This document describes a series of three experiments to explore the possibility of a non-white light interferometric method of distinguishing between 3-5 and 8-10 Å RMS parts. The experiments may or may not lead to a prototype instrument that can be delivered to our customer, Sydor Optics. If a prototype is designed this document will also detail the prototype design.
Surface Roughness Inspector 03 Design Description Document

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(See digital document 1)

Experimental Design Descriptions
1) An experiment using Fourier analysis to analyze the optical flats
2) An experiment using a Zygo VeriFire GPI to analyze the optical flats
3) An experiment using scatterometry to analyze the optical flats

Fourier Analysis

Overview:
The purpose of the Fourier analysis experiment is to convert the small spatial modes of the surface roughness (3-10 Å RMS) of the sample into the frequency domain and detect slight differences in the high order frequency fluctuations between samples. The light used will be a HeNe operating at 633 nm. There will be two types of set ups in this method. One method will be done in transmission (as seen below in Figure 1) and the other will be done in reflection at Brewster’s angle off of the first surface of the object (part being tested). In order to validate the experiment, get an idea of the differences in signal from different surface roughness values, and to determine the correct size for the spatial filter (aka DC dot), if one is to be used, a simulation of the experiment will be carried out. The general experimental set up is pictured below in Figure 1.

![Figure 1: Fourier transform of the object (samples under test) using a single lens. The experiment will be based off of this set up in various configurations.](image)

GPI Description

Overview:
The concept with the use of the 4” Zygo VeriFire GPI is an attempt to correlate surface roughness to surface form. In theory a part with greater surface roughness will also have greater form error. This experimental method tests to determine if that theory is correct and useable for our customer. This is done through a statistical analysis of laser grade and standard grade parts as measured in reflection. In reflection mode the GPI has a similar configuration as seen in figure 2. The GPI compares the surface under test and compares it’s wavefront to the wavefront of a reference element. By use of the Metropro software the wavefront error of the part as a function of deviation from the reference element is given. In our case the reference element used is a 4” reference flat.
Figure 2: General configuration for a phase shifting Fizeau interferometer.

The Metropro software is used in a specific configuration in order to minimize error. Through the use of this software piston, tilt, power, and 3rd order aberrations is removed from the analysis. A default low band filter is also applied. This is done in order to get a measurement of the error of the wavefront that is contributed by only the surface form. After some experiments it was concluded that the best mode for these measurements is to use Metropro’s batch mode allowing it to take 10 measurements and reports the average of these measurements as a final value. For initial, smaller, parts the 4” beam is measuring over the whole part. For real, larger, parts the measurement features a 4” section within the clear aperture of the part.

**Scatterometry**

**Overview:**
The scatterometer is designed to scan the angular scattering intensity distribution of a non-perfect surface over desired angular range. The mechanical arm of the goniometer can cover desired angular range up to 180° as seen below in Figure 2. A power meter is mounted at the end of the arm of the goniometer. The goniometer stops at each designated angular location (angle of detection) and measures the intensity for a set period of time. It is thought that the amount of scattered power in the wings of the angular light distribution will vary with surface roughness. By comparing the intensity profiles of different surfaces, it would then be possible to classify the roughness level of the surface.

In this experiment, the scattering power measured is Rayleigh scattering, but not Mie scattering. The reason is because the RMS roughness of the sample surface ranges from 3~10 Å, while the visible laser that would be used for this setup has a wavelength that is at least about 400 times larger than the surface particle size. Since Mie scattering is more suitable for scattering from particle with diameter larger than 10% of the wavelength, Rayleigh scattering is more significant in this scatterometric setup.

There are two modes for this setup, transmission mode and reflection mode (Fig.14). Light source used is laser. In transmission mode, the incident beam directly passes through the sample and hits the detector. In reflection mode, by setting the sample at θ, ideally all the p-polarized light would be eliminated. If the incident beam is previously polarized as p-polarized light before striking the sample, then there should be very little directly reflected power detected and the majority of the signal will be the scattered light. This method can potentially completely remove the peak power at small angle of detection.
Test Plan / Validation

Fourier Analysis

The experiment will consist of three main exercises. The first will simulate the Fourier transform experiment in software. This will help form our understanding of the way signal in the Fourier plane changes due to varying surface roughness in the sample, test out if this experiment is theoretically possible, and to determine the optimal spatial filter size if one were to be used. The second exercise will be an experiment set up in a transmission mode through the part. The third will be a series of reflection mode measurements at Brewster’s angle. The light will reflect off of the sample at Brewster’s Angle. The purpose of doing the experiments in this reflection mode is to reduce the specular reflected signal and increase the chance of detecting signal variations from different the different surface qualities. By far the greatest threat to the success of this experiment is scattered light from surfaces other than the sample. There is no way to minimize this other than taking measurements without the sample (“dark” measurements) and subtracting this from measurements with the sample in place.

Simulation

As stated above the first phase to be completed is the simulation of the experiment to test the feasibility of the experiment. It will also serve as a validation of the next two experimental phases. In the simulation the wavelength of light assumed is 633 nm and the beam is modeled to have the same power (1.9 mW) and Gaussian beam waist as the experimental beam. Shown below in equation 1 the function used to model the light incident on the part.

\[
f(x, y) = A \times e^{\left[-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma_x^2 + 2\sigma_y^2}\right]}\]

(1)

Where A is the electric field amplitude, \(x_0\) and \(y_0\) are the center of the Gaussian beam, and \(\sigma_x\) and \(\sigma_y\) are the spreads of the blob, and \(\sigma_x = \sigma_y = 7.97 \text{ mm}\). The beam was modeled to be 3 cm in diameter so
x and y went from -1.5 to 1.5 cm with the beam centered at zero. All points outside of this radius were set to zero. The modeled beam was then sent through a phase map randomly applying phase due to optical path difference from surface roughness of the part. The spatial frequency qualities of the surface roughness were not taken into account. Figure 4 below shows the input Gaussian beam after the phase map was imparted.

