Manufacturing of super-polished large aspheric/freeform optics

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ABSTRACT

Several next generation astronomical telescopes or large optical systems utilize aspheric/freeform optics for creating a segmented optical system. Multiple mirrors can be combined to form a larger optical surface or used as a single surface to avoid obscurations. In this paper, we demonstrate a specific case of the Daniel K. Inouye Solar Telescope (DKIST). This optic is a 4.2 m in diameter off-axis primary mirror using ZERODUR thin substrate, and has been successfully completed in the Optical Engineering and Fabrication Facility (OEFF) at the University of Arizona, in 2016. As the telescope looks at the brightest object in the sky, our own Sun, the primary mirror surface quality meets extreme specifications covering a wide range of spatial frequency errors. In manufacturing the DKIST mirror, metrology systems have been studied, developed and applied to measure low-to-mid-to-high spatial frequency surface shape information in the 4.2 m super-polished optical surface. In this paper, measurements from these systems are converted to Power Spectral Density (PSD) plots and combined in the spatial frequency domain. Results cover 5 orders of magnitude in spatial frequencies and meet or exceed specifications for this large aspheric mirror. Precision manufacturing of the super-polished DKIST mirror enables a new level of solar science.

Keywords: Large optics, Astronomical mirror, Optical fabrication, Super-polished mirror, Optical metrology, Freeform optics

1. INTRODUCTION

1.1 Optical Engineering and Fabrication Facility overview

The Optical Engineering and Fabrication Facility (OEFF) at the College of Optical Sciences, University of Arizona (Figure 1) is a fully functional optical fabrication and testing facility with demonstrated capability for manufacturing 4.2 m diameter optics. Currently being upgraded to process 6.5 m diameter optics, facilities include state-of-the-art computer controlled grinding and polishing machines along with a 40 m vertical optical test tower in a temperature stabilized environment. Successfully completed projects include a technology demonstrator for the James Webb Space Telescope (JWST) and a convex mold to be used for the technology demonstrator in the Far Infrared Space Telescope (FIRST) program. Among other projects, the OEFF group includes experienced designers and fabricators of large optical telescopes and telescope subsystems, space-based detectors, as well as airborne optical instruments for government and industry.

Figure 1. Optical Engineering and Fabrication Facility at the College of Optical Sciences, University of Arizona with specialized facilities and integrated testing tower for large optics fabrication, engineering and testing.

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1.2 4.2m primary mirror for the Daniel K. Inouye Solar Telescope

The 4.2 m Daniel K. Inouye Solar Telescope (DKIST) is the National Solar Observatory's next-generation solar telescope, which contains a thin, off-axis primary mirror shown in Figure 2 (left). The large primary mirror provides diffraction-limited imaging resolution and superb light collecting ability to achieve ~20 km spatial resolution on the Sun's surface for studying very fine magnetic structures.[1] The off-axis optical design enables non-obscured secondary mirror location to minimize stray light. Thermal control against solar radiation is critical for maintaining the shape of the primary mirror, and so the substrate is manufactured with extremely low expansion glass-ceramic ZERODUR.

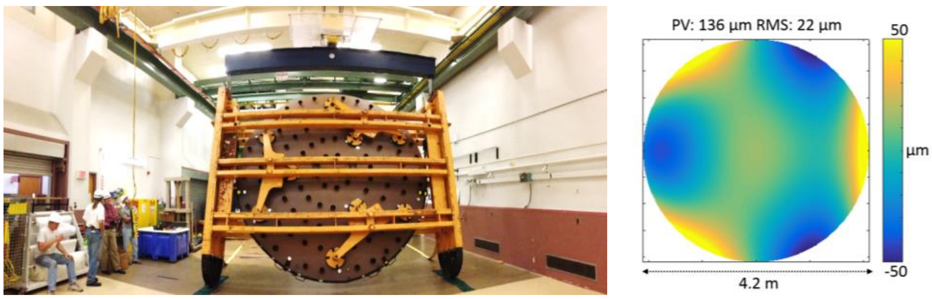

Figure 2. (left) 4.2 m DKIST off-axis primary mirror substrate being turned over at the College of Optical Sciences, University of Arizona. (right) High order freeform departure of the nominal primary mirror shape after subtracting the first 8 standard Zernike terms.

