TECH NOTE

Wavefront Testing at Omega Optical

Demanding imaging applications such as microscopy or satellite-based imaging requires optics of the highest quality. One often overlooked specification is that of wavefront error of filters, windows and mirrors in your system. Imperfections in the optics can cause plane waves to become distorted which degrades image quality. Substrate quality, stress in the thin-films, and lamination of multi-component assemblies all contribute to various levels of wavefront distortion. This document summarizes methods for measuring the wavefront distortion caused by optical filters used at Omega.

Figure 1 (below) shows how an incident plane wave can be distorted during transmission through both sides and the interior of the part. For instance, float glass has one side that is flatter. Striae and bubbles within the glass itself can also cause distortions of the wavefront. We call this transmitted wavefront distortion or TWD. Omega uses high-quality borosilicate and fused silica in our products to reduce TWD of the bare substrate.

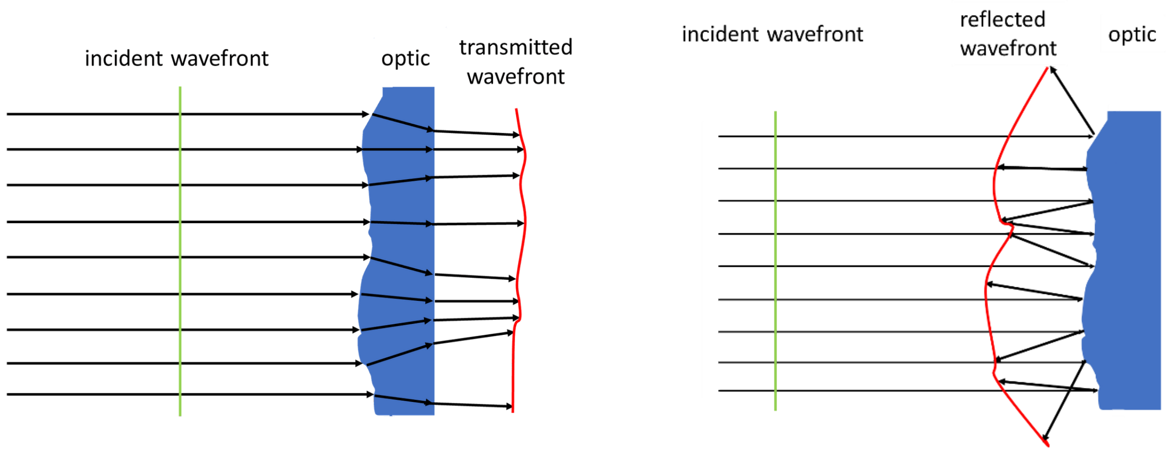

Figure 1 = Transmitted Wavefront Distortion (left) and Reflected Wavefront Distortion (right) for Angle of Incidence (AOI) = 0 degrees. Flatness = RWD / 2 cos (AOI)

Figure 1 (above) shows how an incident plane wave can be distorted during reflection from the incident side of an element. We call this reflected wavefront distortion or RWD. The RWD from a highly-stressed coated optic is always much greater than TWD of the same part. Note that flatness is equal to RWD divided by 2*cosine(AOI).

Specifying Wavefront Distortion

Both TWD and RWD must be specified over a given area. As described below, most of the measurement methods involve measuring a circular area on the part, so the specification should be over some given diameter. Further, it is often specified in “waves” or the number of fringes observed at a certain wavelength (typically 633 nm). This can also be specified as a distance (from flat = 0) by multiplying the “waves” by the wavelength. For example, ¼ waves/inch at 633 nm would be equal to 158 nm per inch diameter.

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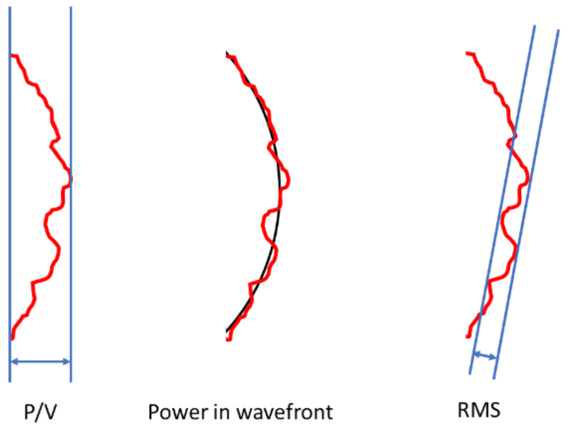

Figure 2. Peak-to-valley (P/V) wavefront error (left), effects of power or spherical aberration in wavefront error (middle) and root-mean-square (RMS) wavefront error (right).

