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Improvements in the Scanning Long-wave Optical Test System

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ABSTRACT

The Scanning Long-wave Optical Test System (SLOTS) is a slope measuring deflectometry system that provides accurate measurements on ground surfaces. As it uses a thermal source, we can measure an optic during the grinding phase which allows us to correct figure errors when material removal is much faster. We have made improvements in SLOTS, such as the step-and-stare method, the ceramic rod, and the Gaussian fitting processing software, so that this system supports higher accuracy and resolution. As a result, SLOTS is an optical testing system that covers a huge portion of the fabrication process from the grinding to the figuring. It is a complementary solution for other metrology systems such as the laser tracker, SCOTS, and null interferometry. SLOTS can reduce the manufacturing time by producing ground aspheres that have low errors of the surface figure when polishing begins.

Keywords: SLOTS, optical testing, deflectometry, slope measurement, ground surface, aspheric mirror

1. INTRODUCTION

The Scanning Longwave Optical Test System (SLOTS) is an infrared deflectometry system that reduces manufacturing time while offering high accuracy surface slope measurements of large optics. SLOTS was developed by College of Optical Sciences, the University of Arizona, for measuring ground optical surfaces [2]. Previously, SLOTS technology was demonstrated when testing the 4.2 m off-axis aspheric primary mirror of Daniel K. Inouye Solar Telescope (DKIST) while it was in the grinding stage [3]. This proved that SLOTS functions as a guide to fabricate the mirror down to approximately 1 μm RMS surface roughness with 12-25 μm grit loose abrasives.

Metrology typically used for coarse grinding is a laser tracker surface scan. However, the laser tracker measurement takes a long time and has poor sampling across the surface, limiting our ability to shape the optical surface during the grinding stage. Because we need to wait until the surface is smooth enough for interferometry or visible deflectometry, we must do most of the optical surface figuring during the polishing stage. Unfortunately, polishing is very slow to remove glass. Therefore, polishing is the longest process during mirror fabrication. We need a more powerful instrument that can replace the laser tracker and reduce the polishing portion.

Although the Software Configurable Optical Test System (SCOTS) is a powerful deflectometry system [4], it is not proper for this purpose because visible light is not specular for ground surfaces. Based on SCOTS, the SLOTS system was developed, changing the LCD screen to a scanning thermal source. Since a longer wavelength, LWIR (7-14 μm) is specular for rough surfaces, it is an effective testing system for controlling the figure during the grinding stage. As a result, the effort needed to polish out the error of the surface figure is minimized.

In this paper, we present improvements in SLOTS that advance its abilities. The biggest advantage of SLOTS now is that it works successfully from 40 μm grit loose abrasives grinding to figuring. For the DKIST mirror, SLOTS was only used for short period of time from the mid-grinding to early polishing stages. Here we show that SLOTS can shorten the manufacturing time significantly and be complementary to other metrology systems such as the visible deflectometry and interferometry. Details of the improvements are explained in the third section, and experimental results obtained from a 6.5 m aspheric primary mirror are provided in the fourth section.

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2. SCANNING LONG-WAVE OPTICAL TEST SYSTEM

2.1 Deflectometry

Deflectometry is an optical testing system that gives surface slope information by tracking an optical beam deflected by an optical surface. To use this, reflection deflectometry needs accurate geometric information of three components, the light source, the illuminated point on the unit under test and the pupil of the lens that define the angle. As shown in Figure 1, an optical beam emitted from the source reflects off the test mirror and is captured by the detector. Depending on the test surface shape, the detector pixels illuminated by the beam change while the aperture limits the rays entering the camera. If we obtain the positions of the three components accurately, we can calculate the slope of the illuminated surface by geometry, and finally compute the shape of the test surface by numerical integration.

Figure 1. Concept of SLOTS showing geometry of the thermal ribbon source, test mirror and camera. As the source scans, the regions of the unit under test that send light to the camera pupil (solid red arrow lines) change while the rest regions look dark at the detector (dotted red arrow lines).

2.2 Principle of SLOTS

The configuration of SLOTS is divided into four elements: the IR camera, the linear stage, the rotary stage and the thermal source.

