Meter-Class Infrared Deflectometry for Visibly Non-Specular Surface Metrology

Joel Berkson[1], Zack Hatfield[2], Alex St. Peter[2], Henry Quach[1], Emily Rodriguez[1], Naomi Nguyen[2], Wyatt Ellis[2], Kevin Derby[1], Christian Davila-Peralta[2], Justin Hyatt[2], Dae Wook Kim[1,2,*]

[1]James C. Wyant College of Optical Sciences, University of Arizona, 1630 E. University Blvd., Tucson, AZ 85721
[2]Department of Astronomy and Steward Observatory, University of Arizona 933 N Cherry Ave., Tucson, AZ 85721
[*]dkim@optics.arizona.edu

Abstract: Large, slow freeform optics are challenging to measure, especially if their surfaces are non-specular in the visible; however, using deflectometry with a thermal source allows measurement of both rough and freeform surfaces to high precision. © 2021 J. Berkson et al.

1. Introduction

As freeform optics become more commonly become key components in optical designs for wavelength bands from UV to radio, the need for a flexible metrology technique grows in tandem. Such optics often go through a grinding phase during manufacturing, which renders many visible wavelength metrology instruments unsuitable for in-process measurement due to surface scattering. This gap often leaves large errors to be corrected for in the polishing phase, which removes material at a significantly lower rate. Since radio telescope and communication dish panels are designed to be visibly non-specular to avoid focusing solar radiation, the reflection of visible light cannot be used for metrology for those either. Other mechanical or contact measurement methods offer low spatial resolution and require movement of components which reduces repeatability and accuracy. Long-wave infrared (LWIR) interferometry can be used, but has limitations in dynamic range and often requires custom infrared (IR) nulling optics which are expensive and difficult to align. Deflectometry is a flexible metrology technique that allows for high precision surface measurement by reconstructing a high spatial resolution slope map. This information is collected by triangulating the reflection from the unit under test (UUT) between a source and a camera image. The IR deflectometry method has a high dynamic range, high spatial resolution, and is low cost.

2. Meter-Scale IR Deflectometry

The two essential hardware components required for a deflectometry system are a camera and a light source to match it. They are typically set up in a configuration with the UUT similar to the schematic shown in Figure 1.

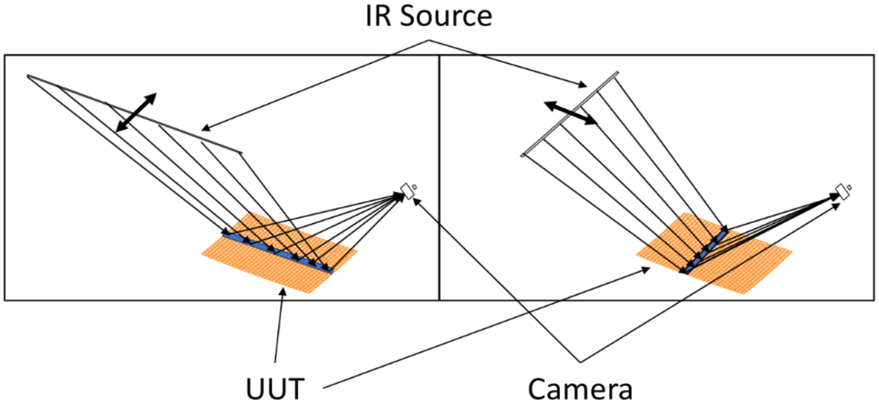
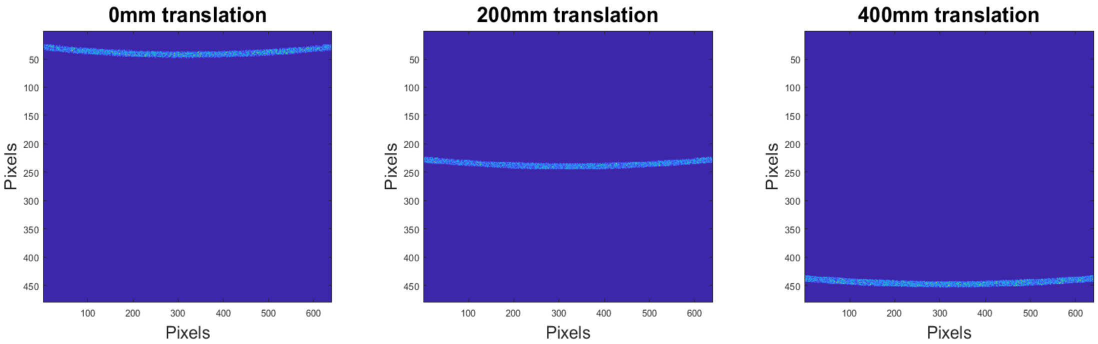


Fig. 1. IR Deflectometry general layout utilizing a meter-scale IR source enabling near-flat large freeform metrology.

