

Measuring surface slope error on precision aspheres

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ABSTRACT

Optical designers are becoming increasingly aware of the importance of specifying and tolerancing slope errors on optical surfaces, especially aspheric surfaces. Slope errors can degrade system optical performance - in some cases even if the peak to valley surface figure errors meets the optical design tolerance analysis. With this awareness, more optical engineers are putting requirements for peak surface slope on optical element drawings. This puts pressure on optical fabricators to understand slope specifications and react to these requirements, and use the appropriate metrology instrumentation to ensure final system performance.

This paper will discuss appropriate ways to specify slope errors, and the challenges and limitations of measuring slope errors with commercial interferometers. The optical designer should be aware of how slope errors are measured on Fizeau interferometers and should specify the spatial intervals of interest when tolerancing aspheric elements. Peak slope error measurement is prone to erroneous measurement errors due to surface contamination, environmental errors, and pupil focus. Finally, filtering has a strong influence on surface slope calculations. Practical examples of slope specifications and experimental results will be presented.

Keywords: Optical metrology, interferometry, profilometry, optical surface specification, slope specifications, MRF polishing, stitching interferometry

1.0 INTRODUCTION

Most optical element drawings and specifications control the amplitude of the surface form error (the optical surface figure error) by setting a maximum limit on the peak to valley or root-mean-squared (rms) departure of the surface from the mathematically perfect form. The rate of change of that surface figure error can also be an important parameter that the optical designer should be concerned with in order to ensure that the final performance of the system meets its requirements.

There are many types of optical surfaces that are sensitive to slope errors on optical surfaces. Laser radar transmitters that project laser beams into the far field rely on a tight point spread function for good signal to noise. High energy laser systems that depend on focusing the majority of the available energy into as small of a spot as possible also must have accuracy and smooth surfaces. Finally UV imaging systems are sensitive to slope errors that are often related to mid-spatial frequency errors because of the short operating wavelength.

2.0 METHODS OF SPECIFYING SURFACE SLOPE ERROR

Surface slope errors are not covered in the reference documents that most optical fabricators use as the standards for surface specification and measurement. MIL-PRF-13830 has a complete discussion of specifying and measuring surface figure errors, but does not cover surface slope errors.

ISO 10110 is similarly silent about how to quantify or measure surface slope errors. ISO 10110 part 5 has 25 pages on surface form tolerances and part 12 has 10 pages on defining aspheric surfaces, but neither mentions how to define a surface slope tolerance.

There are several different units that could be used to specify the slope error of an optical surface:

Table 1: Possible slope error units

POSSIBLE UNITS FOR SPECIFYING THE SLOPE ERROR OF AN OPTICAL SURFACE
Waves per centimeter
Waves per inch
Radians, milliradians or microradians
Degrees
Each of these possible units could be specified in peak slope or rms slope.

In the absence of any widely distributed and accepted standard for specifying surface slope errors, we will survey a few examples of optical specifications and drawings where the slope error of the optical surface has been specified.

2.1 Laser Dimensional Gauging Instrument

A laser dimensional gauging instrument¹ uses a laser beam stripe between confocal parabolic mirrors to measure the physical diameters, lengths or widths of opaque objects. These objects can be as small as fiber optic cables, and as large as lumber, steel bar or large castings. The object passes through the cavity between the confocal parabolas. A linear array then detects the edges of the object being measured.

This type of instrument is sensitive to surface slope errors because surface slope errors on the parabolic mirrors translated directly into measurement error. The optical path is often greater than 200mm in the measurement cavity, therefore rays reflecting off of small surface slope errors have a long enough path length that the ray-retrace errors cause a significant displacement of the marginal rays at the focal plane array.

The example mirror drawing requires that the “reflected wavefront must not exceed $\lambda/15$ per centimeter”. The choice of waves per centimeter is sensible because the clear aperture is 120 mm long. Controlling the errors at cycles of 10-12 per aperture ensures that the mirrors will be smooth enough for the instrument to work correctly, and help limit the potential roll-off that may occur on the final 10% of the mirror aperture.

2.2 Off-axis generalized aspheric and conic mirrors for ozone mapping satellite instrument

Examples of mirrors for imaging systems on satellites have typically had surface slope errors called out in units of microradians. A typical example is “Surface slope errors shall be less than or equal to 50 microradians over the entire clear aperture. The specification is not particularly complete because the specification does not specify what spatial frequencies need to be included in the surface slope measurement.