![Figure 4: Gaussian beam profile after phase map is imparted. The beam is 3 cm in extent in x and y dimensions. The total power is 1.9 mW. The beam is cut off outside of a radius of 3. This keeps the beam’s circular profile instead of creating a square one.](image)

After the beam was modified by the sample it was focused down by assuming a perfect positive lens with a focal length of 100 mm (matching the experimental set up focal length). The Fraunhofer pattern of the focused beam was found at the focal plane. Irradiance was then derived from the electric field at the focal/Fourier plane. This field was then filtered removing the central maximum. Shown below in Figure 5 is the filtered and unfiltered irradiance distribution at the focal plane.

![Figure 5: Irradiance at the Fourier plane filtered (right) and unfiltered (left). A circular mask of ~300 microns was applied to remove the main portion of the central peak. Notice the large difference in the scale of the two plots. Units of intensity are arbitrary (vertical axis).](image)
After the intensity was taken 1D lineouts were taken from the center and plotted in linear and logarithmic scales as seen below in Figure 6.

![Figure 6: 1D lineout of the Fourier plane irradiance plotted on linear and logarithmic scales. Notice how the central peak has been removed. This makes the signal in the wings (random variations in overall slope) due to the random phase variations of the sample more apparent.]

The above example is done with an RMS surface roughness of 20 Å and a DC dot size of ~300 microns (the largest size tested) to accentuate the noise in the plots. However, the actual parts are made with an RMS surface roughness of between 3 – 10 Å. The overall intensity of the filtered focal plane was summed up across the RMS surface roughness range of 0 – 10 Å RMS for different DC dot sizes (300 – 65 microns). The simulation showed that with increasing surface roughness the signal in the wings of the Fourier transform increased. Additionally with decreasing DC dot sizes, 300 to 65 microns, the change in irradiance from 0 to 10 Å RMS decreases from 18% to 5%, respectively. This means that with a smaller DC dot the differentiation between grades will be increasingly fine. The difference between 5 and 8 Å RMS specifically, the threshold between LG and SG, drops from 8.5% to 2% for filter sizes of 300 microns and 65 microns, respectively. Therefore if a DC dot were to be implemented its size should be on the order of 300 microns or larger. However, if the filter becomes too large the signal could become too small for detection. Since the simulation assumes a perfect lens, aberrations were not be taken into account. As such, the aberrations will increase the size of the PSF and the central “blob” will increase in size. An aperture should be chosen to account for this. Therefore whatever size is determined to be “large enough” by the simulation will be increased in size for actual experimentation, it has not been researched how much bigger said DC dot should be. In the end, a knife edge was chosen to be used over a DC dot. Finally, and most importantly, the simulation does not take into account the scattering from the lenses and other surfaces in the system. This is potentially very problematic since the surface roughness of the lenses is around 150 nm PV. This is 3 orders of magnitude larger than the surface roughness of our samples. It is unrealistic to get lenses made with surface quality similar to the surface quality of the samples under test. It has been suggested that getting around this by using a mirror to focus could help get around this. However, it was not implemented in this project.

**Transmission Modes:**

In the transmission mode experiment light is sent through a spatial filter, expanded and collimated, and sent through the part under test (object). The detector will be placed at the focal plane with a knife edge
blocking out the central point of the focus. This ensures that the detector will not sample the central point’s (DC) signal. This signal is far larger (many orders of magnitude, ~6 orders of magnitude) than the signal associated with the scattered light in the edges of the Fourier pattern. Controlling the DC part of the Fourier signal will be a paramount priority in this set up. Shown below in Figure 7 is the first order design of the first transmission set up. Data was taken both with and without the knife edge (referred to as the spatial filter) in the system. This accounts for two of the four configurations that yielded results.

A knife edge was used to block out the central point. In this configuration the knife edge was not acting as a spatial filter as it was not at the Fourier plane. When the knife edge was not present ND filters were introduced into the system before the first spatial filter to attenuate the laser as to not saturate the detector (this was after already lowering the detector’s exposure time to its lowest value). Note, do not confuse the spatial filter before the object under test with the knife edge. At first the detector was in place such that the focus spot of the lens was in the center of the imaging plane. When the knife edge cut out the central maximum the scattering signal was seen at one edge of the image. Data was taken in this configuration and then the detector was moved such that the light on the edge filled the detector and data was again taken in this sub configuration (i.e. the detector was moved to the side). There were two configurations (with and without the spatial filter) with the spatial filter configuration having two sub configurations with the detector in two different positions. Upon taking data in the above configuration it was seen that the system was not resolving the features in the Fourier plane. The pixels in the camera are 4.5 micron squares and the diffraction limited spot size was approximately 5 microns. As such, it was magnified 4x using a 100 mm focal length lens to resolve the central maximum and the scattering signal around it. The configuration can be seen below in Figure 8. Data was taken with and without the knife edge (now acting as a true spatial filter) in the system. The knife edge blocked out half of the wings of the Fourier transform along with the central maximum (DC signal).
Without the spatial filter present an ND filter was used to cut back the amount of light so the detector was not saturated. This ND filter was placed before the first spatial filter, therefore it did not induce scatter into the system as the first spatial filter cleaned the beam up. Camera exposure times were between 33 ms and 1 s for all data taken. The intensity of the laser was increased when the spatial filter was in place (by removing ND filters) because the central maximum was not saturating the detector and signal around it became more visible in doing so. The detector used was an Imaging Source DMK 31BF03 used with ASTRO II software (CCD).

**Brewster’s Angle Mode**

The final phase of the Fourier process was to perform the same testing done in the transmission mode but in reflection off of the first surface of the sample at Brewster’s angle. This would minimize specular reflection off of the part and in turn minimize the DC signal and increase the contrast between the signal and the other light not due to surface defects. Shown below in Figure 9 is the first order set up.

![Figure 9](image.png)

**Figure 9:** Experimental set up of the Brewster’s Angle set up. Reflected beam will have a far lower intensity compared to that of the transmitted beam. A polarizer will be inserted after the collimating lens to make the light P-polarized so the specular beam will mostly transmit through the sample.

For this method to work the incident beam must be uniformly polarized as P-polarized light. This will ensure that across the entire beam the light will behave the same way. When the part was inserted in this configuration interference was seen across the reflected beam from the back surface. As such the back side was nulled out with Pre-Cote #33 Blue. However the scattering off of the back surface was far greater than the signal off of the first surface. Therefore this method was not viable for testing and data was not taken in this configuration.