Another parameter that needs to be specified is what part of the wavefront error you would like measured. Peak-to-valley (P/V), as the name suggests (figure 2, left), describes the maximum deflection of the wavefront from planar. Most thin-film filters are stressed in such a way that the P/V wavefront error is dominated by a spherical distortion (power) as illustrated in figure 2, middle. This type of distortion can be reduced in some systems by refocusing the other optics. If this is the case, the customer should specify that spherical aberrations (or power) is removed from the measurement. RMS wavefront distortions refer to aberrations over smaller areas of the part. RMS is always smaller than P/V results. Wavefronts are measured using two basic methods- interferometry and direct wavefront sensing

Interferometry

Interferometry measures wavefront distortion by interfering a plane reference beam with the distorted beam. The Michelson interferometer is a good example. As shown in Figure 2, the Michelson uses a beam splitter to generate two beams. If the two mirrors are both perfectly flat and the two beams are identical, the screen will show a uniformly white or dark field (for constructive or destructive interference respectively). If one mirror is slightly tilted, the screen reveals a series of straight fringes. If one mirror is both tilted and non-flat, the screen reveals curved fringes. When a white light is used as in figure 2, left, the resulting interference pattern shows color separation as you look to the edges of the image. This illustrates why a monochromatic light source is typically used (633 nm).

The right side of figure 3 shows how a Michelson is used in a Fourier transform infrared (FTIR) spectrometer. In this case the mirrors are flat and well aligned, but one mirror is translated back and forth along the optical axis. If the source was a laser, the signal would be a sine wave – ie the interference is now displayed as a function of time rather than as a function of space. The Fourier transform of a sine wave is a single value at one point in frequency space. This corresponds to one wavelength in the spectrum. If the source is broadband, the signal will be a sum of sine waves - each of a different frequency (shown in the “raw signal” panel). The Fourier transform of this sum provides signal as a function of wavelength. The FTIR is used to measure spectra, but is introduced here because the same physics is employed to measure distortion with other interferometers.

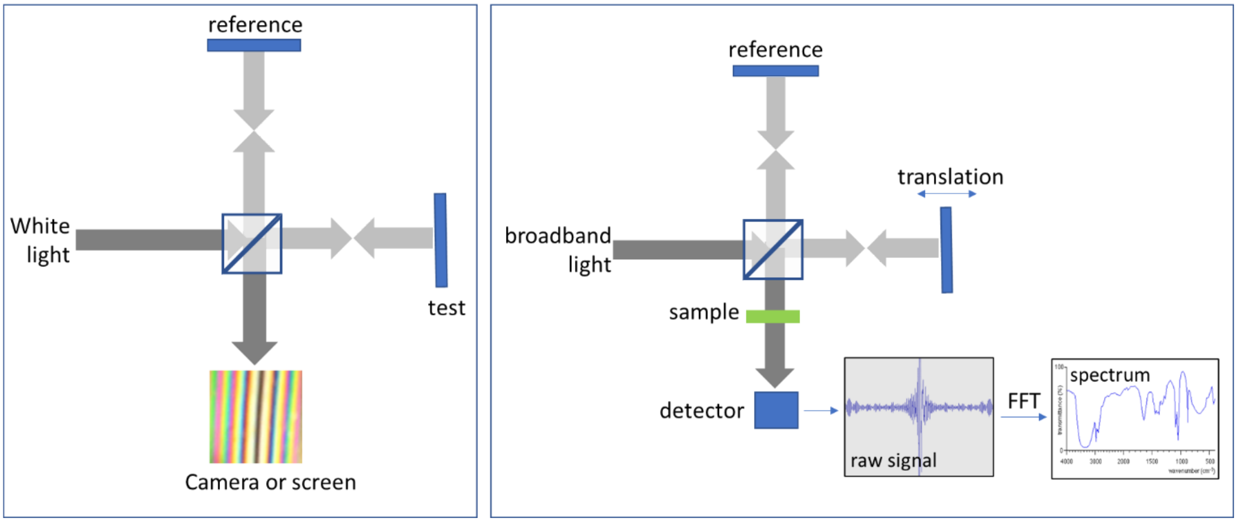

Figure 3 – Michelson Interferometer with Screen (left) and with Detector (right). The Fourier transform of the raw signal on the right results in a spectrum.

