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Improving Aspheric Lenses with

TRANSMITTED WAVEFRONT ERROR CORRECTION

***T*olerancing optical lenses in transmission rather than reflection offers financial, performance and delivery advantages for a given class of aspheric optics.**

During design and manufacturing, optical systems and lenses are toleranced and tested to ensure the smallest possible performance error. Matching most optics manufacturing companies' capabilities, lenses are traditionally toleranced with individual surface specifications—surface power and irregularity or, form, error. These tolerances and the associated tests control performance of a single surface, not the entire lens. Lens designs are built around transmission characteristics such as spot size and RMS wavefront error. Because of this the performance of the entire lens, not the individual surfaces, is the true target. This can be tested by measuring the Transmitted Wavefront Error (TWE), the error in transmission of light through a lens. For aspheric surfaces, traditional single-surface three-dimensional surface form metrology is not easy. Aside from testing the true target, it may be easier and faster to make use of TWE for aspheric lenses. Using innovative metrology and developing a feed-forward manufacturing strategy, TWE tolerancing and testing can reduce risk in optical designs, improve performance and reduce cost and lead time.

Optics fabrication goes hand-in-hand with optics metrology—metrology capabilities are just as important as fabrication capabilities. As aspheric lens precision increases, metrology must also become more accurate. For molded and fire polished aspheres, with surface form accuracies ranging from 50-200 microns, two-dimensional profiles of the surface are sufficient. Two-dimension profilometry is quick, uncomplicated and can be used reliably to verify surface form accuracies as tight as one micron. This process is used with commercial grade, ground and polished aspheres. However, aspheric lenses are commonly used for imaging applications and are typically toleranced with surface form errors less than 0.633 microns. Two-dimensional surface profiles cannot be used to certify to this accuracy. In order to test a surface's form and prove it accurate to less than one micron, three-dimensional surface metrology is required.

Reflected wavefront three-dimensional surface form testing can be accurate to less than 0.633 microns. It often requires expensive, long lead time holograms or diffractive optical elements, a powerful interferometer and labor intensive setup by a skilled technician. The test setups are often lock-and-key, meaning a very expensive hologram or diffractive element will work only for the one aspheric form it was designed to test. More versatile three-dimensional asphere metrology solutions are available in the marketplace, but they still are limited to measuring certain groups of aspheres based on aspheric departure or slope changes. A step beyond reflected wavefront three-dimensional surface form metrology is TWE testing. TWE is the sum of all transmission errors. It takes into consideration material defects, wedge, thickness variation, irregularity and power. Virtually all errors



can be checked and with a feed-forward process, corrected at the same time. Testing and correcting aspheric lenses in transmission tests the true performance of the lens and can eliminate the need for expensive and long lead time holograms or diffractive elements. The test can also be quicker and easier than a reflected wavefront test.

Depending on lens material, departure and rate of change of aspheric form relative to a spherical form, there are times where most optics shops may have everything needed to test TWE. The measurement requires an interferometer and a test cavity, both of which require a per test setup. It also requires a part capable of transmission, so any paint or blocking wax would have to be removed. Below are a few easy guidelines listing what makes a specific aspheric lens a good candidate for TWE testing:



Figure 1: Image of an error-laden reflected wavefront of one surface of an asphere.

- ▲ Lens aberrations must not exceed the capabilities of the interferometer to be used. Aberrations need to be modeled and quantified, and interferometric performance must be characterized.
- ▲ The lens must be well behaved interferometrically, meaning that retrace errors and vignetting—light straying from its optimum path—must be considered and if present accommodated for in the test setup.
- ▲ The lens must transmit the test wavelength.
- ▲ Performance differences between test wavelength and design wavelength must be considered. A lens that has a good test at HeNe may not perform as well in the near infra-red (IR).



Figure 2: TWE map showing TWE is $< \lambda/30$.


After performing the TWE test, the next step is interpreting and applying the results and correcting the aspheric form. Traditional polishing is a feedback controlled process. One surface is worked, measured and corrected iteratively until it is within tolerance. The outcome cannot be predicted to the precision needed for many applications. When testing in transmission and using a feed-forward process, a lens' TWE test results are compared to a theoretical target TWE. One surface is modified to directly correct the TWE. A feed-forward process is one where the outcome is predictable—a known

starting point and controlled, deterministic processing can indicate the outcome. The known starting point is set by polishing and measuring the TWE of the lens. The controlled polishing process requires innovative material processing with a known material removal rate and an understanding of how changing one surface alters TWE. By combining the TWE phase map and the known removal characteristics, a deterministic processing strategy is developed and TWE can be corrected and controlled. Individual surface forms are not toleranced or tested; the true target – light transmitting through the lens – is tested and directly controlled during manufacturing. This allows designers and manufacturers the ability to tolerance, manufacture and target TWE as the performance criteria for lenses and systems.

TWE was corrected on a 70mm diameter fused silica asphere with 3.1 microns of departure with the bulk of departure near the edge. The process involved summing up all errors into an accurate, scaled ideal map of TWE. The lens was manufactured and then tested in transmission, generating an actual TWE map. The ideal and actual TWE maps were compared, a deterministic correcting strategy developed, and one of the lens' surfaces had the compensating form embossed on it. The "error" corrected onto the surface manipulates the TWE. The corrected surface will look strange in terms of reflected wavefront, but the lens' TWE will be sub-wave.

