New Phase Measuring Deflectometry Device for Mid-to-High Spatial Frequency Surface Metrology

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Abstract: We present a new high resolution deflectometry technique for mid-to-high spatial frequency measurements of precision optical surfaces. This metrology technique was verified to be accurate to within 1 nm RMS, and repeatable to 300 nrad.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (120.6660) Surface Measurements, roughness; (120.4610) Optical fabrication

1. Introduction

The concept of deflectometry dates back to the first optical tests such as the Foucault knife edge, Ronchi, and Hartmann tests [1]. Deflectometry essentially digitizes the Hartmann test with a much higher spatial resolution. This technique has been in development at The University of Arizona for some time under the name "SCOTS" or Software Configurable Optical Test System. SCOTS aim is to robustly and inexpensively measure a wide variety of optical surfaces from free-forms to flats. Auxiliary lens deflectometry (AKA SPOTS or Slope-measuring Portable Optical Test System) is related to SCOTS, but is quite different in many ways because of the addition of the auxiliary lens.

New optical manufacturing specifications on mid-to-high spatial frequency errors [2] are pushing the limits of conventional optical metrology. Low and high spatial frequency measurements are attained with tools such as interferometers, Micro-Finish Topographers [3], microscopic white light interferometers, and microdeflectometry devices [4]. Interferometers placed at the center of curvature of a mirror are often unable to meet the testing requirements to measure mid-to-high spatial frequencies because they have a limited spatial resolution and slope measurement range, while Micro-Finish Topographers, white light interferometers and microdeflectometry devices provide spatial resolutions that are too fine over ~1 x 1mm area. Profilometry tools and test plates can be used, but they only provide line scans or qualitative information, so a quantitative full surface measurement can be time consuming depending on the desired spatial resolution. Deflectometry is able to satisfy this demand because it can provide a large measurement dynamic range. As shown in Figure 1, SPOTS bridges the gap between traditional metrology, and high spatial frequency metrology in terms of spatial frequency.

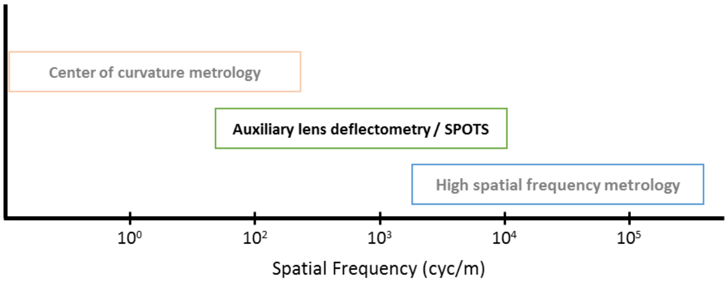

Figure 1: Auxiliary lens deflectometry in the world of optical surface metrology.

In this summary we show the basic principles of auxiliary lens deflectometry, and we also provide initial results comparing an interferometric measurement to SPOTS. We will discuss SPOTS in detail including the implications, principles, experimental results, error analysis, and system design metrics for measuring global (low order) and local (higher order) surface shape errors in a separate paper [6].

2. Principle of SPOTS

When measuring concave mirrors with deflectometry, we place a camera and display near the center of curvature of the mirror [5], as shown in Figure 2. This technique allows us to measure surface slopes using known display patterns, and then compute surface sag by integration. However, for large radius of curvature mirrors, with the camera place far from the mirror, we are not able to achieve high spatial resolution. In contrast, auxiliary lens deflectometry enables us to place a compact system near the surface of large radius mirrors and achieve high spatial resolution, as shown in Figure 3.

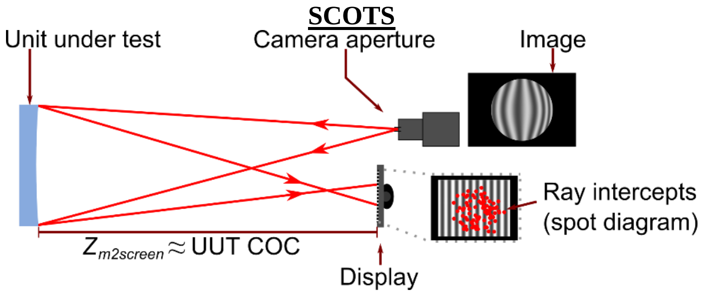

Figure 2: SCOTS measuring a concave mirror with arrows indicating reverse ray model arrows indicate the reverse ray direction, and dots on the display representing the ray intercepts (spot diagram). $Z_{m2sceen}$ is the distance from the mirror to the display.

