Comparison of contact and non-contact asphere surface metrology devices

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ABSTRACT

Metrology of asphere surfaces is critical in the precision optics industry. Surface metrology serves as feedback into deterministic grinding and polishing platforms. Many different techniques and devices are used to qualify an asphere surface during fabrication.

A contact profilometer is one of the most common measurement technologies used in asphere manufacturing. A profilometer uses a fine stylus to drag a diamond or ruby tip over the surface, resulting in a high resolution curved profile. Coordinate measuring machines (CMM) apply a similar concept by touching the optic with a ruby or silicon carbine sphere. A CMM is able to move in three dimensions while collecting data points along the asphere surface.

Optical interferometers use a helium-neon laser with transmission spheres to compare a reflected wavefront from an asphere surface to a reference spherical wavefront. Large departure aspheres can be measured when a computer generated hologram (CGH) is introduced between the interferometer and the optic. OptiPro Systems has developed a non-contact CMM called UltraSurf. It utilizes a single point non-contact sensor, and high accuracy air bearings. Several different commercial non-contact sensors have been integrated, allowing for the flexibility to measure a variety of surfaces and materials.

Metrology of a sphere and an asphere using a profilometer, CMM, Interferometer with a CGH, and the UltraSurf will be presented. Cross-correlation of the measured surface error magnitude and shape will be demonstrated. Comparisons between the techniques and devices will be also presented with attention to accuracy, repeatability, and overall measurement time.
1. INTRODUCTION

1.1 Computer Generated Hologram (CGH)

Interferometric null testing of aspheres with computer generated holograms is an established metrology technique. A standard interferometer compares a spherical wavefront to the surface under test. An asphere will aberrate the reflected wavefront. A CGH will shape the wavefront to the predicted aberration by the asphere. A typical CGH is a diffractive plate placed in-between an interferometers transmission sphere and the asphere under test. CGH’s must be placed at a specific distance from a given transmission sphere, and the asphere. Therefore it can be difficult to align. Each CGH is manufactured for a specific asphere prescription and F-number transmission sphere.

Figure 1: CGH on vertical interferometer, from bottom to top: interferometer, transmission sphere, CGH, asphere (not visible, but in holding assembly)
1.2 Profilometer

A profilometer is a device that measures surface topography with a contacting stylus tip (Figure 2 & Figure 3), such as a diamond tipped cone with a tip radius of 10 µm or a ruby sphere with 0.5 mm radius. The stylus pivots about a point as it traverses along the surface. The pivoting motion is typically measured with helium neon interferometry, lending to very high vertical resolution. The system relies on accurate characterization of the stylus tips. Steep slopes can cause the stylus to slip and loose contact. With an added rotary table, multiple line traces can be used create an interpolated 3D set of data from the 2D profiles.

![OptiPro OptiTrace profilometer measuring an asphere with a ruby tip stylus. Rotary table is visible below the clamping chuck](image1)

Figure 2: OptiPro OptiTrace profilometer measuring an asphere with a ruby tip stylus. Rotary table is visible below the clamping chuck

![Close in view of asphere profile measurement](image2)

Figure 3: Close in view of asphere profile measurement
1.3 UltraSurf

OptiPro Systems has been developing the UltraSurf, a non-contact measuring system using state of the art, air-bearing, precision motion control (Figure 4). The five-axis, non-contact single point measurement is flexible enough to handle common metrology problems such as surface roughness, slope error, and high departure from base radius.

UltraSurf measures with sub-micrometer non-contact point sensors to collect surface information. Various sensors are commercially available from multiple companies, each with their own distinct optical measuring technology. One optical sensor uses white light confocal chromatic imaging to measure individual optical surfaces. Another optical sensor uses low-coherence interferometry with a near infrared laser, and is able to measure the inside, outside, and thickness of optical materials at a single point.

![Figure 4: UltraSurf axes of motion, three linear (X,Y,Z) and two rotary axes (B,C). Non-contact probe is attached to B and Z axes. The part under test is held by the C-Axis, and can move in the X and Y directions.](image)

2. METHODOLOGY

2.1 Computer Generated Hologram Process Flow

1. Install CGH and specific transmission sphere on to vertical interferometer
2. Position CGH to the specific distance from the transmission sphere of the interferometer
3. Remove tilt and centration of CGH
4. Place asphere the recommended distance above the CGH
5. Remove tilt and centration of the asphere relative to the CGH iteratively
6. Null the fringes
7. Measure with phase shifting interferometer
8. Phase shifting algorithm will generate the wavefront error map

2.2 Profilometer Process Flow

1. Center and remove tilt in the part using contact stylus, dial indicators, and the built in adjustment table
2. Crown over the center of the part
3. Measure a single line trace
4. Rotate the part a fixed amount with the rotary table, depending on the number of traces
5. Measure again, repeat previous step until all traces have been taken
6. Input asphere definition into measurement OptiTrace analysis software
7. Import all traces into OptiTrace analysis software
8. Compare the line traces to the specified asphere definition
   a. Trace is allowed to tilt and translate to obtain a best fit, allowing for non-perfect centering and tilt removal in the previous steps.
   b. Asphere radius can be optimized and fit
9. Generate an error profile
10. Convert the error profiles into an interpolated 3D plot