The IR camera observes light with wavelength ranging roughly 7-14 μm . There are two things to be concerned about the camera. First, to calibrate the camera, we use a coordinate-measuring machine to measure the pupil center position and four retroreflectors around the pupil. When we make the test mirror measurements, we use the laser tracker to measure the positions of the four retroreflectors and derive the pupil center relatively. Next, camera distortion influences the irradiance profile of the detector pixels. Therefore, we distribute fiducials on the test mirror, measure their positions with the laser tracker, and collect a fiducial image. Using this information, the data processing code can make a distortion correction.

There are two stages: a linear stage and a rotary stage. The linear stage holds the thermal source. By design, the source scans over the test mirror. As we need to calculate the source position accurately, it is necessary to measure the pitch size accurately. We used the laser tracker for this. The second stage, a rotary stage, makes it possible to perform two orthogonal scans. Since SLOTS is a surface slope testing system, we need gradient values of X and Y directions for the numerical integration step.

Lastly, a linear thermal infrared source is connected to the linear stage. Positions of the source and retroreflectors residing next to the source are calibrated with a coordinate measuring machine. Then, while we make measurements, we get the positions of retroreflectors using the laser tracker to derive the relative source position.

By following the principle of the reflection deflectometry, we collect image data with the data collection software we developed. While the source scans across the test mirror, it illuminates some portion of the mirror and certain camera pixels receive a signal. For each pixel, an irradiance profile is recorded as a function of image frame number, and its peak can be found. From this peak position, we can calculate the source position. The camera pupil center, the source position, and the illuminated pixel position on the mirror are required to derive the surface slope at that mirror point.

3. IMPROVEMENTS IN SLOTS

As explained in the section 2, it is necessary to record geometric information about the source position, the illuminated mirror pixels, and the camera aperture as accurately as possible. The efforts to enhance the SLOTS performance are deeply related to this demand. Therefore, we focused on improving the quality of SLOTS components as well as the way of collecting and processing data. As a result, the biggest changes were made on the thermal source, the data collection software, and the processing software.

3.1 Thermal scanning source

The original SLOTS design used a metal wire as a thermal source [1]. The tungsten wire was wrapped in a Nextel ceramic sleeve and was heated up to 300 degrees Celsius with total power of 44 W direct current (5.5 A; 8 V). The weakness of the wire and sleeve is the possibility of bending. The sleeve was not rigidly mounted which could cause the source to be curved. However, the data processing assumes that the source is straight enough to be approximated as a line. The discrepancy between this assumption and reality causes errors in surface slope estimation. According to reference [1], a sine wave shaped source having the peak-valley deviation 0.4 mm could result in a micron RMS errors across the surface. Therefore, we changed the tungsten wire to a ceramic rod having a nichrome wire at the center (Figure 2). The rod is straighter having an error of about 0.05 mm.

Figure 2. The ceramic rod, thermal IR source

Also, we increased the total power up to 192 W direct current (12 A; 16 V). This corresponds to higher source temperature resulting in higher signal power. Higher signal-to-noise ratio of the camera pixels helps to determine the position of the source precisely. As the total power increased, we can find more accurate position of the source while measuring coarser optical surfaces with SLOTS.

3.2 Step-and-stare

Another big change was made in the data collection software. In the original system, the source on the linear stage scanned the mirror with the average scan speed of 5 mm/sec. One of the problems was that, as the camera was run open loop, the number of frames captured during a scan was not constant. In this case, the uncertainty in finding the correct geometric information about the source increased and, as a result, there is less chance to get real surface figure of the target mirror.

Also, the uncertainty in the scan speed could be an explanation for the large standard deviations in power and astigmatism. The standard deviations of Z4 (defocus) and Z6 (astigmatism) in the repeatability test were a few microns while the average values were half a micron and 1.5 μm RMS over the 6.5 m diameter mirror. If the average scan speed is different by a factor of a from what we think, a surface error (ΔW) in the surface aspherical departure (W_a) can be calculated as aW_a . The error in astigmatism is expected if the scan speeds in the X and Y directions are different.

To solve these problems, we have used a new data collecting method called step-and-stare. Unlike scanning, the linear stage is programmed to take a step forward with a given step size and stop for a fixed settling time while the software orders

the camera to take a frame. The step-and-stare method decreases the uncertainty of the source position determination. As a result, the standard deviations of low Zernike terms range from only few hundredths to few tenths of a micron RMS.