**Transmission Mode Results:**

All normalized images used in processing, histograms, and tables quantifying results are located in the appendix at the end of this report. There were four different configurations that were used to acquire data with one configuration having two slightly different sub-configurations. All were in transmission. They
are no spatial filter with no magnification (no SF no Mag, appendix section 2.1), spatial filter with no magnification (SF no Mag, appendix section 2.3), no spatial filter with magnification (no SF Mag, appendix section 2.2), and spatial filter with magnification (SF Mag, appendix section 2.4). SF no Mag is the configuration that, as mentioned above, the detector was moved to the side after initial runs of data showing that the signal was not filling the detector. Appendix section 2.3.1 contains configuration 1 (detector not moved) and 2.3.2 contains configuration 2 (detector moved).

**Note:** It was found after data was taken (without more time to repeat experiments) that the customer mixed up the samples set aside for our testing and the parts were not the same grades the team was told they would be. The samples were all standard grade located in the region of 8 – 12 Å RMS. Trends in the data differentiating LG and SG labeled data as delivered from the customer were not found. However, after finding out the samples were not what was expected it was seen if there were some label-independent trends in the data (looking at any correlations with two distinct groups of parts regardless of their label as LG or SG). In the Fourier results this did not make a difference as the numbers were not consistent from run to run even with same parts due to system variation (laser power/beam stability). It is likely that if there were a trend, this method would not be sensitive enough to find it.

The processing done was the same for all configurations with the exception of SF no Mag sub configuration 1 (detector not moved to the side).

**Main Processing Method:**

For each part three frames were taken in succession. For each run three “dark” frames were taken. The dark frames are taken when no part is in the system but the laser is still on. Therefore the dark measurements are nearly identical to the frames with the parts in the system. In the post processing the three frames for each part and the dark measurements are averaged pixel by pixel and then normalized between 0 and 1. The averaged and normalized dark measurement is then subtracted from each averaged and normalized frame. Aside from just looking at the images to see if there is a difference between parts two things were done to quantify the results from the pictures. The image pixel values were remapped between 0 and 255 and then plotted in histograms and the total intensity was summed up. The total intensity sum was called the overall intensity sum in appendix section 1.0. Getting this number for each image involved summing up each pixel value into one number. Upon looking at the histograms it was seen that the most active region for differences from frame to frame were the pixel values of 15-50. These were what was summed up to give values for each part called the histogram sum in the appendix section 1.0.

**Secondary Processing Method:**

In configuration 1 of SF no Mag the scattering signal around the knife edge was not always located in the same spot on the detector and filled the detector by varying amounts. As such, it was thought that looking at the density of the signal in the images would provide insight into distinguishing parts. Peak density was the route chosen. The images were gathered in the same manner as the main processing method with averaging, normalizing, and dark subtraction. A peak detection algorithm was then applied to the images effectively converting them into binary images. Peaks had a value of one and everything else had a value of zero. The normalized data and peak detection data is located in appendix section 2.3.1. The user then
drew selection boxes around the points in the peak detection images where the signal was located. The number of peaks in these selections was then summed up and divided by the size of the user defined selection. This was done a total of 10 times per part and the values were then averaged to give one final number. This number for each part was called the peak density in appendix section 1.0 for configuration 1 of SF no Mag.

No SF no Mag (raw data/histograms, appendix 2.1):

When looking at tables A1 and A2 for No SF no Mag it was seen that run one LG and run two SG parts have similar values, which means that the system variation, rather than variation due to the parts drove the values for both the overall intensity sum and histogram sum in this configuration. This configuration did not distinguish parts labeled SG and LG and also did not show any trend between parts independent of their label.

No SF Mag (raw data/histograms, appendix 2.2):

In this configuration the airy disk pattern of the focus was visible in the raw data. When looking at tables A3 and A4 trends between customer labeled LG and SG were not seen. Additionally trends independent of labels were not seen. Variation from run to run seemed to be the dominating factor in this configuration. No trend was seen differentiating certain parts from others. Therefore, this configuration did not differentiate parts.

SF no Mag (raw data/histograms, appendix 2.3):

Configuration 1 (raw data/histograms, appendix 2.3.1):

In table A5 from runs one and two it was seen that there was an apparent trend differentiating LG and SG parts (only two parts for each grade were available at the time of testing). When more parts were available it was tested again in run 3 however the trend seemed to reverse itself. No trend was seen differentiating LG and SG parts or parts independent of their “LG” or “SG” labels as runs one and two did not agree with run 3. This configuration did not differentiate parts from one another.

Configuration 2 (raw data/histograms, appendix 2.3.2):

In tables A6 and A7 there is almost an apparent trend differentiating customer defined LG and SG parts, however LG 13 and SG 5 overlap the two regions. The LG and SG labeled samples are not separable from one another statistically as their averages with their respective standard deviation regions overlap in both histogram sum and overall intensity. Comparing these two groups together although they are both SG samples is meaningful because they were cored from different samples and if a difference were seen in SG samples it could be concluded that LG samples would be able to be differentiated by this set up. The numbers for both the histogram sum and the overall intensity from run to run were more repeatable than many other configurations. Although, there was still large variation in some of the parts from run to run such as SG 4. The system was more stable in this configuration than other configurations, much like the SF Mag section below. This was by far the closest to differentiating groups of parts. It may be possible to differentiate parts with this set up if we were comparing SG and LG parts. However, this set up did not definitively prove to differentiate samples.

SF Mag (raw data/histograms, appendix 2.4):
In tables A8 and A9 there is no apparent distinction between the customer-labeled SG and LG. However, like configuration 2 of SF no Mag, directly above, there is a better degree of repeatability in the measurements. There are no label independent distinctions between parts as most of the values for the histogram sum and overall intensity hover around the same values. It seems that the system overall was more stable in this configuration but gave no indication as to the grade of the parts.

**Conclusion:**

While the Fourier system seemed to have promise in the simulation, in practice the various configurations tried ultimately fell short. However, the SF No Mag configuration 2 set up showed some promise. System changes such as laser stability seemed to dominate the results. There is a possibility that differentiations of parts could be found had we had the actual LG parts for testing, however it is more likely that the scatterometric system would have a better chance discerning these parts. Ultimately any system that would differentiate the samples would have to have less variation itself than the variation imparted upon the light by the parts. This system did not achieve that and therefore this method was not successful in differentiating the samples. If this method were to be implemented further one would have to have higher tolerances on the system to make it more temporally stable. Additionally a shorter wavelength should be used to increase the scattering from the object. A higher quality off axis parabola mirror could be used to focus down the light because its surface quality would be higher than that of a commercial off the shelf lens. Lastly, an active compensation loop with active laser power monitoring connected to an AOM to direct the same power to the sample at all times could be helpful in gaining more power stability if needed. Ultimately, higher precision would be needed to continue on with this method. However, it has been shown that initial testing does not yield a positive result and that a more complicated system would be the only route forward with this attempt.