2.3 Non-rotationally symmetric higher order aspheric mirrors for COSTAR

COSTAR (Corrective Optics Space Telescope Axial Replacement)² was the corrective mirrors designed to correct the unexpected spherical aberration in the Hubble Space Telescope. The small mirrors were required to be 0.01 wave rms at 632.8 nm over the 14-18 mm aperture. The mirror specification indicated that surface errors with spatial periods greater than 1 millimeter would be considered surface figure error, and figure errors with periods less than 1 millimeter would be considered surface roughness. Specifying the spatial period of interest was important because of the very small aperture and the several meter path length of the reflected light.

2.4 Large optics example – Interferometric reference mirror for NGST testing

A 0.5 meter diameter mirror was recently finished to better than 0.125 waves peak to valley at 632.8 nm over the 495.3 mm clear aperture. In addition to the surface figure requirement, the mirror has a slope requirement expressed in waves per inch. In this case, the longer 1 inch period makes sense because the mirror is 20 inches in diameter. Adding the slope requirement in addition to the figure requirement will help make sure the mirror is smooth. It should be noted that most commercial interferometers do *not* offer the option of “waves per inch” so data reduction to calculate peak slope must be done outside of the commercial interferometer software working from the raw phase map.

2.5 NIF Small Optics specifications

The NIF Small optics group documented many years ago that the performance of the system depended on the form, figure, and rms slope of the optical surfaces. Furthermore, they realized that since they would be working with many different optics companies, they would have to specify and control the sampling and the filtering allowed when measuring the optics³.

The small optics are required to meet the following requirements:

Lambda/8 peak to valley surface figure accuracy at 632.8 nm over the specified clear aperture

Lambda/40 rms surface figure accuracy at 632.8 nm over the clear aperture

Lambda/30/cm rms gradient at 632.8 nm over the clear aperture

These values were required to be evaluated for spatial periods greater than 2mm. All interferometry is required to have a minimum of 200 pixels across the aperture, so sufficient sampling is ensured.

The NIF small optics drawings also explicitly specify the filter that should be used when using interferometers to evaluate surfaces. As the referenced paper states, “Because of the relationship between the spatial frequency of a given error and its effect on laser system performance, spatial filtering is applied (> 2 mm). This approach is outside the framework of ISO 10110”.

3.0 METHODS OF MEASURING SLOPE ERROR

There are a number of different metrology tools which can be used to measure the surface slope of optics.

Table 2 – Metrology Instruments for measuring surface slope errors

Instrument	Comments	Examples of commercial instruments
Contact profilometers	Profilometers usually measure surface topography (sag) and do not report slope	Taylor Hobson, Mitutoyo and others
Shack Hartmann sensors	Wavefront sensors determine wavefront error through slope measurement	Wavefront sciences and others
Phase measuring microscopes	Measure phase like Fizeau interferometers, do not measure slope directly	Zygo New View 5000, ADE Phase Shift and others
Polarized topology scanning profilometers	Measure slope directly	Chapman Instruments
Fizeau Interferometers	Calculate slope from phase data	Zygo, ADE Phase Shift, 4D and others

The discussion in this paper will be limited to the use of phase measuring Fizeau interferometers for measuring slope because they are the most prevalent tool in optical manufacturing companies.

3.1 Measuring surface slope with phase-measuring interferometers

Fizeau interferometers measure phase differences between a reference wavefront and a test wavefront that includes an optical system or surface. Many commercial interferometers use this phase information pixel by pixel to calculate slope by looking at the change in phase at adjacent pixels in the data file.⁴