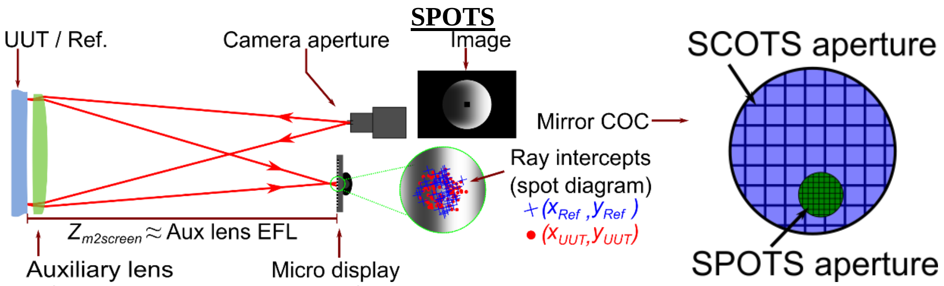

Figure 3: SPOTS configuration. $Z_{m2screen}$ is the distance from the mirror to the screen, (x_{Ref}, y_{Ref}) and (x_{UUT}, y_{UUT}) are the ray intercept locations of reference and measurement optics respectively. Right: grid pattern corresponds to CCD pixels mapped from the camera to the mirror.

The SPOTS method is advantageous for because it allows us to perform portable subaperture measurements of large mirrors, thereby achieving mid-to-high spatial frequency measurements. Additionally, the system can be used on a bench to measure a variety of surfaces, from large to small radii. To measure a small radius of curvature mirror the auxiliary lens can be shifted longitudinally.

A second advantage is that the system is easily calibrated with a reference optic since the auxiliary lens is usually small in diameter. This calibration allows us to determine the (x_{Ref}, y_{Ref}) and (x_{UUT}, y_{UUT}) ray intercepts, and with the distance from the mirror to the screen $(Z_{m2screen})$, subsequently compute the slope departures (w_x, w_y) of the UUT (Unit Under Test) as shown in Eq. (1). In our experiments we calibrated with a reference flat.

$$w_x(x_m, y_m) \cong \frac{x_{\mathrm{Ref}} - x_{UUT}}{z_{m2screen}}, w_y(x_m, y_m) \cong \frac{y_{\mathrm{Ref}} - y_{UUT}}{z_{m2screen}} \qquad (1)$$

In Eq. (1), x_m and y_m are the coordinates of sample points on the UUT.

Another advantage of SPOTS is that it has a flat top instrument transfer function (ITF) for mid-spatial frequencies as shown in Figure 4. This ITF curve means that SPOTS is very sensitive to mid-spatial frequencies. Additionally, high spatial frequency measurements depend on the size of the camera aperture and resulting spatial resolution limit at the mirror [6]. Typically, we consider anything below 70% modulation of the camera MTF as noise in the system ITF.

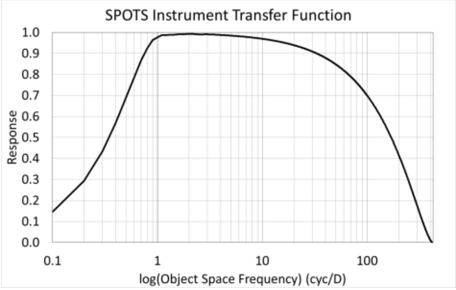

Figure 4: ITF curve of a typical SPOTS device. D is the diameter of the auxiliary lens. Notice it has a flat top for mid-spatial frequencies. ITF tells us how the system responds to spatial frequencies, meaning that some frequencies are inherently filtered by the test.

3. SPOTS performance demonstration against interferometers

Using an experimental SPOTS system we measured a flat (using the reference subtraction method with a λ/10 reference flat), over a 1” diameter that was polished with a stripped tool using a linear motion such that it created 3 groves across the part. To test the accuracy of the SPOTS measurement we also measured the part on a Fizeau interferometer. The direct comparison between SPOTS and interferometric measurement showing good agreement is shown in Fig. 5.