Lenses can be added to a Michelson interferometer for testing curved or flat surfaces. This is the Twyman-Green configuration. Figure 4 shows the Twyman-Green for testing flat surfaces. Omega uses a broadband achromatic Twyman-Green with a tunable lamp in the optics shop to test for TWD in bare substrates. The compensation plate is placed in the reference beam such that the sample and reference beams have the same optical path length. The test side of the light passes through the beamsplitter substrate 3 times, while the reference side passes through the compensation plate twice and the beamsplitter once (the mirrored side is on the top of the beamsplitter in this figure). Both sides of the compensation plate and the bottom surface of the beamsplitter are anti-reflected. This system outputs an interferogram and a report.

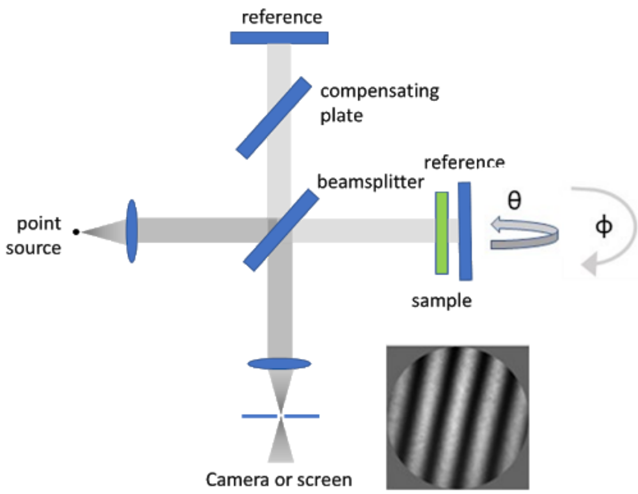

Figure 4 – Twyman-Green Interferometer for Flats

Optical metrology is usually done with a Fizeau interferometer rather than a Michelson. Figure 5 shows two Fizeau arrangements. In this case, the reference and sample beams are co-linear. The beams reflect between the surfaces of the reference and sample object that face each other (black and red surfaces in figure 5, left). The right side of figure 5 shows the design of Omega's Davidson interferometer. The Davidson is currently used manually via direct visual observation for production testing. Omega's Davidson uses the 546 nm line from a mercury discharge lamp.