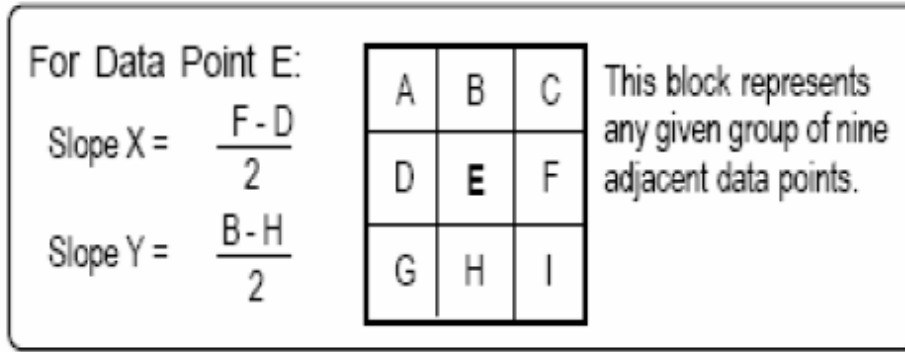


Figure 1 - Adjacent pixel method of measuring the rate of change of a wavefront

Most modern analysis tools report an x-slope, a y-slope and a slope magnitude. Figure 2 illustrates the relationship between these three parameters.

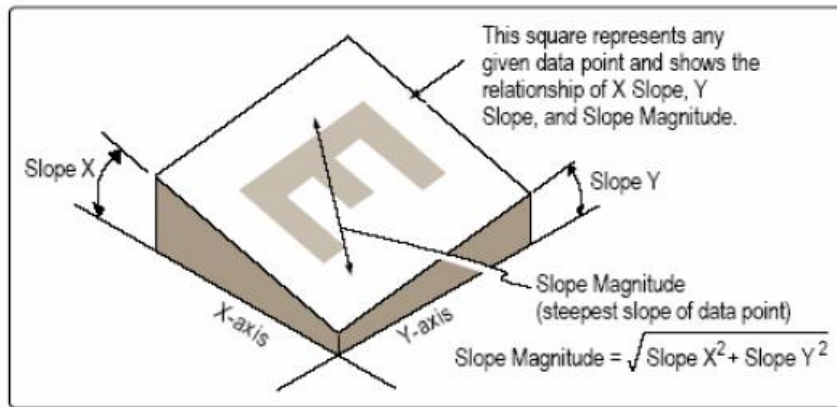


Figure 2 - Illustration showing relationship between x slope, y slope and slope magnitude.

4.0 CHALLENGES OF MEASURING SLOPE ERRORS ON ASPHERIC SURFACES

It is particularly important for the optical designer to consider slope errors on aspheric surfaces because most aspheres are fabricated with sub-aperture laps. Roller lap polishing, stick polishing, MRF® polishing, and even MR Jet™ and ion milling are all sub-aperture polishing if the tool does not contact the entire optical surface at the same time like spherical polishing laps contact spherical surfaces and planetary polishers contact flat surfaces.

Aspheres are also often the hardest optical surfaces to get accurate and repeatable measurements of surface slope for the reasons described below.

4.1 Pupil focus challenges with non-null cavities

There are pupil focus problems on non-null cavities. It is particularly critical to accurately focus the pupil when measuring non-null cavities.⁵

The example shown is a non-null test cavity of an aspheric surface using an $f/3.3$ transmission sphere, three phase averages, no trim, no filters and a 42 mm diameter test aperture. Figure 3 shows the interferogram of the test.

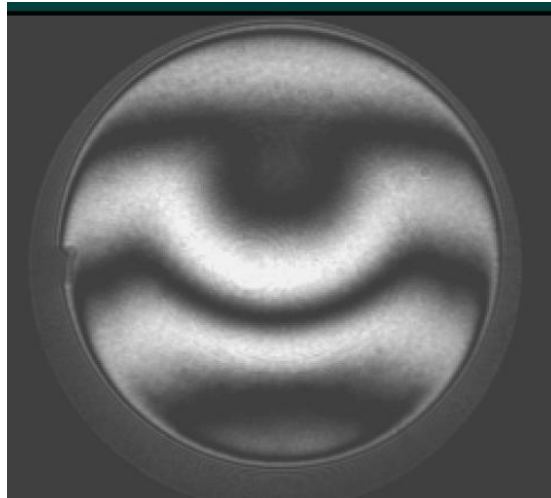


Figure 3 - Interferogram of an aspheric surface with roll-off at the outer edge of the optic

The results of the interferometric test are highly dependent on the metrologist's care in focusing the pupil. This is often done by attempting to adjust the interferometer focus until the hard aperture or an opaque mask at the edge of the surface (like the shim at the left-hand side of the aperture shown in Figure 3).