**GPI**

**Test Set-up**

The GPI was used with a standard 4” flat reference element. Because of the geometry of the part a blue Pre-Cote film was placed on the back surface that was not under test in reflection mode. This film, which is used in industry, comes off easily and does not harm the surface. The 1” thick parts with a 2” diameter was mounted using a standard spider mount as seen in figure 10a. For larger parts, such as the 200mm wafers with 1mm thickness, a special mount was made for use with the spider mount. To reduce the amount of stress induced with the mounting of the 200mm wafer the part was attached to the mounting plate by use of double sided tap, as seen in figure 11b. The surface of the part was not harmed by the tap as the tap was in contact with the blue Pre-Cote film.
Results from tests on 2" diameter parts

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Table 1: Standard Grade results for 10 averages for all samples.

As seen in Table 1 for all but one of the standard grade parts the RMS recorded is larger than the laser grade samples by at least 16Å. The highest Laser Grade RMS recorded is 54.985Å therefore from our results it is fair to say that for any part measured with a RMS larger than 60Å is considered Standard Grade.
There is one Standard Grade sample that recorded results dangerously close to the largest Laser Grade values. The smallest value of that part (55.213) was 0.22Å larger than the largest Laser Grade value (54.985). After measuring these parts on the NewView we saw that part 3 (the SG sample with small RMS) had a roughness of 6.188Å which is in-between the ranges for SG and LG (3-5Å for LG and 8-10Å for SG).

![RMS Averages for 2" parts](image)

**Figure 11:** Graph of all the average measurement values of LG in ascending order and all but part 3’s SG measurement values in descending order

Figure 11 is a compilation of all the average measurement values for all but one part. This includes all 5 average measurement values that were recorded for each 2” thick sample. This graph shows results for 7 standard grade samples and 8 laser grade samples. The data for Laser Grade parts were arranged in ascending order. The data for Standard Grade parts were arranged in descending order. This graph does not include the data from Part 3 side 2.
Figure 12 is a compilation of all the average measurement values. This includes all 5 average measurement values that were recorded for each 2” thick sample. This graph shows results for 8 standard grade samples and 8 laser grade samples. The data for Laser Grade parts were arranged in ascending order. The data for Standard Grade parts were arranged in descending order. On this graph it appears that the two lines intersect there is actually a 0.223 separation.

Additional Findings

After taking a single batch measurement for both a laser grade and standard grade of a 1mm thickness it was determined that the thickness of the part causes the value of the RMS due to form to differ. Therefore real parts will need to be measured to determine an appropriate threshold.

An attempt at testing real size parts of 1mm thickness was made. These parts consisted of 200mm diameter wafers, small pentangles, and small rectangle (as described by customer). Due to the size and thickness of these parts they were unable to be measured with the horizontally mounted 4” GPI that was at our disposal. This was because of the thickness of the parts and the way they had to be mounted. Due to horizontal mounting of the parts a large amount of stress was induced causing the GPI to give a false reading. Nulling out is a process of reducing the number of fringes measured to one, and is the standard operating procedure for use of the GPI. With our GPI the larger parts were unable to be nulled out, which also caused for unreliable measurement. Due to this set-back further testing of this method was unable to be done. We recommend a vertically mounted GPI if further testing of this method is to be done at a later time.
Figure 13: Figure xxa shows the 3D plot of the surface form for the 2” diameter part. Figure xxb shows the 3D plot of surface form for the 200mm wafer.

Scatterometry

Theoretical Background:
The scatterometric setup provides an angular intensity distribution of a test surface. Theoretically, the intensity detected would reach maximum at 0° angle of detection, then the intensity would rapidly drop down to scale of pW which consists mostly of Rayleigh scattering light at larger angle of detection. Higher surface roughness level of the test surface should deliver higher scattering intensity at larger angle of detection than smoother surface.

General Experimental Setup:
The experiment consists of two modes: transmission mode and reflection mode (Figure 14). Attenuator on the power meter was taken off, thus the sensitivity increases to pW for all measurements. Samples used were 2” diameter and 1 mm thick fused silica flats with same grade of roughness on both sides. Sample was set inside a ring mount on a rotary table with adjustable tilt angle. For the most accurate result, stray light was minimized by turning off all room illumination and covering all reflective mounting surfaces with black tape.

Figure 14: Experimental setup for scatterometry: transmission mode (left) and reflection mode (right). The power meter mounted on the goniometer rotates around the origin to scan over desired angular range. Under transmission mode (left), the sample lays horizontally. Under reflection mode, the sample makes an angle of θ with horizontal plane. Two mirrors ensure the beam path is vertically entering the power meter.

Transmission Mode:
In the transmission mode setup (Figure 14, left), the incoming laser beam enters the system horizontally. Then the laser is reflected by a mirror at 45° and hits the power meter vertically at 0°. The sample is mounted horizontally between the mirror and the power meter. A 632.8 nm 5 mW laser is used as light source, and a 150 µm diameter pinhole is attached to the detector head. Measurement averaging over one second is taken for every 0.125° over the entire 180° angular range. Average time for scanning one surface for full angular range is 50 minutes.

![Intensity vs. Angle of Detection Transmission](image)

**Figure 15:** Intensity vs. angle in log scale. Red lines represent standard grade samples and blue lines represent laser grade samples. Blank data points indicate zero signal detected. No clear distinction between the two grades is shown.

**Analysis**

The angular intensity plot (Figure 15) shows no significant difference between standard grade and laser grade samples. Many readings were plain zeros, which indicate that the signal was too low for the power meter to respond at certain locations. This was most likely due to the fact that the pinhole was covering much of the detector. The reflection mode was then set up without the pinhole to allow more light to pass through.