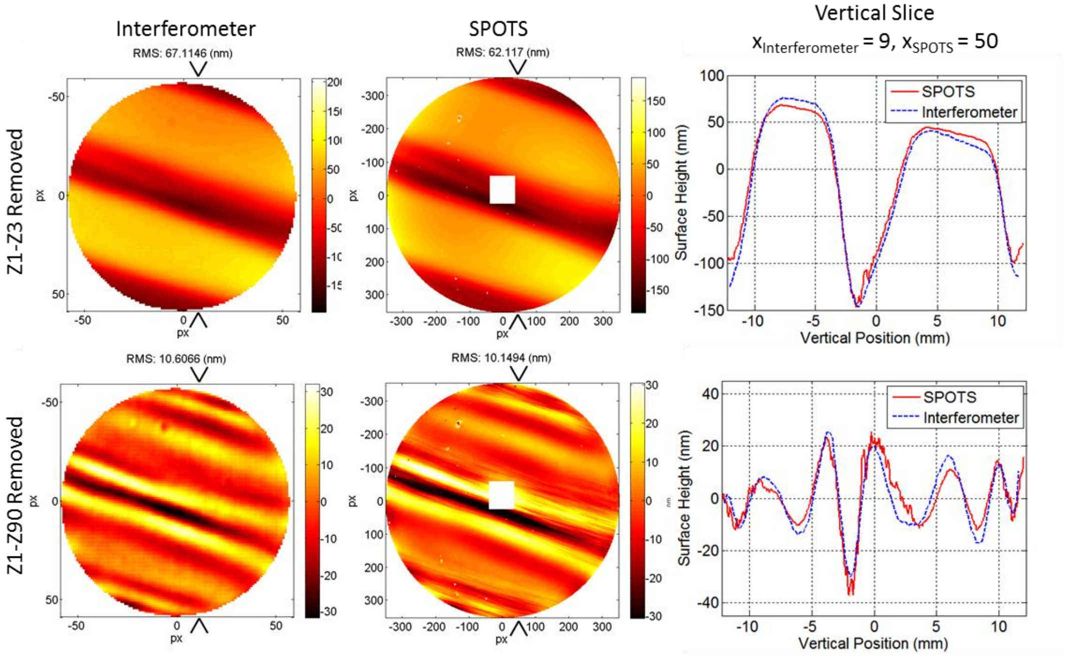

Figure 5: Noll Zernike terms removed shown on far left. Left column: Interferometric measurement. Center column: SPOTS measurement with flat reference subtraction method. Right Column: 1D vertical slice at arrow locations, comparison between SPOTS and interferometer. Note that SPOTS measures higher spatial frequency scratch marks on the mirror because it has a higher spatial resolution than the interferometer as indicated by the spikey nature of the line profile. Confirmation of the linear marks was performed with a rotation test. The rectangular region masked in the SPOTS data is due to the ghost reflections from the auxiliary lens faces.

As shown in Figure 5 the SPOTS measurement has a comparable RMS surface for residual surface features. In the surface maps shown, the surface residuals with up to Z90 removed are all within 1 nm RMS, which shows high accuracy for SPOTS in comparison to interferometry. The SPOTS measurement shows the fine detail of the tool markings because it samples the part’s diameter with over 700 pixels, which is much higher than the 120 pixels of the interferometer.

4. References

[1] D. Malacara, *Optical Shop Testing*, 3rd ed. (2007).

[2] D. W. Kim, W. H. Park, H. K. An, and J. H. Burge, “Parametric smoothing model for visco-elastic polishing tools.,” *Opt. Express* **18**(21), 22515–22526 (2010).

[3] R. E. Parks, “Micro-Finish Topographer: surface finish metrology for large and small optics,” in *SPIE* **8126**, J. H. Burge, O. W. Fähnle, and R. Williamson, Eds., p. 81260D–81260D–7 (2011) [doi:10.1117/12.892283].

[4] G. Häusler, C. Richter, K. Leitz, and M. C. Knauer, “Microdeflectometry — a novel tool to acquire three-dimensional microtopography with nanometer height resolution,” *Opt. Lett.* **33**(4), 396–398 (2008).

[5] P. Su, R. E. Parks, L. Wang, R. P. Angel, and J. H. Burge, “Software configurable optical test system: a computerized reverse Hartmann test.,” *Appl. Opt.* **49**(23), 4404–4412 (2010).

[6] T. Su, A. Maldonado, P. Su, P. Zhou, and J. H. Burge, “Study of the instrument transfer function of a free-form optics metrology system: SCOTS,” *Proc. SPIE* **9046**, H.-Y. Tam, K. Xu, H. Xiao, J. Zhu, and C.-L. Zhao, Eds., 904602 (2013) [doi:10.1117/12.2037040].

[7] A. Maldonado, P. Su, D. W. Kim, J. Burge, “Development of an Optical System to Enhance Resolution, Accuracy, and Flexibility of Deflectometry Surface Measurements,” *Opt. Express*, **TBD**