To do this, the step size should be precise. We simulated the step size sensitivity in SLOTS by perturbing measured data from the 6.5 m diameter mirror and concluded that the step size error should be smaller than 5 μm to explain a figure error about 3 parts in a thousand, which is safe to ignore. Because this was easily achievable with our hardware, the step-and-stare has been accepted as the preferred method for SLOTS.

3.3 Data processing software improvements

Lastly, we present two noticeable improvements in the data processing software. First, we changed the code to fix a sub-pixel calculation offset between an ideal surface and a measured surface. In the software, we calculate the error of the surface figure by subtracting the measured surface by an ideal mirror surface, with a fiducial image used to register the two datasets. An error in the data registration presented itself as a fixed coma error in an aspheric. To observe the fixed coma, a surface map was determined by collecting and averaging 13 measurements where the mirror was rotated 30 degrees between each measurement. Errors that don't vary with mirror rotation are the fixed errors in the system, and we found a fixed coma error of a few microns RMS which correspond to a half of a pixel center offset. Fixing the software eliminated the center offset and reduced the fixed coma error down to a few tenths of a micron.

Figure 3. The irradiance profile of a single detector pixel as a function of source position.

Second, we changed from centroiding to Gaussian fitting for the irradiance profile of a detector pixel as shown in Figure 3. Using centroiding, the final source position, x_c , can be calculated by Equation 1 where the signal count value is N_i and the source position is x_i [5].

$$x_c = \frac{\sum_i N_i x_i}{\sum_i N_i} \quad (1)$$

A disadvantage of the centroiding is that it cannot eliminate the effects of ghosts. There is always the possibility that the ghosts change the irradiance of the hump unevenly or cause other small humps in other scan positions. Also, another factor is the small number of points in the irradiance profile. If the number of points is not large enough, the effects of noise can be big so that a peak estimation becomes poor. These errors can cause a shift error in finding the source position. Through experimentation, we observed ghosts in the image and were able to eliminate some, but others such as reflections from the source hardware were difficult to remove structurally. The Gaussian fitting finds a best fit for the irradiance profile and, therefore the source position is determined more precisely.

4. EXPERIMENTS AND RESULTS

To verify the performance of SLOTS, we used a 6.5 m aspheric primary mirror to collect data. The manufacturing process was completed for this mirror and the surface figure is well-known as it was measured with null interferometry. By obtaining SLOTS measurements corresponding to interferometry-measured surface features, we show the ability to accurately measure low-order terms of the surface figure with a long-wavelength tool. In this section, we provide setup properties for the data collection and results demonstrating the advantages of SLOTS.

Figure 4. The 6.5 m aspheric primary mirror

4.1 Experimental setup

Experimental parameters and their values are listed on Table 1. These values are optimized considering both measuring time and uncertainties in the surface figure. For example, if we decrease the step size, we may have more data points in the irradiance profile, but it increases the measuring time.

Table 1. Information on the experimental setup properties for SLOTS.

Parameters	Values
Step Size	1.6 mm
Number of Camera Frames Averaged	1
Settling Time	0.25 sec
Current for the final averaged map	12 A
Table clocking angle step	30 degrees

4.2 6.5 m primary mirror surface map

With a current of 12 A and one frame averaged for the camera, thirteen clocking angle datasets rotated 30 degrees for each measurement were averaged to reduce systematic errors not in the mirror. This averaged map is defined as a final surface map representing how the mirror looks (Figure 5, Left) after subtracting the surface generated by the mirror prescription. The power is dominant in this map (Z_4 , $\sim 3.04 \mu\text{m}$). However, much of this comes from mirror bending resulting from room temperature gradients. The glass in this mirror is borosilicate, which has a low but not near-zero thermal expansion. To eliminate the thermal bending effect from the mirror, this final map is subtracted by a thermal deformation model which was derived from temperature sensors recorded simultaneously with the data. This is also shown in Figure 5 (Right).

Figure 5. The 12 A final averaged surface map of the 6.5 m diameter aspheric mirror having an RMS figure of $3.09\ \mu\text{m}$ (Left) and the final map after thermal deformation correction having an RMS figure of $1.01\ \mu\text{m}$ (Right).