**Reflection Mode (Brewster’s Angle):**

In the reflection setup (Figure 14, right), the incoming beam is reflected first by mirror 1 at 45°, then reflected by mirror 2 at θ_b, and again reflected by the front surface of the sample at θ_b, finally enters the power meter vertically. Since too much power was cut down in the previous experiment (transmission mode), the pinhole on detector was replaced by a roughly 5 mm diameter iris to let the entire beam diameter to pass through. Two sources were tried: a 632.8 nm 5 mW laser and a 405 nm 4 mW laser.
Measurement averaging over one second was taken for every $1^\circ$ over the entire $180^\circ$ angular range to decrease scan time. Average time for scanning one surface for full angular range was 6 minutes.

**Figure 16:** Intensity vs. angle in log scale with 632.8 nm laser as source. Red lines represent standard grade samples and blue lines represent laser grade samples. No apparent distinction between the two grades is shown.

**Figure 17:** Intensity vs. angle in log scale with 405 nm laser as source. Red lines represent standard grade samples and blue lines represent laser grade samples. There is a weak trend that is illustrated as the laser grade samples mostly seem to have fewer scattering intensity than the standard grade samples.

**Analysis**
The angular intensity distribution from 632.8 nm laser (Figure 16) demonstrates no clear distinction between standard grade and laser grade. This method did not yield a distinguishing result between grades.

However, the angular intensity distribution from 405 nm laser (Figure 17) does display a weak tendency as the standard grade samples seem to scatter more light than the laser grade ones. If the average scattering intensity is calculated from all ten surfaces of the same grade, there is a clear difference of average angular scattering intensity between standard grade samples and laser grade samples from about -60° to -10° and from +10° to +60° (Fig.14). If the total intensity received is integrated over from -50° to -20° and from +20° to +50°, there is also a 15 nW separation of average integrated power between standard grade and laser grade samples (Fig.15).

![Average intensity vs. angle in log scale with error bars using 405 nm laser](image)

**Figure 18:** Average intensity vs. angle in log scale with error bars using 405 nm laser. Red lines represent standard grade samples and blue lines represent laser grade samples. Each data point is an average of ten scattering intensity at the same angle. Error bars were calculated as standard deviation divided by square root of ten. There is a clear distinction between standard grade and laser grade averages from about -60° to -10° and from +10° to +60°.


**Figure 19:** Average integrated intensity of each grade from -50° to -20° and from +20° to +50° with error bars. The average is calculated from averaging integrated intensities from individual surface of the same grade. There is about 15 nW distinguishing between the averages of the two grades.

**Note:** All the above "standard grade" and "laser grade" samples mentioned in the scatterometry section are actually "standard grade" samples with surface RMS roughness value ranging from 8 – 12 Å RMS, when tested under NewView interferometer. Customer did not supply actual laser grade samples in 1 mm thickness. The “laser grade” samples currently used have RMS roughness ranging from 7.9 to 9.5 Å, about 2.7 Å better than the “standard grade” samples with RMS roughness ranging from 9.2 to 12.7 Å. However, there is still a loose correlation between the actual surface RMS roughness and the integrated scattering intensity from ±50° to ±20° (Fig. 16). Rougher surface tends to scatter more overall.

**Figure 20:** Correlation between integrated intensity and surface RMS roughness of each individual surface. Integrated intensity is from -50° to -20° and from +20° to +50°. The surface RMS roughness was measured using NewView white light interferometer. There is a loose connection between them as the rougher surface produces more overall scattering intensity.

**Risk Assessment**

**Fourier Analysis**

The most concerning risk is the surface quality difference in the samples and in the lenses being used in the set up. The surface quality of COTS lenses will not be as good as the surface finish of the samples under test.

**GPI Description**

One risk to the experiment is that when testing parts that are in-between the two ranges (3-5A for LG and 8-10A for SG) the part becomes hard to qualify as a specific grade. There is very minimal risk to the part
in this method. The main risk is the stress induced by mounting these thin 1mm parts. This risk can be mitigated with a vertically mounted GPI. There is a blue pre-coat that is put on the back surface. In theory this could cause scratching. However, this is frequently used in industry and these same parts often go through this same process later on. Therefore, there is no additional risk to the part. This process just involves a laser and cleaning chemicals as well as the pre-coat. The laser is relatively self-contained in the Zygo Verifire. However, proper laser safety and chemical handling procedures should be taken. Laser googles are not needed.

**Scatterometry**

There are several possible risks with the scatterometric method. One of these risks is the overall sensitivity of the system. Rayleigh scattering is inversely proportional to the fourth power of wavelength, thus shorter wavelength should deliver stronger scattering power. The wavelength for visible (400~700 nm) might still be too long compared to the size of surface features on the order of 3-10 Å. This could cause extremely low signal and the signal due to roughness may be covered up by stray light or systematic noise. In addition, the thickness of sample might affect the intensity received by the detector. Besides, the current setup is not capable of measuring larger or thicker samples, because the mechanics might damage the sample. Either a longer arm for goniometer or a smaller angular range is required to achieve measurement for large sample, but both methods could lead to lower or fewer signal received. This current setup is very sensitive to alignment, therefore a more stable system is preferred.

**Conclusion and Further Recommendations**

**Final Discussion**

The most successful and realistic method for testing these parts was the scatterometry method followed by the GPI method. The Fourier method would need major changes to be made before it could become a viable option for testing. In the end, the 2.6 Å RMS average difference between the two SG groups given to us was seen by the scatterometry method. This is just under the size of the gap between LG and SG samples. The weak correlation between the NewView RMS measurements and the scatterometric data looks promising. In future testing a more powerful laser with shorter wavelength, testing the correct parts, and setting up the system so that it can accept larger parts should be done to definitively prove this concept. It is strongly suspected that if observation of slight differences in SG parts was possible with this set up that the threshold between LG and SG would also be observable especially when done with an improved design. The current method scans over a full 180° (±90°) around the incoming beam path and takes around 6 minutes to characterize one side of the part. However, in the future this method could be sped up by decreasing angular resolution and only looking over a smaller range (such as ±20° to ±40°). This will significantly speed up the scanning per side. The system will have to be redesigned if it is to scan over larger parts up to ±90° range to avoid crashing into them (this means having a longer goniometer arm, etc.). However, if only the angles of ±20° to ±40° are used this may not have to be done. Finally, the system will need to have a significant mechanical redesign to improve the speed and accuracy of inserting samples into the system to maintain alignment.
The GPI set up also showed a correlation between surface form and surface roughness. However, lack of parts for scaled up testing and difficulty mounting them in our system did not allow the team to definitively prove or disprove the merits of the scaled up system. In the future, if this method were to be attempted for further testing, vertical mounting of a GPI to test full sized parts should be done. It is important to note that this measurement is not a direct measurement of surface roughness, it is a correlation between surface form and surface (nano) roughness. The basic assumption is that parts with a smaller surface roughness are polished longer and therefore also have a better overall surface form. This assumption has not been definitively proven due to lack of parts and figure instability in our current set up. However it has been shown that there are merits to this system.