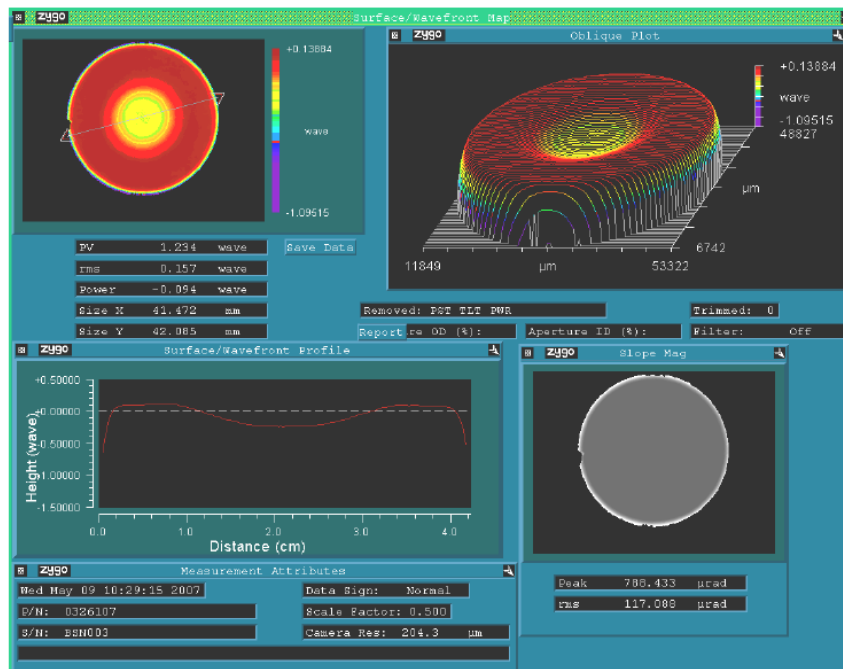


Figure 4 - Phase map and slope map for the interferogram shown in Figure 3

The results of the interferometric test as a function of the focus setting on the interferometer are plotted in Figure 5.