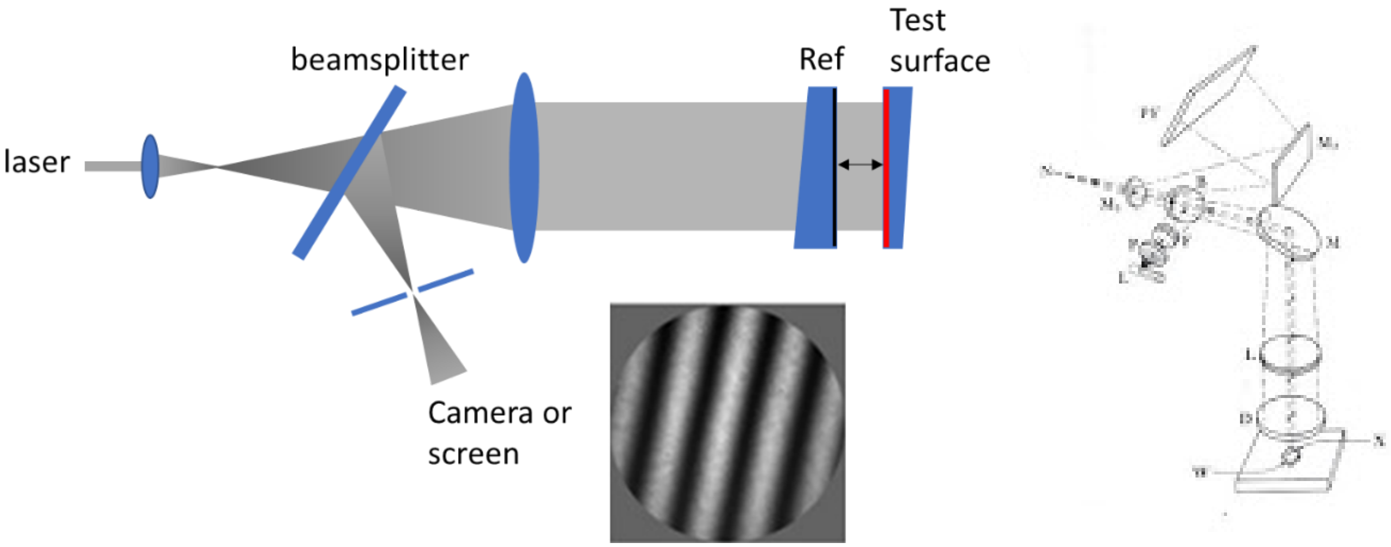

Figure 5 – Fizeau Interferometer with a laser source (left) and a lamp (right, from the Davidson manual)

Figure 6 shows another Fizeau arrangement. The test surface can be a reflector as shown for RWD, or a transmitter followed by a flat mirror for TWD. The reference is shifted along the optical axis – the essence of phase shift interferometry (PSI) as is implemented in Zygo and Wyko systems. These PSI systems usually operate with a 633 nm laser. During PSI, each pixel in the camera observes a sine wave as the reference flat is moved. Fourier transforms of these sine waves enable filtering in frequency space to remove unwanted multiple reflections and to improve fringe visibility. Coated optical parts can make Fizeau interferometry either difficult or impossible, depending on whether the laser wavelength is reflected or transmitted. At 633 nm, a filter must transmit > 10% for TWD (two passes gives 1%), and must reflect > 1% for RWD. This wavelength limitation led Omega to set up a Shack Hartmann wavefront sensor (described below).

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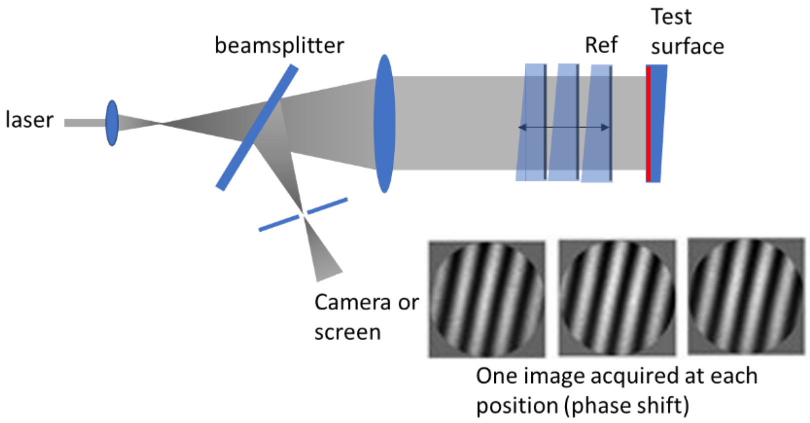

Figure 6 –Fizeau interferometer with shifted reference

Wavefront Sensing

Figures 3-6 all describe interferometers that generate fringe patterns or interferograms. Wavefront distortion is calculated from the fringe patterns. Figure 7 explains how a Shack-Hartmann (SH) sensor measures wavefront distortion. The incoming beam is focused by an array of micro-lenses onto a CCD array. There are many CCD pixels for each lens element. The spot locations are measured both before and after the sample is inserted. Wavefront distortion due to the sample causes the spots to move. The changes in spot locations are used to calculate the number of waves of distortion. Low cost SH sensors are used widely in metrology, astronomy, and the life sciences. Raw data from the SH is the spot pattern shown in figure 7.