2.3 UltraSurf Process Flow

1. Input part definition into measurement software
2. Center and remove tilt in the part using the non-contact probe and the built in adjustment table
3. Locate the part with the non-contact probe, usually over the center of the surface
4. Run the scanning path
5. Convert the multi-axis feedback and non-contact probe readings into a 3-D point cloud
6. Compare the point cloud to the part definition
   a. Point cloud is allowed to rotate and translate to obtain a best fit, allowing for non-perfect centering and tilt removal in the previous step.
   b. Asphere radius can be optimized and fit

3. RESULTS

3.1 Error Map Projections

When displaying error maps from different devices it is important to communicate the type of projection. OptiTrace and UltraSurf use a vertical or top down projection (Figure 5). Interferometers use a surface normal projection. It becomes more complicated with a computer generated hologram. The lateral scaling of the data will change in a linear fashion from center to edge (Figure 6). Another effect is a measured diameter will appear larger than the physical part. There are techniques to correct the variable lateral scaling of the CGH error map, but they were not applied here. The projections for the following CGH data have this issue, and cannot be directly overlaid with the results from OptiTrace and UltraSurf.

![Figure 5: Vertical or top-down projection. This type is used by UltraSurf and OptiTrace](image-url)
3.2 Asphere Surface Error Maps

Two different aspheres of the same prescription were measured on the vertical interferometer with the CGH, the UltraSurf non-contact metrology system, and the OptiTrace profilometer. These parts will be referred two as part number 1 and part number 3. The numbers were previously etched into the side of each optic, and not part of a sequence. UltraSurf measured with a 200 μm resolution. The CGH interferometer measured with a 53 μm resolution. The OptiTrace measured 4 profiles though the center of the part, one trace every 45 degrees. Each profile was measured with a 1 μm resolution, and then the error was interpolated to a 400 by 400 pixel map. Therefore the OptiTrace measured with an effective resolution of 114 μm. The asphere under test has over 400 μm of departure from the base radius at the diameter.

The first three error maps for part number 1 are shown below in Figure 7. The CGH was unable to resolve the center. The different lateral scaling becomes apparent with the diameters of each data set, and the locations of the ripple. The magnitudes of the error are very similar across the board. The Zernike polynomials for first order coma were removed from the CGH data, but not the UltraSurf or OptiTrace. The coma was induced by misalignment in the CGH setup. Iterative alignment showed the coma slowly disappearing, therefore we determined it to be an alignment artifact, and removed it. Obviously this decision has to be made with scrutiny. The interpolation technique for the OptiTrace produces a visibly smoother surface than the other two. OptiTrace displays symmetric astigmatism, where the CGH and UltraSurf do not. This is due to the low amount of angular resolution in the OptiTrace data. UltraSurf shows more high frequency circular error, which could be a measurement artifact from the concentric ring measurement. Regardless, all three error maps show good, but not perfect correlation.

It is good practice to look at other spatial regimes in measurement data between different instruments. Numerous low order Zernike polynomial terms were removed from the measurements of part number 1. The goal is to compare the higher frequency errors measured by the systems. Figure 8 clearly highlights the angular limitation of the multiple trace.
interpolation method. These higher order angular errors correlate between UltraSurf and the CGH, but are not present in the OptiTrace data. The CGH data appears to blur together the top location of the error map where UltraSurf shows individual rings.

The CGH is unable to handle the high slope region in the center of the part number 2 (Figure 9). Also, there is a ring of dropped pixels just outside the central region that corresponds to an alignment feature in the CGH wave plate. Again coma was removed from the CGH data to provide an adequate data set. The error magnitudes for this part don’t agree as well as the previous data. In this case the UltraSurf and the OptiTrace data have better agreement, although they appear to have some residual lower order power error that the CGH data does not. This stems from the UltraSurf and OptiTrace using dimensional information to optimize and fit the radius. Removing power from these two data sets is not necessarily correct from an accuracy standpoint, since power error in an asphere is not the exact same as a radius error in the base shape.
For the sake of comparison we will remove power from the UltraSurf and OptiTrace measurements (Figure 10). The magnitudes with power removed are much more similar. The flat sided oval in the center and the bent astigmatism appear more similar in the CGH and UltraSurf data. Again, this can be linked to only using 4 traces.

