

## **ACCURACY EVALUATION OF WHITE LIGHT INTERFEROMETER REFERENCE SIGNAL**

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White light interferometry is a powerful tool for surface profiling over large vertical ranges (up to 8 mm). Using the principle of independently determining the zero optical path difference (OPD) condition for each point within the field of view, the profile of the test surface is determined without the step and slope limitations associated with phase shifting interferometry. The zero OPD condition can be determined with accuracy on the order of a small fraction of the wavelength of light used ( $1/100^{\text{th}}$  to  $1/1000^{\text{th}}$  of wavelength). Various methods of finding the zero OPD position have been implemented to achieve the accuracies mentioned above. These include the use of maximum fringe visibility, zero-phase fringe location, correlation methods, wavelets, and other techniques [1][2]. This method can be implemented on a microscope-based profiler to provide high vertical and lateral resolution. High accuracy and non-contact operation has made these systems widely employed as the metrology tool of choice for such fields as MEMS, semiconductors, data storage, micro-optics, and medical instrumentation.

The way to achieve the zero OPD condition using an interferometric profiler is to scan either the optical profiler or the test surface with respect to the other, until the OPD has been varied over the entire height range of the test piece. When a feature on the test surface is well focused, the location of zero OPD is found by the methods stated above. The accuracy of a profile measurement using any of the zero-OPD determination techniques is therefore highly dependent on knowing the exact behavior of the scan mechanism. Scanners have been calibrated using known steps with heights similar to those of the test objects. The step standards, however, have higher uncertainties than many processes now require. The validity of the step calibration is also subject to change due to wear, friction and other factors, which can reduce the repeatability of the scanner motion. In order to improve the knowledge of the scanner position, to the accuracy required by the most challenging applications, we have recently implemented a HeNe laser distance measurement interferometer (DMI) on an optical profiler. The DMI continuously monitors the scanner location and this information is used to dynamically correct the algorithms involved [3]. This distance measurement information is called 'reference signal for white light interferometry'. Figure 1 shows schematically an optical profiler with a reference signal. In order to evaluate the accuracy of this reference signal, we will analyze the various sources of error and use experiments to find the dominant error on a reference signal prototype. Even with these errors, this prototype profiler with the reference signal shows an order of magnitude improvement in accuracy over those calibrated with the step height method.

As in any distance measurement, environmental effects need to be considered first. The distance measured by the reference signal is the optical path, which is the distance times the refractive index of air. The change of refractive index of air with temperature, pressure and relative humidity are calculated according to a general formula [4]. For

normal lab environments, as temperature is maintained between 24°C to 25°C, pressure from 29.9 to 30 in Hg, and humidity variation within 10%, the change of optical path due to these variations over a distance measurement of 1 mm are: 1 nm, 1 nm and 0.1 nm respectively. This is less than other errors associated with DMI itself.

We will discuss three other sources of error associated with this reference signal: cosine error, Abbe error and the phase fitting or non-linearity error.

Cosine error results from non-parallelism between the reference signal DMI laser beam and the axis of scanner motion. This makes the measured distance shorter than actual as expressed by  $L\cos(\alpha)$ , where  $L$  is the actual distance and  $\alpha$  is the angle between the laser beam and the axis of scanner motion. Since  $\alpha$  is typically very small, the difference between  $L$  and  $L\cos(\alpha)$  can be expressed as  $L\alpha^2/2$ . In the prototype system, the highest contribution to this error is from mechanical tolerance stack-up and it is estimated to be 0.3°. The calculated cosine error for a 1 mm distance measurement is 27 nm. This error can be decreased by more careful control of mechanical tolerances.

Abbe error is a factor in the prototype since the reference signal axis is offset from the OPD or scanner measurement axis. Angular irregularities (tip and tilt) in scanner stage motion cause axial motion at off-axis points equal to the sine of the rotation angle multiplied by the distance from the center of rotation. Figure 2 diagrams Abbe error from a scanner stage rotation. The reference signal and the OPD axes are both offset from the rotation center and not coincident so the difference between their Abbe error induced axial motions will be equivalent to the sine of the angle multiplied by the distance between the axes.