The DKIST off-axis primary mirror optical prescription is presented in Table 1. The aspheric departure from the best-fit sphere is ~9 mm peak-to-valley. Figure 2 (right) illustrates local shape variations after subtracting the first 8 standard Zernike terms (Piston, Tip, Tilt, Power, Astigmatism and Coma).[2]

Table 1. DKIST 4.2m off-axis primary mirror optical design prescription[2]

Optical parameter	**Value**	**Note**
Radius of curvature	16 m	
Conic constant	-1	Parabola
Off-axis distance	4 m	Distance from the parent vertex
Mirror diameter	4.2 m	
Aspheric departure	~9 mm	Peak-to-valley departure

2. WIDE SPECTRUM METROLOGY SYSTEMS

2.1 Principal interferometry system

A null interferometry system using an instantaneous phase shifting interferometer and a custom, 220mm diameter Computer Generated Hologram (CGH) served as principal optical testing system for the DKIST primary mirror. As shown in the schematic optical layout in Figure 3, the interferometric test utilizes a 1.8 m large fold sphere to compensate for most of the astigmatism present when testing an off-axis parabola at its center of curvature. Residual wavefront error is corrected by a CGH to achieve a null condition for an ideal system. In practice, the large fold sphere is also interferometrically measured at its center of curvature to compensate for its shape errors.

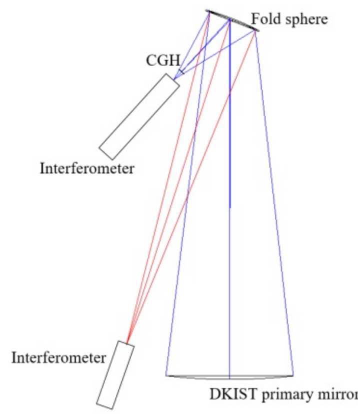

Figure 3. Schematic optical layout of the principal interferometric test system using a 1.8 m fold sphere and a 220 mm diameter CGH. A wavefront (blue rays) matching DKIST ideal primary mirror surface shape is produced from combination of the tilted fold sphere and the CGH. To compensate for fold sphere shape errors, the fold sphere is also interferometrically measured (red rays) during a measurement.

As the main component of the metrology system, an instantaneous phase shifting interferometer (PhaseCam 6000 from 4D Technology) was selected to overcome the turbulence in the 16m optical path length in the testing tower. Interferometer specifications are listed in Table 2. The high-speed optical phase sensor makes wavefront measurements in as little as 30 µs, which is more than 5000 times faster than a typical temporal phase shifting interferometer. Any residual atmospheric turbulence effects are washed out by averaging multiple (e.g. 100 or more) measurements.

Table 2. PhaseCam 6000 interferometer specification for the DKIST principal interferometry system

Parameter	**Value**	**Note**
Wavelength	632.8 nm	Stabilized
Image resolution	1000 by 1000 pixels	
Beam size	9.0 mm	Diameter
Diverging lens f/#	1.5	Effective focal length: 14 mm
Minimum exposure time	30 µs	

2.2 Infrared deflectometry system

Prior to the interferometric test, the optical surface must undergo fine grinding to convert the machine-ground surface into a specular surface ready for final polishing. Efficient processing dictates that large surface errors should also be corrected in this stage. In order to achieve this, an infrared deflectometry system was developed.

The Scanning Long-wave Optical Test System (SLOTS)[3] employs a ~300°C hot wire emitting ~7 - 14 µm thermal long-wave infrared (LWIR) light, as shown in Figure 4.

Figure 4. (left) Schematic diagram of the SLOTS deflectometry concept. Solid red lines represent infrared rays propagating toward the detector of the long-wave infrared camera. (middle) SLOTS hardware. (right) Four infrared camera images captured during a SLOTS scanning process.[2]

The accurately measured DKIST mirror surface map (~400 by 400 pixel resolution) efficiently guided the computer controlled fabrication process during the fine grinding phase. In this phase, surface roughness was reduced to approximately 0.7 - 1.6 μm root mean square (RMS), and visible-light reflectivity of the freeform surface increased.