Before comparing the SLOTS final surface map with the interferometry result, we had to make coma corrections in the interferometry surface map. This is because coma appears as an alignment error between the null corrector and test mirror, and the interferometer was therefore aligned to minimize coma in its measurement. The mirror's axis centration was measured using a different technique and agreed well with the coma measured using SCOTS, so we used the SCOTS values for coma.

Figure 6 (Left) is a difference map that shows the agreement between the SLOTS result (with thermal compensation) and the interferometry result. Table 2 shows the fitted low order Zernike terms of the difference map. According to this data, the RMS difference is only $0.73\ \mu\text{m}$ which is mostly coming from power. The differences in the other terms are mostly few hundredths of a micron to a fifth of a micron. The total difference for the terms higher than power is $0.33\ \mu\text{m}$ which is very low in terms of IR measurements made with 7-14 μm wavelength light.

Table 2. The RMS and the fitted low order Zernike terms of the difference map. Z7 and Z8 values are marked as * because their values were measured from SCOTS and not directly from the interferometry. Zernikes are the ZEMAX Standard (Noll) set.

Differences	Units (μm)
Peak-to-Valley	3.40
Residual	0.04
RMS	0.73
Z4 (Power)	0.67
Z5 (Astigmatism)	0.07
Z6 (Astigmatism)	-0.20
Z7 (Coma)	0.21*
Z8 (Coma)	0.07*
Z9 (Trefoil)	-0.05
Z10 (Trefoil)	0.05
Z11 (Spherical)	-0.05
Z22 (Spherical)	-0.09

Figure 6. The difference between the 12 A final averaged surface maps of SLOTS (including thermal bending correction) and null interferometry (including coma correction) having the RMS difference of $0.73 \mu\text{m}$ (Left) and the residual of the difference map with 37 Zernike terms removed having an $0.04 \mu\text{m}$ RMS difference (Right).

Also, we checked the residual after removing the first thirty-seven lowest Zernike terms (Figure 6, Right). In this map, we see spots circling in the middle. They are artifacts which may be defects on the camera lens. The pattern is because we rotated back the thirteen clocking angle measurements before we averaged. However, despite this pattern, we still see the residual is $0.04 \mu\text{m}$ RMS difference. This demonstrates that the mid spatial frequency surface errors of the test mirror from SLOTS are consistent with interferometry.

4.3 Repeatability

Repeatability of the SLOTS measurements was checked by collecting fifteen repeated datasets at a fixed table angle. This shows uncertainties in the surface. All fifteen datasets were collected in one day to minimize the effects from the mirror bending. Table 3 shows uncertainties in the low order Zernike terms of the surface figure. The uncertainties are mostly close to a tenth of a micron except Z4.

Table 3. The standard deviations of the low order Zernike terms of the surface figure.

Terms	Standard Deviation (μm)
RMS	0.28
Z4 (Power)	0.30
Z5 (Astigmatism)	0.07
Z6 (Astigmatism)	0.16
Z7 (Coma)	0.06
Z8 (Coma)	0.11
Z9 (Trefoil)	0.06
Z10 (Trefoil)	0.11
Z11 (Spherical)	0.07
Z22 (Spherical)	0.05

According to this analysis, we can estimate the level of uncertainties in the surface figure for the final averaged surface map from section 4.2. Under the assumption that the measurements are uncorrelated, we can divide the uncertainties at the fixed angle by root of number of clocking angles to determine the standard deviations of the final averaged surface map. In this case, the randomness is within tenths of a micron.

4.4 40 μm grit surface test

SLOTS was originally designed to test ground surfaces finished with 25 μm grit. In this section, we would like to show the availability of SLOTS with 40 μm grit loose abrasive grinding. Unfortunately, we did not have a coarse ground surface when we completed making improvements in SLOTS. To simulate a coarse surface, we set the current in the thermal source to be 2 A. As the signal power decreased, the signals received by the detector also decrease and the mirror may look less specular. Figure 7 shows the comparison between images for the 2 A source illuminating the finished mirror and the 12 A source illuminating the coarse ground mirror (from an earlier test of this mirror before all of the current improvement were implemented). The signal count range is around 40 counts for both cases. As we can assume that the noise in the camera doesn't vary significantly, it is likely that the SNR is comparable for both cases.

Figure 7. The image captured by the camera with 1 frame averaged for the 2 A source illuminating the finished mirror (Left) and the image captured by the camera with 1 frame averaged for the 12 A source illuminating the coarse ground mirror (Right). The latter shows some of the stray light that was ultimately removed from the system.