In order to quantify the Abbe error, two DMIs and a Michelson interferometer were used on the scanner stage, as shown in Figure 3. One DMI is placed at the designed position for the reference signal in the profiler prototype (25mm from the optical axis). The second DMI is placed on the optical axis and directly evaluates motion of the microscope objective. The Michelson interferometer is set to measure the tip and tilt of the scanner stage as it translates. The tip and tilt information is used to determine if the difference between the two DMI measurements is from Abbe error. Figure 4(a) shows typical results of this setup for the difference between the two axes measured. The peak to valley difference for a scan distance of 1 mm is 0.45 micron. The predicted Abbe error, calculated using the product of the axis spacing and the measured tip and tilt angle, is shown in Figure 4(b). The calculated peak to valley change for a scan distance of 1mm is 0.35 micron. Comparison of the two shows good correlation and indicates the Abbe error for this prototype system is the dominant factor in the difference between the two axes. The discrepancy between the difference result and the tip and tilt result is probably caused by uncertainty in the tip and tilt measurement. The large scaling factor, due to spacing between the axes, means that 0.8 arc-seconds of tip and tilt corresponds to 0.1 microns of motion difference along the translation axis. The repeatability of the tip and tilt measurement on a stationary scan stage over ten minutes is 0.6 arc-seconds. This shows that Abbe error is a dominant factor so a modified optical design, placing the DMI on the same axis as the objective, could greatly reduce the overall system error.

Finally we tested the phase fitting algorithm for the reference signal distance measurement. Here the distance measurement is based on quadrature detection [5], and the Lissajous figure from the outputs of two detectors is shown in Figure 5. As the scanner stage moves a longer distance the Lissajous figure traces over itself at slightly different position due to the non-linearity of the scanner. The distance is found by fitting ellipses for the Lissajous figures. In order to check the validity of the fitting algorithm, we compared the distance retrieved from fitting the Lissajous figure shown in Figure 6 just once with the distance found by fitting fifty consecutive Lissajous figures. The results of the one-time fitting and the fifty-times fitting are within 1 nm. This shows that the ellipse-fitting algorithm is robust and able to detect the non-linearity of the scanner.

In conclusion, step height calibration based optical profiler system uncertainty of 0.5% can be improved to 0.05% ( 0.4 micron / 1 mm ) by implementing the HeNe laser based DMI. Residual errors, primarily Abbe but also cosine error still exist but can be greatly reduced by careful redesign of the mechanics. These changes could potentially lead to accuracy in the range of  $1/100^{\text{th}}$  to  $1/1000^{\text{th}}$  wavelength over an 8 mm scan length. That will be another one to two order of magnitude reduction of uncertainty from the current prototype.

#### References:

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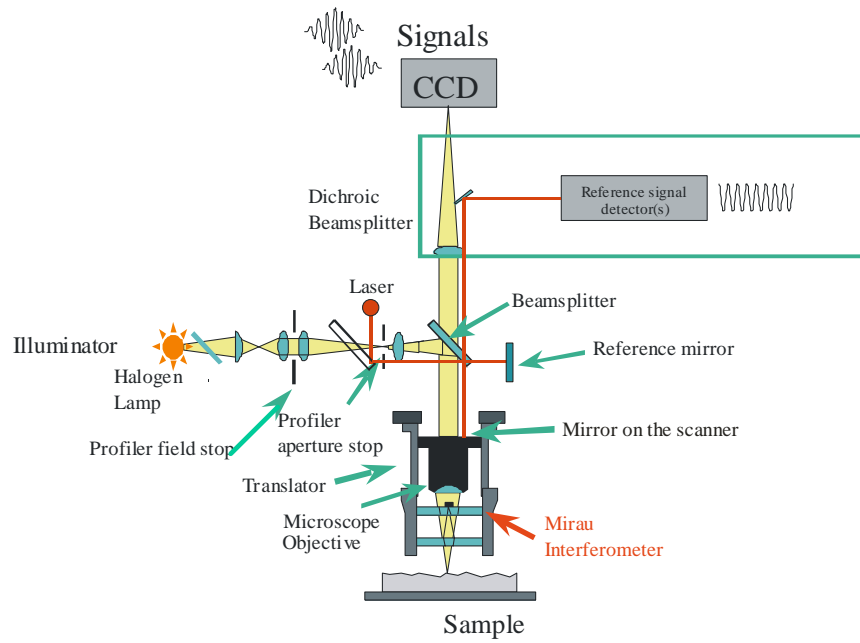


Fig. 1 Schematic diagram of optical profiler with reference signal.