2.3 Software Configurable Optical Test System

Between infrared deflectometry and the interferometric test lies a regime where the optical surface error is too fine to be measured by the infrared deflectometry system, and not close (to the ideal shape) enough to be measured with the interferometer. To address this, a slope measuring technique called Software Configurable Optical Test System (SCOTS)[4], was developed and applied to the DKIST mirror.

SCOTS advantage is high accuracy and dynamic range. The system employs a computer monitor to create a modulated fringe pattern which is reflected off of the specular surface under test and captured with a video camera as shown in Figure 5.

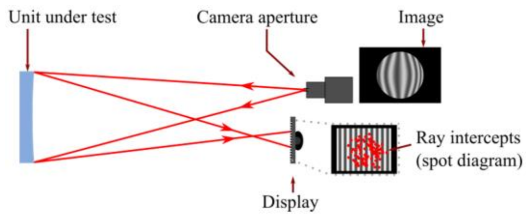

Figure 5. Schematic diagram of the SCOTS deflectometry concept. Solid red lines represent the ray paths for the display. The display and camera are located at the center of curvature of the test optic.

This technique works for any specular surface and has been used for diverse high precision applications, including astronomical telescope mirrors. With careful calibration, we measure slope variations to a precision of 100 nrad, enabling surface measurement accuracy of 1 nm.[5] In addition to guiding the polishing process, SCOTS serves as independent verification of the final surface accuracy.

2.4 Slope-measuring Portable Optical Test System

Bridging spatial frequencies between full aperture measurements (e.g. interferometry or SCOTS) and surface roughness measurements (e.g. microscope interferometer) is a tool known as Slope-measuring Portable Optical Test System (SPOTS)[6] shown in Figure 6. This portable deflectometry system uses a camera and small OLED display to measure surface shape over a 127 mm diameter circular area with 0.18 mm spatial resolution. SPOTS played an important role in acquiring mid-to-high spatial frequency surface error information for DKIST metrology.

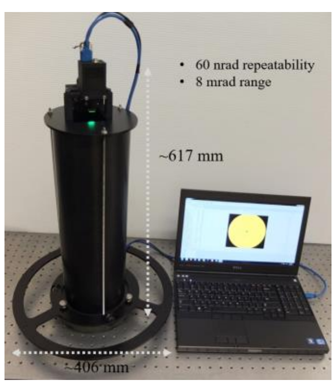

Figure 6. The SPOTS system, placed directly on the 4.2 m DKIST primary mirror surface, was used for the mid-to-high spatial frequency surface error measurements.

2.5 Micro Finish Topographer

The Micro Finish Topographer (MFT)[7] pictured in Figure 7, measured high-spatial frequency errors (i.e. surface roughness) of the DKIST primary mirror surface. The portable MFT form factor enables direct measurement on the large 4.2 m mirror surface. Three nylon support balls gently contact the surface to prevent surface damages, and because the MFT sits directly on the mirror surface, vibration isolation is not needed. A 2.5X Nikon interferometric microscope objective, provides 2.25 by 3 mm field of view (with 767 by 1023 pixels).

Figure 7. (left) The portable MFT system. (right) 2.5X Nikon interferometric microscope objective used for the high spatial frequency measurements for the DKIST primary mirror.

3. COMPUTER-CONTROLLED OPTICAL SURFACING

3.1 Computer-controlled optical surfacing machine

A gantry-type, computer-controlled optical surfacing machine (Figure 8) was employed to fabricate the 4.2 m DKIST primary mirror at the OEFF. The system has 7 axes of motion including mirror rotation to deterministically figure the aspheric/freeform optical surface using dwell time control technology.[2]