![Figure 10: CGH, UltraSurf, and OptiTrace error maps of Part #3. CGH has piston, tilt, power, coma terms removed, UltraSurf and OptiTrace are radius optimized to geometry with power term removed](image)

### 3.3 Asphere Surface Parameters

The CGH data has significant regions of dropped data. Also, with uncorrected lateral scaling, we are unsure if we are measuring the exact same area with the CGH. UltraSurf and OptiTrace appear to have data beyond the lateral positions measured with the CGH. Therefore the CGH results will be omitted from the parameter comparison in Table 1. The parameters will be calculated with a dataset having a 3 x 3 box median filter to remove any errant spiked pixels for a more appropriate peak to valley number while not drastically altering the results. The peak to valley (PV) and root mean square (RMS) errors appear to match approximately 10%. The optimized radii agree to better than 0.02%.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UltraSurf #1</th>
<th>OptiTrace #1</th>
<th>UltraSurf #3</th>
<th>OptiTrace #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV (μm)</td>
<td>1.957</td>
<td>1.880</td>
<td>4.472</td>
<td>4.991</td>
</tr>
<tr>
<td>RMS (μm)</td>
<td>0.385</td>
<td>0.430</td>
<td>0.835</td>
<td>0.929</td>
</tr>
<tr>
<td>Radius (mm)</td>
<td>45.024</td>
<td>45.018</td>
<td>45.085</td>
<td>45.087</td>
</tr>
</tbody>
</table>

Table 1: Asphere Parameter Comparison
3.4 Asphere Measurement Times

Manufacturing aspheres at the production level requires metrology time information. The time table below shows the minutes required for setting up each metrology instrument, measuring the first part, and then measuring a subsequent part (Table 2). Usually there is a time reduction in the repeated measurements. The CGH and interferometer test is much faster on the second part, but iterative alignment still requires some effort. UltraSurf is easy to set up, but the single point scanning method is the slowest, so it does not gain a huge improvement on the second part. The OptiTrace requires approximately the same amount of time for every asphere measured. The posted times could have their setup time significantly reduced if the parts were contained in a fixture, as opposed to loose optics.

Table 2: Asphere Measurement Times in Minutes, measurement times for non-fixture optics

<table>
<thead>
<tr>
<th></th>
<th>Initial Setup</th>
<th>Measurement Total</th>
<th>First Part</th>
<th>Next Part Setup</th>
<th>Next Part Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGH</td>
<td>60</td>
<td>0</td>
<td>60</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>UltraSurf</td>
<td>15</td>
<td>25</td>
<td>40</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>OptiTrace</td>
<td>10</td>
<td>3</td>
<td>13</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>

3.5 Asphere Repeatability

UltraSurf collected three separate measurements of each asphere. Repeatability of the error maps can be calculated by averaging the three error maps, then comparing each of maps to the average. A standard deviation calculation of the three combined data sets should provide a good measure of the repeatability. The average removed maps can be seen below in Figure 11 for part number 1 and in Figure 12 for part number 3.

Figure 11: CGH, UltraSurf, and OptiTrace repeatability maps of Part #1. Average error map of three measurements was removed from each map to produce these plots
Circular residual errors can be shown in each of the repeatability maps that correspond to the annular ring data collection of UltraSurf (Figure 12). The difference from average for each asphere measurement is on the order of ± 0.1 μm. The standard deviation for part number 1 is 53 nm, and 30 nm for part number 2. These numbers are less than half of the accuracy specification for the non-contact probe. The shape produced in the error maps may be due to inherent probe accuracy or drift. More testing would be required to determine error sources. The repeatability test presented should be expanded to the CGH and OptiTrace measurements and would provide valuable comparison.

The radius was optimized during the UltraSurf analysis procedure. The radii are summarized below in Table 3. The total variation is at most 8 micrometers in radius, which is less than 0.02% of the total radius. Actual radius can be difficult to measure on an asphere. The cloud of points UltraSurf uses to calculate the radius appears to be a very repeatable. The sample size of three is small, but the total variation can be expected to stay less than three standard deviations, i.e. 13 μm.

Table 3: Radius Repeatability, N=3

<table>
<thead>
<tr>
<th>Part #</th>
<th>Radius Average (mm)</th>
<th>Total Deviation (μm)</th>
<th>Standard Deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.0196</td>
<td>8.3</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>45.0810</td>
<td>6.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The two aspheres were chosen for this paper based upon the magnitude, shape, and slope of the error. They represent surfaces a manufacturer could see, and try to measure with any of these systems. The aspheres were expected to challenge the capabilities. All three instruments showed good levels of agreement. Profilometers are currently used in most asphere manufacturing labs, creating an interpolated map to gain 3D information could be useful for sub-aperture correction. UltraSurf showed very good correlation with the CGH as well as the OptiTrace. Although measurement times are longer, and there is some systematic ripple apparent in the error maps. Repeatable errors can be compensated, so it will be beneficial to continue studying how they affect the UltraSurf.

Future work will center on using an asphere with lower figure and slope error to allow more resolvable CGH information. A repeatability study with the OptiTrace and CGH will also be performed. The UltraSurf, and OptiTrace with 3D interpolation show promising correlation against each other and interferometric CGH null tests.