Another example of TWE correction is a 203mm diameter, 180mm clear aperture n-BK7 asphere with 2.1 microns of departure. Again, the bulk of departure is near the edge. The same feed-forward process described previously was used. The test layout involved an incoming collimated wavefront and a spherical mirror, producing a double pass schematic. This is shown to the right in Figure 3. The resulting OPD fans are shown in Figure 4. A MetroPro plot of the corrected transmitted wavefront is shown in Figure 5. The MetroPro plot shows that after correction, the TWE tested to 0.020 waves RMS, ~0.0126 microns RMS.

Working with NASA on the Orbiting Carbon Observatory Program (OCO), three optical systems were manufactured using TWE tolerances. For each of the OCO elements, a TWE target was provided and a lens was manufactured to provide the desired transmitted goal. When the lenses were completed and assembled, the final system performed as designed. NASA's OCO instrument will be integrated onto a satellite scheduled for a 2008 launch and will provide global measurements of atmospheric carbon dioxide levels. The study will give new insight into the Earth's carbon cycle. In this case, tolerancing and manufacturing toward TWE goals allowed for an accurate optical performance model and reduced risk in the optical design. TWE targets were set and lenses were manufactured that meet specifications within budget and on time.



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OPTICS MANUFACTURING TOLERANCES

ATTRIBUTE	COMMERCIAL QUALITY	PRECISION QUALITY	MANUFACTURING LIMITS
GLASS QUALITY (n_d, v_d)	$\pm 0.001, \pm 0.8\%$	$\pm 0.0005, \pm 0.5\%$	Melt controlled
DIAMETER (mm)	+0.00/-0.10	+0.000/-0.025	+0.000/-0.010
CENTER THICKNESS (mm)	± 0.150	± 0.050	± 0.025
SAG (mm)	± 0.050	± 0.025	± 0.010
RADIUS (mm)	$\pm 0.2\% \text{ \& } 5 \text{ fr}$	$\pm 0.1\% \text{ \& } 3 \text{ fr}$	$\pm 0.0025 \text{ or } 1 \text{ fr}$
IRREGULARITY (fringe)	2	0.5	0.1
ASPHERIC PROFILE (microns)	± 10	± 1	± 0.1
WEDGE LENS (ETD, mm)	0.050	0.010	0.002
WEDGE PRISM (TIA, arc min)	± 3	± 0.5	0.1
BEVELS (face width @ 45°, mm)	<1.0	<0.5	No Bevel
SCRATCH - DIG (MIL-PRF-13830B)	80 - 50	60 - 40	10 - 5
SURFACE ROUGHNESS (\AA rms)	100	20	2
AR COATING (R_{Ave})	MgF ₂ R < 1.5%	BBAR, R < 0.5%	Custom Design

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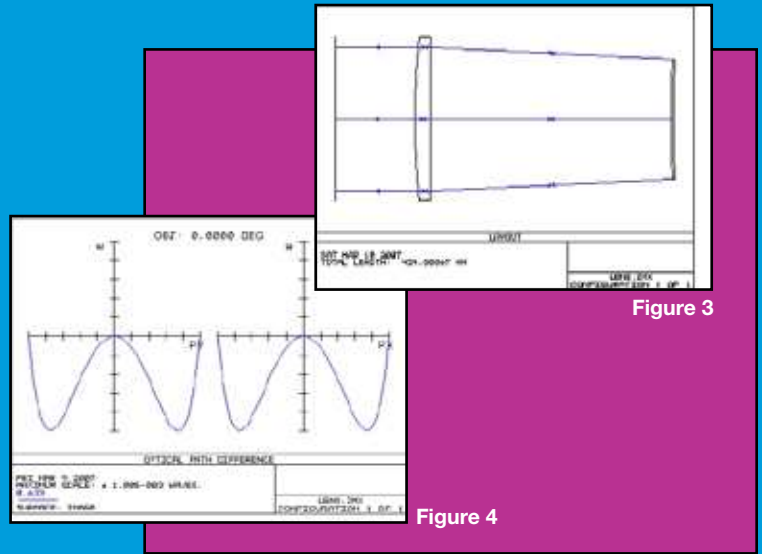


Figure 3

Figure 4

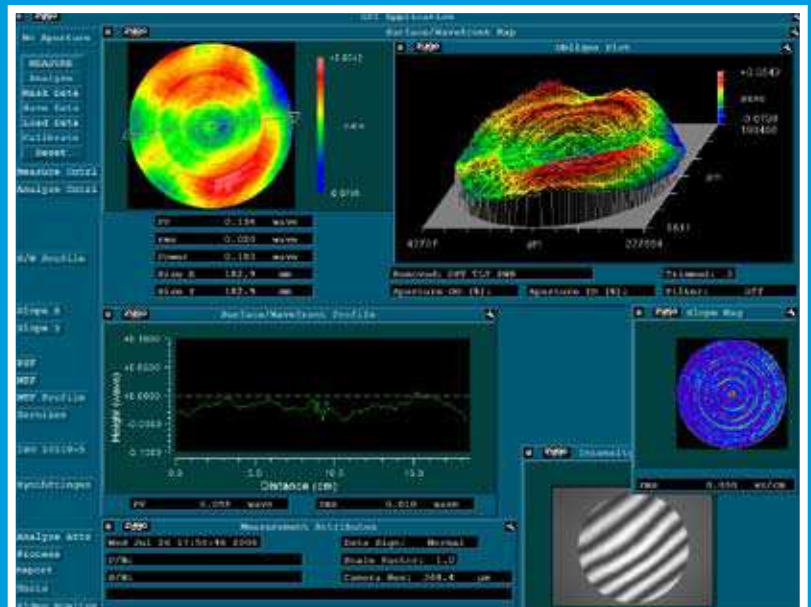


Figure 5: MetroPro plot of corrected transmitted wavefront.

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