Optical Metrology Systems Spanning the Full Spatial Frequency Spectrum

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Abstract: We present a collection of unique, collaborative, optical metrology systems that are fully capable of measuring the extensive spectrum of low-to-mid-to-high spatial frequencies, corresponding to surface shape information.
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1. Introduction

Many future optical systems utilize aspheric/freeform optics, which have great advantages over conventional designs in terms of optical performance and form-factors. In order to measure, evaluate and analyze such systems, we present a distinctive set of metrological tools and techniques that are able to span the broad spectrum of low-to-mid-to-high spatial frequencies and produce reliable results. To demonstrate the competency of our metrological set, measurements and analysis from the 4.2 m Daniel K. Inouye Solar Telescope's (DKIST) primary mirror are presented.

2. Metrology systems

2.1 Interferometry system using Computer Generated Hologram (CGH)

An instantaneous phase shifting interferometer and a customized Computer Generated Hologram (CGH) in a null configuration are used as the primary test in most projects because of their high accuracy and precision. This test is able to measure low-to-mid spatial frequencies, but cannot measure the surface roughness or the high spatial frequencies required for a super-polished optical surface.

2.2 Visible deflectometry system

A precise freeform metrology system with a large dynamic range, named Software Configurable Optical Test System[1] (SCOTS), has been developed and applied to DKIST primary mirror testing. This system displays a modulated pattern on screen and the camera acquires an image of the pattern, which is distorted by the mirror slope, as shown in Figure 1.

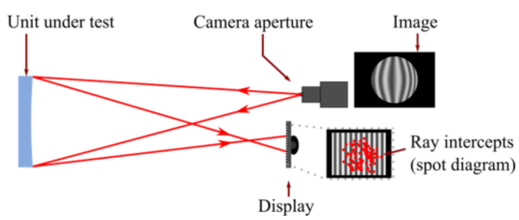

Figure 1. Schematic diagram of the SCOTS deflectometry concept[2].
The camera and monitor are placed near the center of curvature of the test optic.

In practice, SCOTS has been successfully used for various freeform optics and astronomical telescope mirrors because of its high accuracy3 and wide dynamic range.

2.3 Infrared deflectometry system

An accurate and rapid fine grinding process is essential to minimize mid-spatial frequency surface errors during the small tool polishing and figuring process. To guide this process accurately an infrared deflectometry system, the Scanning Long-wave Optical Test System (SLOTS)4, was developed. This system utilizes a ~300º C scanning hot wire with strong emission in the 7-14 µm band as the source, with rays reflecting off of the test surface being recorded by an IR (i.e. infrared) camera, to determine surface shape through a reverse ray trace process. The measured DKIST mirror surface map successfully guided the computer controlled fabrication process during the fine grinding phase, taking the surface roughness from ~50 µm root mean square (RMS) to ~1 µm RMS.

2.4 Auxiliary lens deflectometry system

An auxiliary lens deflectometry system, Slope-measuring Portable Optical Test System (SPOTS)[5], is a portable deflectometry system that bridges the gap between full aperture measurements (e.g. interferometry or SCOTS) and the surface roughness measurements (e.g. microscope interferometer). The measurement is over a 127 mm diameter circular area with ~0.18 mm spatial resolution.

2.5 Microscopic interferometer system

The Micro Finish Topographer (MFT)[6] is a precision phase measuring interferometer. It is a good solution for obtaining surface micro-roughness data, or the high-spatial frequency errors in the test surface. A 2.5× Nikon interferometric microscope objective, which provides a 2.25 by 3 mm field of view, was used for the DKIST mirror roughness measurements. These measurements are an indirect alternative to calculate the Bi-directional Reflectance Distribution Function (BRDF). This instrument's portability allowed direct measurements on the large mirror surface, eliminating the need for vibration isolation.

3. Measured data for 4.2 m super smooth optical surface

The 4.2 m DKIST primary mirror successfully met surface specifications in January 2016 after having gone through the fine grinding, polishing, and figure phase with a high convergence rate. All metrology data collected from various instruments showed excellent surface quality that met specifications.

The surface figure accuracy requirement is an RMS of 25 nm, after accounting for active correction (with 30 bending modes) of the primary mirror through its support. 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 2 (left). The maximum force required for the bending was 11.2 N, well below the 20 N allowance. The RMS figure error in the map is 19.4 nm.

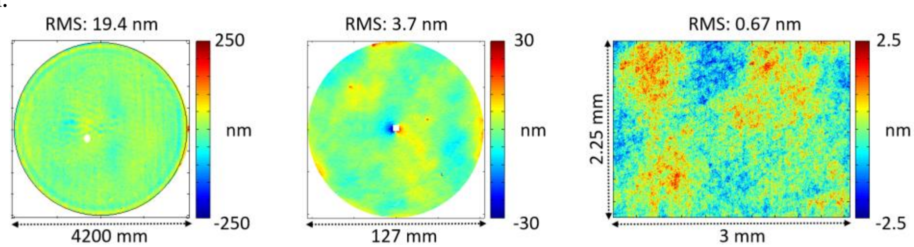

Figure 2. The completed DKIST primary mirror metrology data showing its extremely smooth surface quality over the entire range of the spatial frequencies[2]. Principal interferometry map (left), SPOTS map (middle) and MFT map (right).

For the 100 mm diameter aperture, the minimum requirement of mid-spatial frequencies is < 8 nm RMS with SPOTS measurement. We sampled various areas on the 4.2 m DKIST mirror surface and the final surface has an RMS below 8 nm. The RMS value in Figure 2 (middle) is 3.7 nm and the average RMS values (from multiple sampling locations) are 5.3 nm for 127 mm circular area. The MFT was used for measurement of surface roughness at high spatial frequencies. The MFT local surface roughness is less than 20 Angstroms RMS for 20 arbitrary locations. Figure 2 (right) represents one of the results, for 0.67 nm RMS.

4. References

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