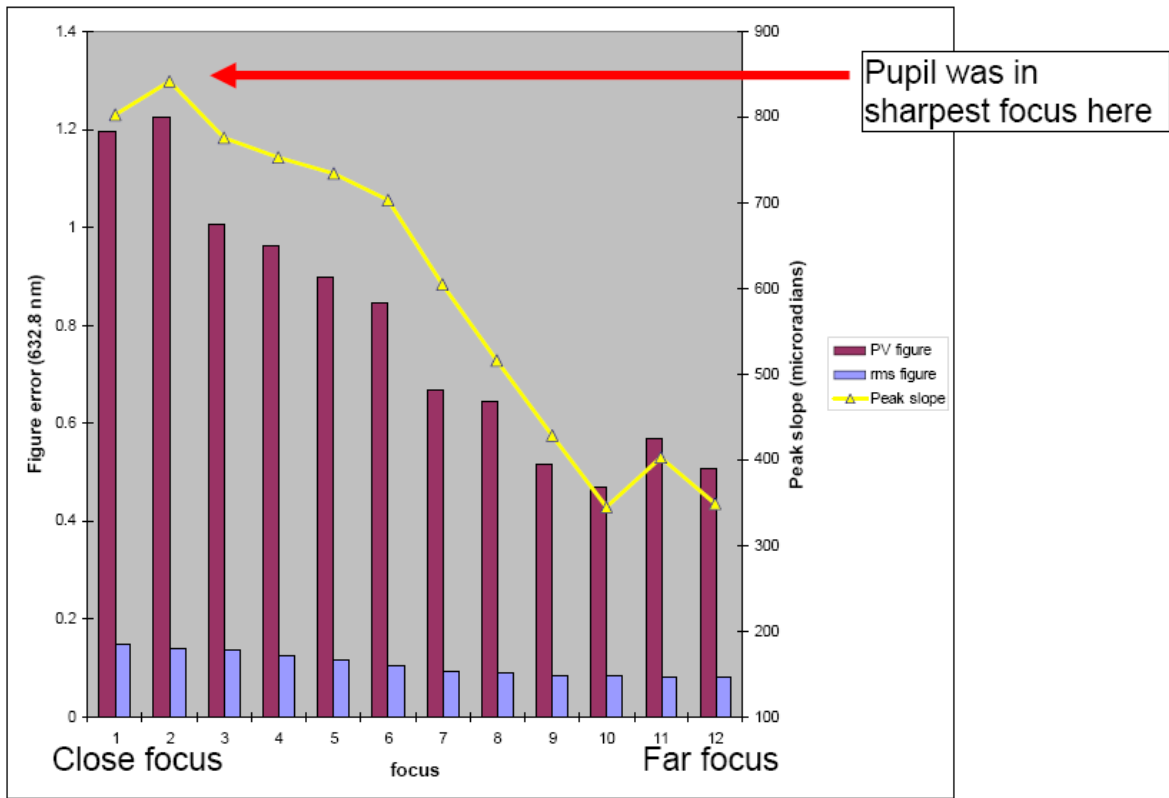


Figure 5 - Figure error and peak slope error as a function of interferometer focus

The surface figure measurement and the surface peak slope measurement can be incorrectly reports by a factor of almost 3 if the interferometer is not focused at the correct conjugate. The correct measurement of this non-null cavity is 1.22 waves peak to valley with peak slopes of 840 microradians. If the interferometer is focused at a distance farther than the surface under test, the test results were as low as 0.4 waves peak to valley and 350 micro-radians slope.

4.2 Surface defects influence measurements on high-resolution interferometers

It is important that the metrologist uses the highest resolution interferometer possible to provide high resolution error maps for aspheric correction to the deterministic polishing equipment. These higher resolution 1k x 1k error maps sometimes resolve small defects on the surface like dust or digs that would normally not be resolved by lower resolution interferometers. This is true of fixed aperture interferometers and stitching interferometers such as the QED SSI-A. This added sensitivity puts additional demands on the cleanliness of the reference optics (the Fizeau reference surface) and the part under test.

4.3 Environmental cavity errors from long cavity lengths

Testing large aspheric telescope mirrors is a challenge due to thermal gradients, turbulence, acoustic and vibration noise. These cavity errors impact surface figure measurements and similarly impact surface slope measurements. Phase averaging and flash phase techniques dramatically decrease the influence of temporal variations in the cavity. The metrologist needs to take care that flash phase instruments have sufficient spatial sampling of the surface to cover the spatial periods of interest. Low spatial sampling will hide mid-spatial frequency figure errors and therefore decrease the calculated surface slope from the phase measurement.

4.4 Tilted apertures and surfaces under test

Off-axis aspheric mirrors are often tested with the surface normal of the surface under test tilted (sometimes highly tilted) with respect to the optical axis of the interferometer. Accomplishing a sharp focus on the aspheric surface under test is difficult when the distance from the close edge of the asphere and the far edge of the asphere are different enough that the depth of focus of the instrument can not cover this variation. This sometimes results in unusual slope errors at the edge of the asphere even at the best compromise focus position.

4.5 Slope measurements and figure measurements are strongly dependent on spatial sampling and filtering

MetroPro and other commercial interferometric analysis software tools offer a wide range of post-processing options including low pass filtering. This can be useful for removing the influence of dust and defects discussed in section 4.2, but filtering can also change the reported peak slope and peak to valley surface figure error of the optic under test.

In figure 5, the peak to valley surface figure accuracy and peak slope are both plotted as a function of the width of the low pass filter. Depressed peak slope measurements will be reported if the filter settings are allowed to be arbitrarily set by the metrologist.