For further analysis, we used 32 frames for the camera frame averaging to increase the SNR. As we did for the 12 A measurements, thirteen measurements were collected, rotated every 30 degrees from 0 to 360 degrees. We used the twelve datasets to obtain the 2 A final averaged surface map. Then, the difference map between the 2 A final map and the interferometry map is derived to check the SLOTS performance at 2 A (Figure 8). The fitted low order Zernike terms of the difference map is presented on Table 4. The standard deviations of the fitted low order Zernike terms in the 2 A surface map were derived by collecting fifteen repeated datasets at a fixed angle (Table 5).

Figure 8. The difference between the 2 A final averaged surface maps of SLOTS (including thermal bending correction) and null interferometry (including coma corrections) having an RMS difference of $0.77 \mu\text{m}$ (Left) and the residual of the difference map having the residual of $0.20 \mu\text{m}$ RMS difference (Right).

Table 4. The RMS and the fitted low order Zernike terms of the difference map including their estimated uncertainties. Z7 and Z8 values are marked as * because their real values were measured from SCOTS not the interferometry.

Differences	Units (μm)
Peak-to-Valley	4.12
Residual	0.20
RMS	0.77
Z4 (Power)	0.32
Z5 (Astigmatism)	0.27
Z6 (Astigmatism)	-0.08
Z7 (Coma)	-0.18*
Z8 (Coma)	0.46*
Z9 (Trefoil)	0.02
Z10 (Trefoil)	0.12
Z11 (Spherical)	0.04
Z22 (Spherical)	-0.10

Table 5. The standard deviations of the low order Zernike terms of the surface figure measured with 2 Å.

Terms	Standard Deviation (μm)
RMS	1.00
Z4 (Power)	1.90
Z5 (Astigmatism)	0.50
Z6 (Astigmatism)	1.66
Z7 (Coma)	0.54
Z8 (Coma)	0.67
Z9 (Trefoil)	0.84
Z10 (Trefoil)	0.82
Z11 (Spherical)	0.38
Z22 (Spherical)	0.27

This result shows that we can still measure the figure at 2 Å with the uncertainties being less than few tenths of a micron after dividing by root 12 to get the uncertainty in the final averaged map. Also, as the peak-to-valley value is around 4 μm, it is reasonable to think that SLOTS will work for 40 μm grit. As the mirror surface gets smoother, the accuracy should improve to the level we showed in the previous sections. This shows that SLOTS can be used for figuring with 40 μm grit all the way to capturing fringes with interferometry.

Lastly, we applied the new processing code with the Gaussian fitting on one of the datasets obtained at the 40 μm grit grinding stage. In this case, the data was collected with the scanning process. Figure 9 shows the surface map of which the RMS figure is 31 μm. While this number is much larger than what we report above, this data was collected early in the fabrication process, so the figure errors in the mirror were much larger. While we don't have laser tracker measurements of the mirror at this point in the processing, the measured surface is reasonable. This result shows that the new processing code can be applied to coarser ground surfaces giving us reasonable surface maps without significant defects. We believe that increasing the number of camera frames averaged will increase the SNR. Also, if we use the step-and-stare in future, we should be able to get more accurate surface maps at the beginning of the 40 μm grinding stage.

Figure 9. The surface map of the 40 μm grit grinding stage obtained by using the new processing software with Gaussian fitting having the RMS figure around 31 μm.

5. CONCLUSIONS

Based on the data collected by SLOTS on a 6.5 m diameter aspheric mirror, we verified that improvements in SLOTS enhanced its performance. The improvements are related to finding the geometric information of SLOTS elements more precisely and accurately as well as improvements to the source. As a result, SLOTS is a solution that can cover metrology needs from the early grinding stage to final figuring. Although designed only for ground surfaces, it now works as a complementary testing system for the laser tracker, SCOTS and null interferometry. The greatest advantage of this is that SLOTS can shorten the manufacturing time. Laser tracker measurements can be replaced with SLOTS earlier in the processing. Also, SLOTS can help control the figure during the grinding stage, meaning less time required for figuring during polishing. For the next step, SLOTS will be applied to the Giant Magellan Telescope project for testing its 8.4 m off-axis aspheric primary mirrors. We are hoping to present the results in the near future.

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