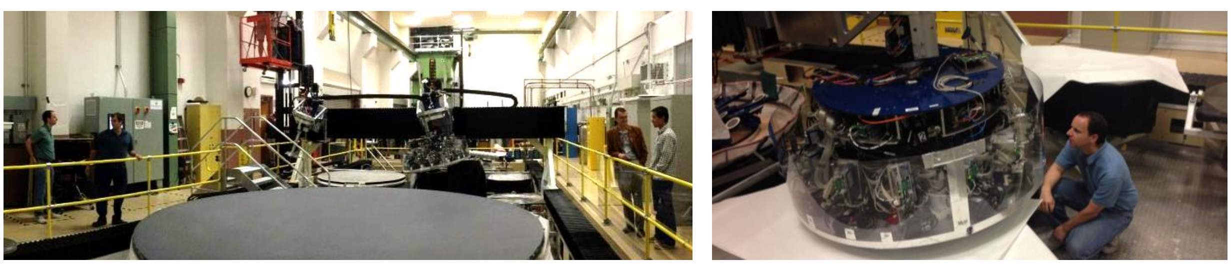

Figure 8. (left) DKIST 4.2m primary mirror substrate made of ZERODUR with computer-controlled optical surfacing machine in the background. (right) 60 cm stressed lap with active shape control.

Active shape control of the polishing lap is achieved via a stressed lap shown in Figure 8 (right). This tool has 12 real-time actuators to dynamically modify its 60 cm diameter surface for optimal polishing performance.[2] In practice, the stressed lap provides a stiff contact surface that automatically adjusts to match the local shape of the aspheric/freeform mirror. This smooths and removes mid-to-high spatial frequency errors that deviate from the desired surface shape.

3.2 Grinding, polishing and figuring process

The IR deflectometry system, SLOTS, provides an opportunity to execute aggressive computer-controlled optical surfacing that targets high fidelity and high resolution surface error maps during early optics grinding phases. Four consecutive SLOTS data sets illustrating DKIST surface error maps between three fine grinding runs are presented in Figure 9. The grinding process parameters are summarized in Table 3.

Table 3. DKIST primary mirror grinding parameters[2]

Parameter	**Value**	**Note**
Grinding tool pressure	0.3 psi	Stabilized
Tool size	~300 - 600 mm	Stressed lap / Passive lap
Orbital stroke speed	~30 rpm	
Orbital stroke radius	~75 – 150 mm	

RMS of the surface error quickly improved from 15 μm to 9 μm, then 6 μm and finally to 2 μm within only 97 hours of directed figuring run time.

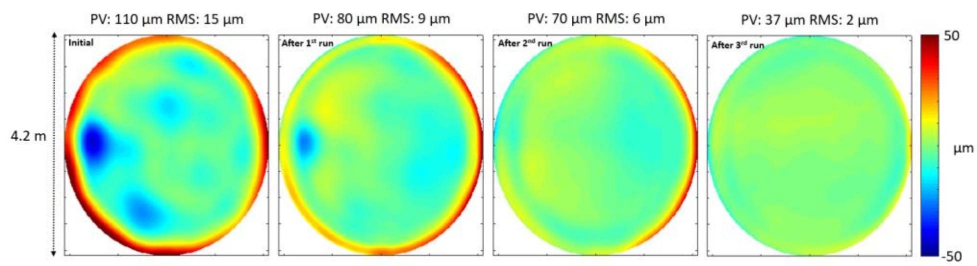

Figure 9. Four SLOTS surface maps demonstrating the rapid and deterministic evolution of the DKIST primary mirror surface shape errors. These measurements were obtained during three successive computer-controlled fine grinding runs (totaling a run time of 97 hours).

After fine grinding, the DKIST mirror was polished and figured using various sub-aperture pitch laps employing Cerium based polishing powder, Rhodite 906, and guided by the MATRIX[8] computer-controlled optical surfacing process optimization software. The high convergence of the surface figure error RMS value is well demonstrated in the three consecutive SCOTS surface maps in Figure 10.

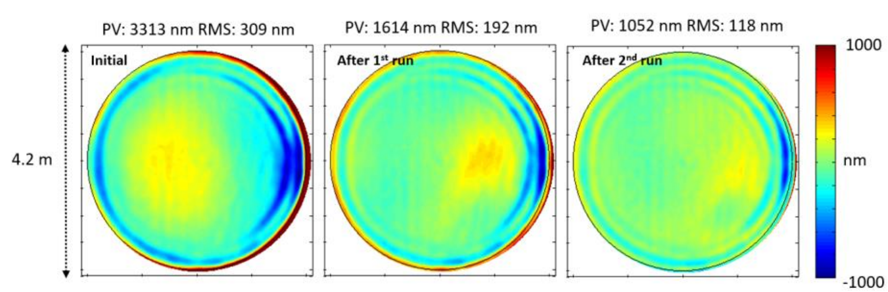

Figure 10. Three SCOTS surface maps showing the rapid evolution of the DKIST primary mirror surface shape errors during the two consecutive figuring runs.