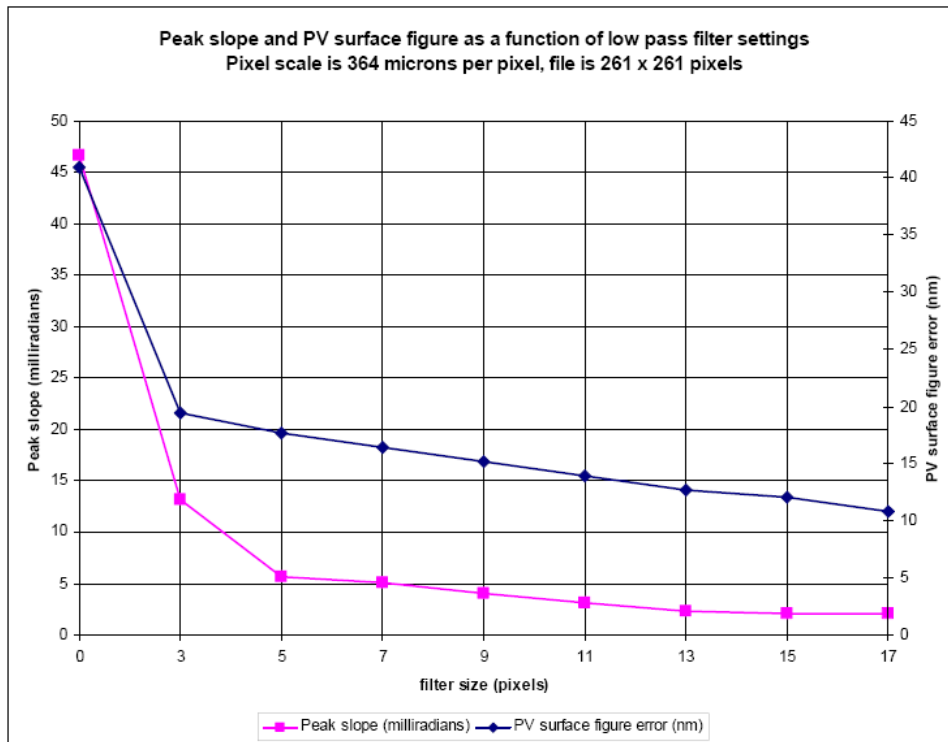


Figure 6 - Slope and figure as a function of low pass filter size in pixels

5.0 EXAMPLE OF THE EFFECTS OF SLOPE ERROR ON IMAGE QUALITY

A 300x zoom has recently been designed and built by Panavision Federal Systems⁶. The zoom lens in production was not meeting the image quality expectations at the long focal length end of the zoom range. Performance testing and testing with a knife edge (Foucault test) in front of a collimator suggested that the aspheric surfaces in the system may be the major contributor to the reduced image quality.

The aspheres were tested using a QED SSI-A stitching interferometer. The advantage of this metrology approach was that the stitching interferometer does not require null optics (be it refractive null or computer generated hologram). The test results with the SSI-A indicated that the aspheric surfaces were well made and met the surface figure accuracy requirements of the drawings, but there were radial zones that were apparent when the lower order Zernike coefficients were subtracted that had relatively high slope transitions (300 microradians peak). Even though these zones were low amplitude (<60 nm), it appeared that these zones were degrading the image quality.

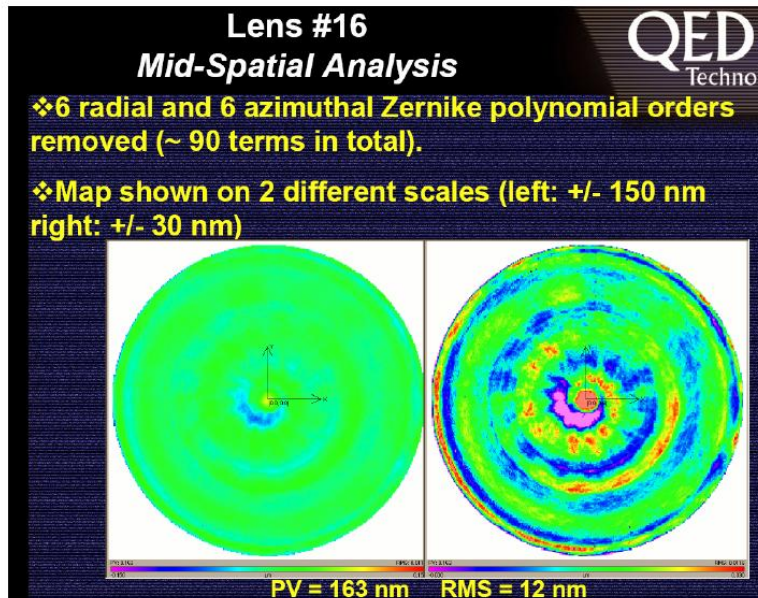


Figure 7 - Interferometric test with the stitching interferometer

Once the problem had been identified, the aspheres were re-manufactured with very tight peak slope. The slope errors on the aspheric surfaces were reduced from over 300 micro-radians to 60 microradians. The results of the knife edge test of the 300x zoom lens in collimation (as a system) are shown in Figure 6.