In the Fourier set up it was shown that there was no correlation between the grades of parts and the signal seen in a variety of configurations. This set up was theoretically similar to the scatterometry set up with an extra lens inserted between the part and the stationary detector. There was lack of consistency seen in the measurements even for the same parts from run to run. Long term and short term drift in laser power were ultimately responsible for the lack of consistency in these results. A more stable laser along with real time compensation for laser power fluctuations could solve this issue. While the other two methods have some merits, it is our recommendation to the customer and/or those who will attempt this project in the future to focus on improving the scatterometry set up and scaling it up for larger parts. The simplicity of the set up along with the absence of optics between the sample surface and the detector means that signal is directly measured from the surface defects.

**Future Work**

It is our recommendation that future work on this project be focused on the scatterometry set up. This method has been proven to show a correlation between surface roughness and scattering power over a distinct angular region. Mechanical redesign of the system for repeatability in an industry setting and creating a user interface to run the system and pass or fail the parts would be likely next steps. In addition, using a shorter wavelength laser for the system will increase scattering, and hopefully distinction between samples. The GPI set up is a viable alternative as this method, if proven to be correct, could be implemented on instruments the customer already has. The Fourier set up is not recommended for future work as the scatterometry method has been shown to have more merits and is measuring the same phenomena in a different manner (without optics between the part and the surface under test).
Appendix

Fourier Data

1.0 Quantified Results

No Spatial Filter, No Magnification:

NOTE: All comparisons made in appendix sections 1.0 and 2.0 in captions compare parts labeled by the customer as LG and SG. Comparisons and/or trends in data other than comparing LG and SG labeled parts are not commented on here. These comments are located in the “Transmission Results” section of the Fourier experimental/discussion section.

Histogram Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
<th>SG6</th>
<th>SG7</th>
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<tr>
<td>Run 2</td>
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<td>81</td>
<td>22</td>
<td>40</td>
<td>49</td>
<td>336</td>
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</tbody>
</table>

Table A1: Histogram sum of no SF No Mag for each part. Units are in counts. Summing up the values of the histogram counts from values of 15 to values of 50 (the number of pixels that contain the values of 15-50). There is no trend between run 1 and run 2. It also seems that there is an overarching variation in the system that causes the values of the histogram sum to vary with no dependence upon grade. Additionally there is no repeatability from run to run for the same parts. This could be due to system variation rather than variation from the parts themselves.

Overall Intensity Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
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<td>6351</td>
<td>9401</td>
<td>10461</td>
<td>17736</td>
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</tbody>
</table>

Table A2: Overall intensity sum of SF No Mag for each part. This was done by summing up all pixels in the image and getting an overall intensity in pixel counts. Pixel values varied from 0-255. There is no trend to discern LG from SG as there is no region of values in which only SG or only LG parts fall. Additionally there is no repeatability from run to run for the same parts. This could be due to system variation rather than variation from the parts themselves.
No Spatial Filter, Magnification:

### Histogram Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
<th>SG6</th>
<th>SG7</th>
<th>SG8</th>
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</thead>
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<tr>
<td>Run 2</td>
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<td>6128</td>
<td>4715</td>
<td>4199</td>
<td>3421</td>
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</table>

Table A3: Histogram sum of no SF Mag for each part. Units are in counts. Summing up the values of the histogram counts from values of 15 to 50 (the number of pixels that contain the values of 15-50). There is no trend to discern LG from SG as there is no region of values in which only SG or only LG parts fall. Additionally there is no repeatability from run to run for the same parts. This could be due to system variation rather than variation from the parts themselves.

### Overall Intensity Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
<th>SG6</th>
<th>SG7</th>
<th>SG8</th>
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</table>

Table A4: Overall intensity sum of no SF and Mag for each part. This was done by summing up all pixels in the image and getting an overall intensity in pixel counts. Pixel values varied from 0-255. There is no trend to discern LG from SG. Additionally there is no repeatability from run to run for the same parts. This could be due to system variation rather than variation from the parts themselves.

Spatial Filter, No Magnification:

Configuration 1:

### Peak Density:

<table>
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<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
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<th>SG5</th>
<th>SG6</th>
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<tbody>
<tr>
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<td>0.001064</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Run 2</td>
<td>N/A</td>
<td>N/A</td>
<td>0.03682</td>
<td>0.02724</td>
<td>N/A</td>
<td>0.01742</td>
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<td>N/A</td>
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<tr>
<td>Run 3</td>
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<td>0.1017</td>
<td>0.0943</td>
<td>0.0813</td>
<td>0.1164</td>
<td>0.0561</td>
</tr>
</tbody>
</table>

Table A5: Peak density in the Fourier plane from user defined selections. Data taken with SF and no Mag. This set of data was the first set to be taken and due to the inconsistency in the location of the scattering pattern the user had to select specific regions to count peaks. The number of peaks was then divided by the area of the selection and averaged for 10 selections/frame (each number in the table is an average of 10 selections). Units are in peaks/pixel. There was an apparent trend for run 1 and 2. Run 3 was taken to verify this trend, however, the trend was not upheld and there is no correlation in this configuration/method between the values and LG and SG parts. This could be due to system variations similar to the ones that plagued the other configurations.
Configuration 2:

Histogram Sum:

<table>
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<tr>
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<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
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<td><strong>122030</strong></td>
<td>147745</td>
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</table>

Table A6: Histogram sum of SF no Mag for each part. Units are in counts. Summing up the values of the histogram counts from values of 15 to values of 50 (the number of pixels that contain the values of 15-50). There is no trend between the sum and the grade of the parts as there is no numerical region in which only SG or LG parts lie. SG 5 and LG 13 overlap the two regions. However, this configuration had the most repeatability between runs and was the closest to differentiating parts as a result.