These surface maps are shown after subtracting 30 bending modes within the given force limits. The residual surface RMS reduces from 309 nm to 192 nm, then further to 118 nm between the two directed figuring runs.

4. SUPER-POLISHED OFF-AXIS PARABOLIC MIRROR

4.1 Super-polished 4.2 m DKIST primary mirror

The 4.2 m DKIST primary mirror successfully transferred through fine grinding, polishing and figuring phases with a high convergence rate and the super-smooth surface shown in Figure 11.

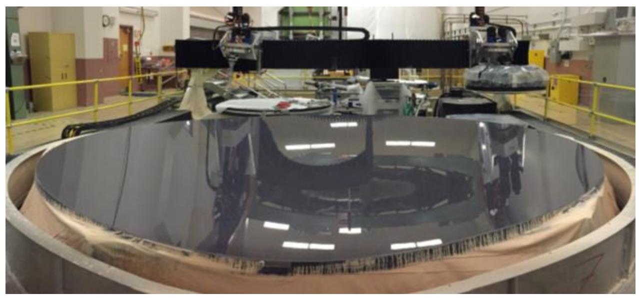

Figure 11. Super-smooth 4.2 m DKIST primary mirror optical surface showing reflections of the polishing machine and overhead lights.

The DKIST primary mirror fabrication completed successfully in January 2016. All metrology data collected from measurement sources show excellent surface quality which meets or exceeds specifications. Surface figure accuracy requirement is an RMS of 25 nm, after accounting for active correction (30 bending modes) of the primary mirror through its support. The RMS figure error from measurements is 19.4 nm.

The final figure estimate is calculated using an error budget that accounts for the measured support forces, random noise estimate, and measured alignment of the test subsystems during acceptance testing. One of the final maps by the principal interferometry system, over the required clear aperture with the allowable 30 bending modes subtracted, is presented in Figure 12 (left). The maximum force required for the bending was 11.2 N, well below the 20 N allowance.

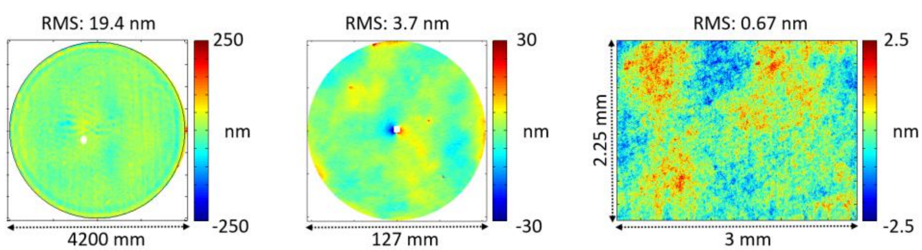

Figure 12. The completed DKIST primary mirror metrology data showing smooth surface quality over the entire range of the spatial frequencies. (left) Principal interferometry map, (middle) SPOTS map and (right) MFT map.

The surface figure accuracy requirement for mid-spatial frequencies (measured by the SPOTS) is < 8 nm RMS over a 100 mm diameter aperture. Various locations on the 4.2 m DKIST mirror surface were sampled and each of the final surface maps from SPOTS has an RMS value below the requisite 8 nm RMS. The average of the measured RMS values is 5.3 nm. One of the SPOTS maps is shown in Figure 12 (middle), which has surface RMS of 3.7 nm, over the 127 mm circular area.

As a surface roughness requirement, the optical surface must be polished to less than 20 Angstroms RMS surface roughness. More than 20 arbitrary locations were sampled and measured using the MFT in order to ensure the high spatial frequency surface roughness quality. A representative MFT local surface map displaying 6.7 Angstroms RMS surface roughness is shown in Figure 12 (right).