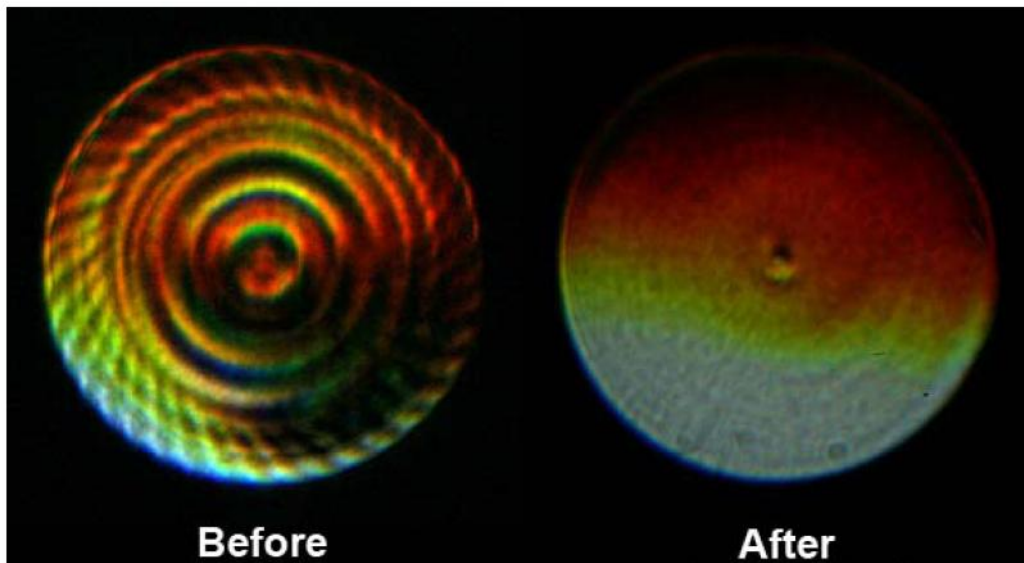


Figure 8 - Knife edge test (end to end) of the 300x zoom lens in collimation.

The image quality of the 300x zoom was improved almost as dramatically as the improvement in the Foucault test and the full potential of the refractive system was realized with the smoother aspheric elements.

6.0 CONCLUSIONS

Slope errors on surfaces are not often specified by optical designers and are not easy to tolerance in optical design codes. Our experience has shown that slope errors can have an impact on system performance and image quality. Although industry standards for specifying surface slope errors are not widely distributed, we can make the following observations and recommendations.

- The optical designer should define what spatial frequencies must be captured when specifying slope requirements. The metrologist can then make sure that they have sufficient interferometric pixel sampling to cover the spatial frequencies of interest
- You can not scale slope measurements like you can scale surface figure accuracy (when converting waves peak to valley at 632.8 nm to some other reference wavelength for example). If a part measures 0.25 wave per centimeter, that does not mean you can state that the part is also 0.635 wave per inch.
- In order to make accurate slope measurements,
 - a. Zoom up the pupil image to use the most pixels in the aperture
 - b. Always use the 4" to 33mm aperture converter for small pupils
 - c. Use care when focusing the pupil
 - d. For aspheres, you should have 200+ pixels across the aperture because there may be mid-spatial frequency error
 - e. Powerful analysis tools like sampling and filtering options will often distort the slope results. Filter with caution

7.0 ACKNOWLEDGEMENTS

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¹ Musto, Dominick J., Lerner, Harold, Laser Dimension Gauge, US Patent #4,201,476 dated May 6, 1980.

² M. Bottema, "Reflective correctors for the Hubble Space Telescope axial instruments", Appl. Opt. **32**, 1768- (1993)

³ Lawson, Aikens, English, Whistler, House and Nichols, "Surface Figure and Roughness Tolerances for NIF Optics and the interpretation of the gradient, P-V wavefront, and RMS specification", UCRL-JC-134534 presented in Denver, CO, July 1999.

⁴ From MetroPro Reference Guide OMP-0347J (figures used with permission)

⁵ Lowman and Greivenkamp, "Modeling an interferometer for non-null testing of aspheres", SPIE 2536, p. 139.

⁶ U.S. Patent **6,961,188**, "Zoom Lens System", Betensky et al., filed July 18, 2003.