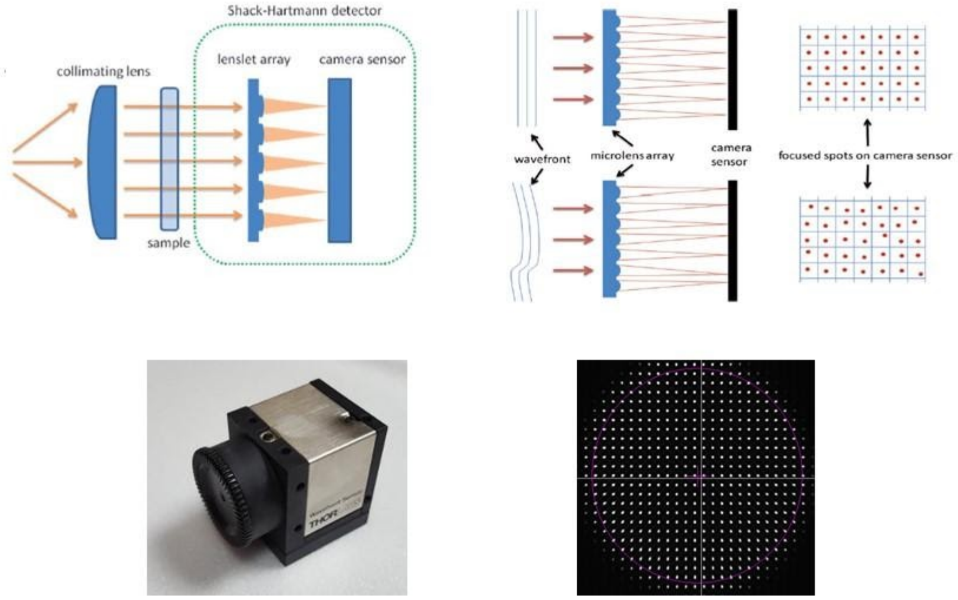

Figure 7– The principle of a Shack-Hartmann (top), the sensor (bottom left)
and the raw spot pattern (bottom right) (from the ThorLabs Shack-Hartmann sensor manual)

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Wavefront Testing at Omega Optical

Omega's SH sensor is integrated with a telescope that expands the beam to 3 inches and it uses filters to select wavelength bands of interest. It is calibrated with known samples for both TWD and RWD. Instead of the familiar interferogram, the output of this software is a wavefront map. Omega uses the Shack Hartmann sensor to measure the majority of its coated parts. An example report is appended to the end of this document (figure 8). The wavefronts are presented with deflection in waves on the z-axis with position in x-y. The Shack-Hartmann can measure wavefront error in the 1/5 wave- 20 wave/in regime. For smaller wavefront errors, Omega sends parts out for Zygo interferometric measurement.

Omega has a range of options for measuring TWD, RWD and flatness of both uncoated and coated glass parts. Uncoated glass is measured primarily with interference-based methods (BAT and Davidson), while coated glass is measured in-house with the Shack-Hartmann or sent out for Zygo measurements.

Date	4/19/2019
Operator	SAL

Test (x)	
TWD	
RWD	x

With defocus? (x)	
yes	x
no	

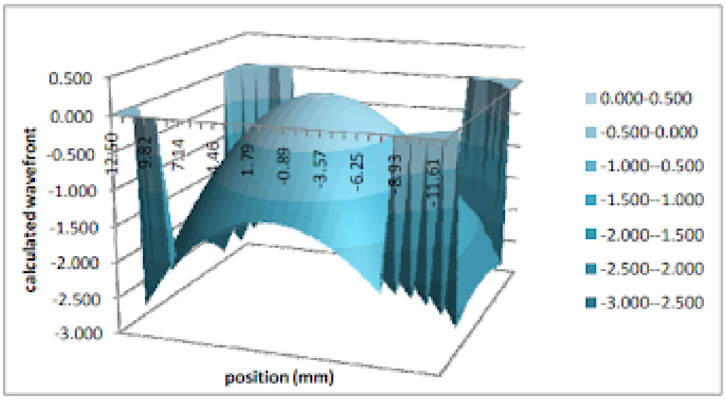
Detector	WFS150-7AR

Aperture (mm)	25
Wavelength (nm)	900

Results

Peak-to-Valley (waves)	2.876
RMS (waves)	0.712

corrected to 633



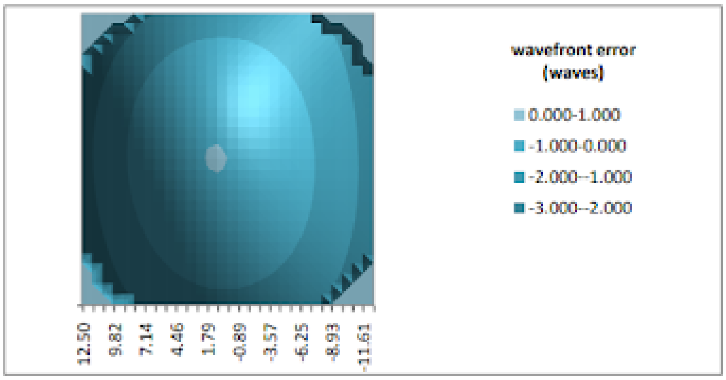


Figure 8. Example report from the Shack-Hartmann sensor

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