The slope of each point on the UUT can be found by triangulating the camera position, source position, and mirror position, and leveraging the law of reflection to correlate them and calculate local slopes. Scanning the source in two orthogonal directions gives orthogonal slope information that is used to reconstruct the original surface sag using a slope integration method, like Southwell integration. This method has been used to measure the Daniel K. Inouye Solar Telescope (DKIST) 4.2m diameter primary mirror [1]. For the DKIST setup, the source and the thermal camera were placed near the center of curvature of the UUT, allowing for a smaller source size and smaller required scanning distance to cover the whole UUT. However, access to the focal point for metrology may not be an option for nearly flat (or long radius of curvature) large freeform optics due to limited space, and for concave optics the focal point is virtual. In this scenario, the source needs to be sufficiently large such that each UUT measuring point has a ray path from the source to the measuring point on the UUT and to the camera aperture.

We employed a long ~1 m Nichrome ribbon that is pulled taut as our source. Nichrome has a high elastic modulus, a low coefficient of thermal expansion, and a high thermal conductivity, making it a great candidate as an extended thermal source. A spring is used to compensate for the thermal expansion in the ribbon as the temperature rises. With a small voltage of 5V, this 1 m ribbon reaches ~120°F and holds a stable temperature, which is a significant temperature contrast to typical room temperature. Testing potential source scanning configurations was simulated in a non-sequential raytracing software to identify requirements for the source size and scanning dynamic range through the expected IR camera image scanning patterns as shown in Figure 2.


0mm translation

200mm translation

400mm translation

Fig. 2. Non-sequential raytracing simulation results for 0.5 × 0.5 m aluminum panel with a 5.5 m radius of curvature to be tested showing the IR detector images for 0 mm (left), 200 mm (middle), and 400 mm (right) of translating the ribbon source in one direction.

3. Experimental Setup

We chose curved aluminum panels as our demonstration UUT since they have a rough surface (i.e., visibly non-specular) and various irregular surface errors. The hardware configuration is shown below.

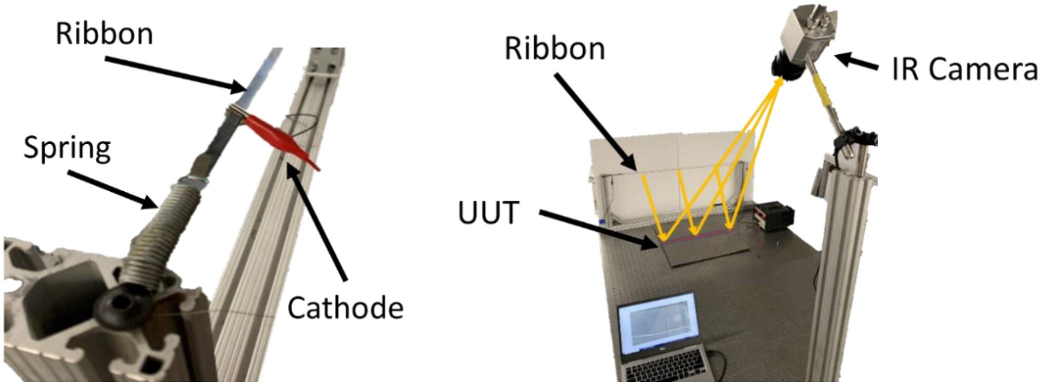


Fig. 3. Meter-class nichrome ribbon source with compensating spring (left). Test configuration for aluminum panel measurement with an IR camera and the ribbon source. (right)

Implementing source scanning in X and Y will then allow reconstruction of the entire surface. The full scanning system will measure surfaces to a micron-level precision for mid-high spatial frequency shape errors [2].

4. References

[1] T. Su, S. Wang, R. E. Parks, P. Su, J. H. Burge, Measuring rough optical surfaces using scanning long-wave optical test system. 1. Principle and implementation, Appl. Opt. 52, p. 7117-7126, 2013.

[2] Kim, Dae Wook, Tianquan Su, Peng Su, Chang-jin Oh, Logan Graves, and James Burge. "Accurate and rapid IR metrology for the manufacture of freeform optics." SPIE Newsroom (2015): 9-11.