4.2 Power Spectral Density and Bidirectional Reflectance Distribution Function (BRDF) analysis

Surface figure and finish (i.e. roughness) are conventionally specified as RMS errors over a respective low and high spatial frequency bandwidth.[9] However, advanced precision optical systems such as the DKIST require a comprehensive surface quality specification over a wide range of spatial frequencies. PSD plots, using a single datum (among multiple data sets), from each DKIST metrology system are plotted together in Figure 13, to demonstrate the abundant coverage of the spatial frequency spectrum of measured surface data.

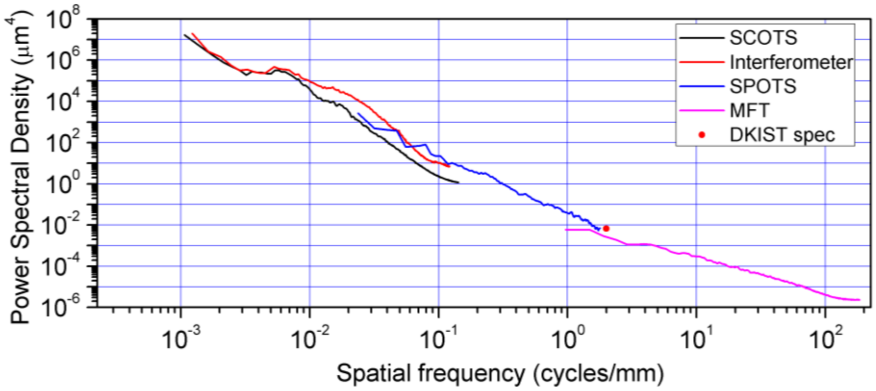

Figure 13. Combined PSD plots from all 4 DKIST measurement systems, along with the computed PSD specification for DKIST mirror.

Designed as the most powerful solar telescope, the DKIST primary mirror's surface specification included a Bidirectional Reflectance Distribution Function (BRDF) merit, which is converted to a Power Spectral Density (PSD) value, using the Rayleigh-Rice formula for super smooth surfaces.[10] The DKIST optical surface specification demands a BRDF of less than 1.0 sr^{-1} at 0.002 radians from the specular direction. The converted PSD value is 0.0067 μm^4 at a frequency of 2 cycles/mm (marked as the red dot in Figure 13).

Since spatial frequencies and angular directions are related to each other, and because the MFT measurements reliably cover a large range of spatial frequencies from 0.1 - 200 cycles/mm, the BRDF including angles very close to specular direction (i.e. 0.002 radians from the specular direction) can be predicted based on the PSD result from MFT measurements. The pink line representing PSD values from MFT data, is under the DKIST specification (red circle) at the 2 cycles/mm frequency, in Figure 13.

5. CONCLUDING REMARKS

Manufacturing large, super-polished optics with aspheric or other freeform surfaces is becoming increasingly important. Off-axis mirrors are sometimes employed as part of a segmented mirror construction or as a way to obtain obstruction-free imaging. Similarly, super-polishing is key to meeting diffraction-limited spatial resolution and improved light collection efficiency. In this paper, we demonstrate both super-polishing and off-axis manufacturing can be successfully combined in the polishing process.

The 4.2m, off-axis Daniel K. Inouye Solar Telescope has strict surface scatter specifications as well as significant free-form departure. Through several techniques developed and tested at the Optical Engineering and Fabrication Facility in the College of Optical Sciences at the University of Arizona, we demonstrate PSD results over 5 orders of magnitude in spatial frequency that meet or exceed requirements for the DKIST mirror. Infrared deflectometry (SLOTS) and visible-wavelength deflectometry (SCOTS) efficiently guided the computer-controlled processing from coarse machine-ground surface to super-smooth specular surface. Interferometry provided final verification of low-order surface figure. Covering the mid-spatial-frequency to high-spatial-frequency range were the subaperture deflectometry (SPOTS) and micro-finish topographer (MFT) measurements. These measurements prove the mirror meets BRDF specifications for scattered light. Combined together, the PSD plot demonstrates high-performance optical polishing of a large, super-polished, off-axis optic.

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