Overall Intensity Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
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<td>7046816</td>
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<td>7164030</td>
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</table>

Table A7: Overall intensity sum of SF no Mag for each part. This was done by summing up all pixels in the image and getting an overall intensity in pixel counts. Pixel values varied from 0-255. There is no apparent trend between the overall intensity and the grade of the part. SG 5 and LG 13 overlap the two regions in which LG and SG parts lie. However, this configuration had the most repeatability between runs and was the closest to differentiating parts as a result.

Spatial Filter, Magnification:

Histogram Sum:

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
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<td>244307</td>
<td>190250</td>
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</tr>
<tr>
<td>Run 2</td>
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<td>212164</td>
<td>219858</td>
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Table A8: Histogram sum of SF Mag configuration for each part. Units are in counts. Summing up the values of the histogram counts from values of 15 to values of 50 (the number of pixels that contain the values...
of 15-50). There is no trend to discern SG from LG as there is no numerical region where only SG and LG lie. System variations may be the cause of the variation in the values.

**Overall Intensity Sum:**

<table>
<thead>
<tr>
<th></th>
<th>LG12</th>
<th>LG13</th>
<th>LG14</th>
<th>LG15</th>
<th>LG16</th>
<th>SG4</th>
<th>SG5</th>
<th>SG6</th>
<th>SG7</th>
<th>SG8</th>
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</thead>
<tbody>
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Table A9: Overall intensity sum of SF Mag for each part. This was done by summing up all pixels in the image and getting an overall intensity in pixel counts. Pixel values varied from 0-255. There is no trend between overall intensity for the parts and their different grades. Therefore this method does not work. Variations in the values may be due to variations in the system not related to the parts.
2.0 Raw Data

2.1 No Spatial Filter, No Magnification

Run 1 Histograms:

**Figure A1:** Histogram plot from 10-255 of No SF No Mag SG parts Run 1. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Figure A2: Histogram plot from 10-255 of No SF No Mag LG parts Run 1. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Run 2 Histograms:

Figure A3: Histogram plot from 10-255 of No SF No Mag SG parts Run 2. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Figure A4: Histogram plot from 10-255 of No SF No Mag LG parts Run 2. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Run 1 Processed Pictures:

Figure A5: Processed images (averaged, normalized, dark subtracted) for no SF no Mag for SG run 1. In these images the light pixels are not visible. The central maximum appears around the size of a pixel (4.5 micron pixels). Due to the large difference between the central maximum intensity and the rest of the picture these images appear completely dark.
Figure A6: Processed images (averaged, normalized, dark subtracted) for no SF no Mag for LG run 1. In these images the light pixels are not visible. The central maximum appears around the size of a pixel (4.5 micron pixels). Due to the large difference between the central maximum intensity and the rest of the picture these images appear completely dark.
Run 2 Processed Pictures:

Figure A7: Processed images (averaged, normalized, dark subtracted) for no SF no Mag for SG run 2. In these images the light pixels are not visible. The central maximum appears around the size of a pixel (4.5
micron pixels). Due to the large difference between the central maximum intensity and the rest of the picture these images appear completely dark.

Figure A8: Processed images (averaged, normalized, dark subtracted) for no SF no Mag for LG run 2. In these images the light pixels are not visible. The central maximum appears around the size of a pixel (4.5 micron pixels). Due to the large difference between the central maximum intensity and the rest of the picture these images appear completely dark.
2.2 No Spatial Filter, Magnification

Run 1 Histograms:

![Histogram plots from 10-255 of No SF Mag SG parts run 1. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.](image)

**Figure A9**: Histogram plot from 10-255 of No SF Mag SG parts run 1. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Figure A10: Histogram plot from 10-255 of No SF Mag LG parts run 1. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Run 2 Histograms:

Figure A11: Histogram plot from 10-255 of No SF Mag SG parts run 2. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
**Figure A12:** Histogram plot from 10-255 of No SF Mag LG parts run 2. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Run 3 Histograms:

Figure A13: Histogram plot from 10-255 of No SF Mag SG parts run 3. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Figure A14: Histogram plot from 10-255 of No SF Mag LG parts run 3. Black, and very close to black counts are not plotted so the differences from plot to plot can be seen. The black pixels far outnumber other counts.
Run 1 Processed Pictures:

Figure A15: Processed images (averaged, normalized, dark subtracted) for no SF Mag SG run 1. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
Figure A16: Processed images (averaged, normalized, dark subtracted) for no SF Mag LG run 1. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
Run 2 Processed Pictures:

Figure A17: Processed images (averaged, normalized, dark subtracted) for no SF Mag SG run 2. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
**Figure A18:** Processed images (averaged, normalized, dark subtracted) for no SF Mag LG run 2. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
Run 3 Processed Pictures:

**Figure A19:** Processed images (averaged, normalized, dark subtracted) for no SF Mag SG run 3. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
Figure A20: Processed images (averaged, normalized, dark subtracted) for no SF Mag LG run 3. Central maximum is visible along with its structure. However, scattering around the central maximum is not visible by eye. The images in run 1 had saturation, therefore runs 2 and 3 were done such that there was no saturation in the image.
2.3 Spatial Filter, No Magnification

2.3.1 First Configuration (aligned such that central maximum would be in center of image plane)

Run 1 Processed Pictures:

![Processed images](image1)

**Figure A21:** Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 1 run 1. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Run 2 Processed Pictures:

**Figure A22:** Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 1 run 2. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Run 3 Processed Pictures:

Figure A23: Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 1 SG parts run 3. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Figure A24: Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 1 LG parts run 3. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Run 1 Peak Detection:

**Figure A25:** Peak detection processed images (binary images) for SF no Mag configuration 1 run 1. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Run 2 Peak Detection:

**Figure A26:** Peak detection processed images (binary images) for SF no Mag configuration 1 run 2. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this setup (SF no Mag).
Run 3 Peak Detection:

Figure A27: Peak detection processed images (binary images) for SF no Mag configuration 1 SG parts run 3. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
Figure A28: Peak detection processed images (binary images) for SF no Mag configuration 1 LG parts run 3. Only two SG and LG parts were available during the measuring of the first two runs of data. The third run had all five parts. Variation in the location of the light in this configuration led to the modified processing that was not done with all other configurations. A kinematic mount and adjusted detector position was introduced for configuration two of this set up (SF no Mag).
2.3.2 Second Configuration (detector moved to the side such that scattering fills the image plane)

Run 1 Histogram:

![Histogram plots for SG4 R1, SG5 R1, SG6 R1, SG7 R1, SG8 R1 configurations](image)

**Figure A29:** Histogram plot from 10-255 of SF no Mag SG parts run 1 configuration 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts. Configuration two had a kinematic base mount for the sample implemented for improved repeatability from configuration 1 and moved the detector such that the scattering signal filled the detector better.
Figure A30: Histogram plot from 10-255 of SF no Mag LG parts run 1 configuration 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts. Configuration two had a kinematic base mount for the sample implemented for improved repeatability from configuration 1 and moved the detector such that the scattering signal filled the detector better.
Run 2 Histogram:

**Figure A31:** Histogram plot from 10-255 of SF no Mag SG parts run 2 configuration 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts. Configuration two had a kinematic base mount for the sample implemented for improved repeatability from configuration 1 and moved the detector such that the scattering signal filled the detector better.
Figure A32: Histogram plot from 10-255 of SF no Mag LG parts run 2 configuration 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts. Configuration two had a kinematic base mount for the sample implemented for improved repeatability from configuration 1 and moved the detector such that the scattering signal filled the detector better.
Run 1 Processed Pictures:

Figure A33: Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 2 SG parts run 1. A kinematic mount and adjusted detector position was introduced for this configuration of this set up (SF no Mag). This allowed the standard image analysis process to be used rather than the one used in configuration 1.
Figure A34: Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 2 LG parts run 1. A kinematic mount and adjusted detector position was introduced for this configuration of this set up (SF no Mag). This allowed the standard image analysis process to be used rather than the one used in configuration 1.
Run 2 Processed Pictures:

**Figure A35:** Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 2 SG parts run 2. A kinematic mount and adjusted detector position was introduced for this configuration of this set.
up (SF no Mag). This allowed the standard image analysis process to be used rather than the one used in configuration 1.

**Figure A36:** Processed images (averaged, normalized, dark subtracted) for SF no Mag configuration 2 LG parts run 2. A kinematic mount and adjusted detector position was introduced for this configuration of this setup (SF no Mag). This allowed the standard image analysis process to be used rather than the one used in configuration 1.
2.4 Spatial Filter, Magnification

Run 1 Histograms:

Figure A37: Histogram plot from 10-255 of SF Mag SG parts run 1. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts.
Figure A38: Histogram plot from 10-255 of SF Mag LG parts run 1. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts.
Run 2 Histograms:

**Figure A39:** Histogram plot from 10-255 of SF Mag SG parts run 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts.
Figure A40: Histogram plot from 10-255 of SF Mag LG parts run 2. Black, and very close to black counts are not plotted. The black pixels far outnumber other counts.
Run 1 Processed Pictures:

**Figure A41**: Processed images (averaged, normalized, dark subtracted) for SF Mag SG parts run 1. The scattering pattern filled the detector and individual spots are resolved. This seemed to be the most promising set up because the scatter was directly resolved. However quantification of the results proved this to be wrong.
Figure A42: Processed images (averaged, normalized, dark subtracted) for SF Mag LG parts run 1. The scattering pattern filled the detector and individual spots are resolved. This seemed to be the most promising set up because the scatter was directly resolved. However quantification of the results proved this to be wrong.
Run 2 Processed Pictures:

Figure A43: Processed images (averaged, normalized, dark subtracted) for SF Mag SG parts run 2. The scattering pattern filled the detector and individual spots are resolved. This seemed to be the most promising set up because the scatter was directly resolved. However quantification of the results proved this to be wrong.
Figure A44: Processed images (averaged, normalized, dark subtracted) for SF Mag LG parts run 2. The scattering pattern filled the detector and individual spots are resolved. This seemed to be the most promising set up because the scatter was directly resolved. However quantification of the results proved this to be wrong. Congratulations on making it to the end.
Scatterometry Data

1.0 632.8 nm Laser under Transmission Mode

1.1 Configuration
Measurements were done under transmission mode with no attenuator, 150 μm diameter pinhole, and 5 mW 632.8 nm laser as source. Measurement was taken every 0.125°. Samples were 2” diameter, 1 mm thick fused silica flats.

All data for sections 2.0 and 3.0 can be found at this link http://bit.ly/1GzYaIr

2.0 632.8 nm Laser under Reflection Mode

2.1 Configuration
Measurements were done under Reflection mode with no attenuator, 5 mm diameter iris, and 5 mW 632.8 nm laser as source. Measurement was taken every 1°. Samples were 2” diameter, 1 mm thick fused silica flats.

2.2 Raw Data

2.2.1 Standard Grade
Angular intensity of standard grade sample vs. angle of detection under reflection mode using 632.8 nm laser.

2.2.2 Laser Grade
Angular intensity of laser grade sample vs. angle of detection under reflection mode using 632.8 nm laser.

3.0 405 nm Laser under Reflection Mode

3.1 Configuration
Measurements were done under reflection mode with no attenuator, 5 mm diameter iris, and 4 mW 405 nm laser as source. Measurement was taken every 1°. Samples were 2” diameter, 1 mm thick fused silica flats.

3.2 Raw Data

3.2.1 Standard Grade
Angular intensity of standard grade sample vs. angle of detection under reflection mode using 405 nm laser.
3.2.2 Laser Grade
Angular intensity of laser grade sample vs. angle of detection under reflection mode using 405 nm laser.

4.0 Surface Roughness Measurements
4.1 Configuration
Surface roughness of each surface was measured by NewView white light interferometer. Several locations on the sample were tried to obtain the best measurement. Five measurements were taken for averaging. Samples were 2” diameter, 1 mm thick fused silica flats.

4.2 Raw Data
4.2.1 Standard Grade

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*Table B7: Surface RMS roughness of each standard grade sample. “S” indicates the surface number of the sample.*

4.2.2 Laser Grade

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*Table B8: Surface RMS roughness of each laser grade sample. “S” indicates the surface number of the sample.*