearly matches their end use in many cases.

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Peng Su received his PhD in optical sciences from the University of Arizona in 2008. His current research focuses on optical metrology of large mirrors. The technologies he developed include a swing-arm optical-coordinate-measuring machine, a scanning pentaprism test for off-axis paraboloidal mirrors, SCOTS, and a maximum-likelihood method for large flats.

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