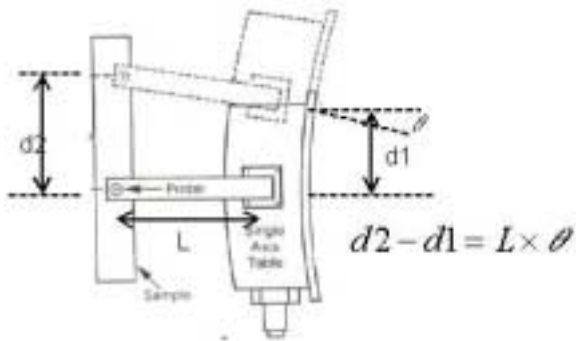


Fig. 2 Abbe error.

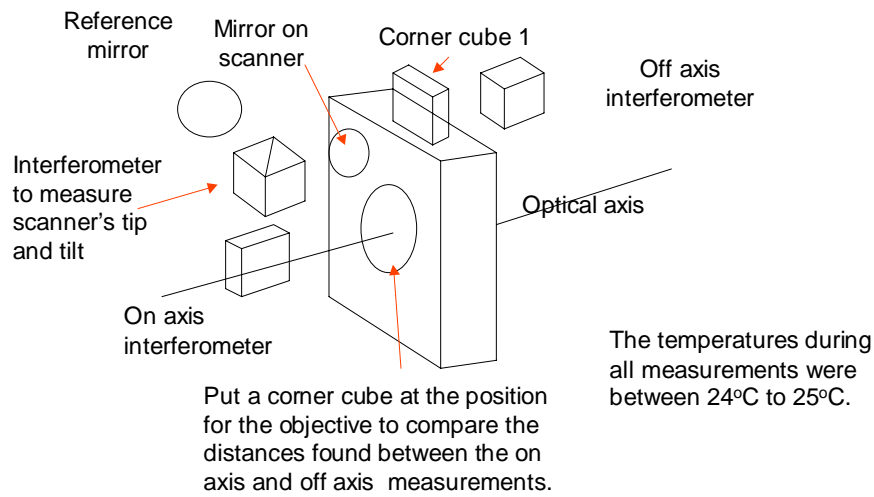
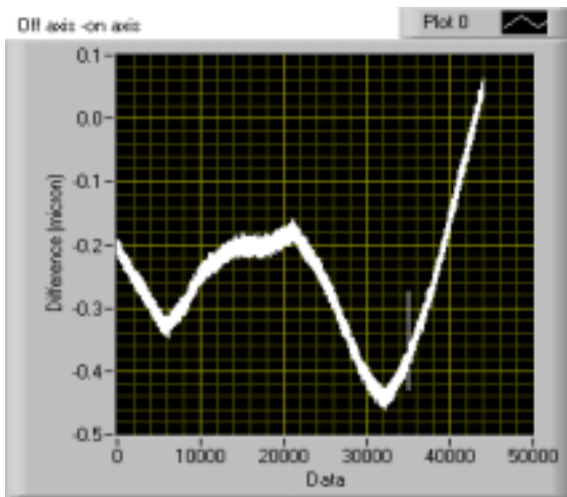
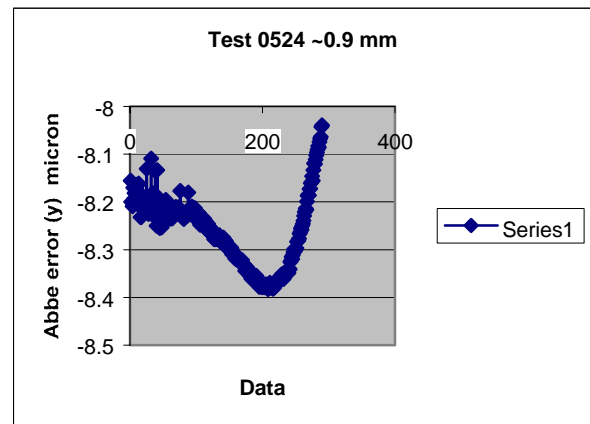


Fig. 3 Experiments to measure Abbe error.



(a) Difference between off axis and on axis measurement over 0.96 mm. Peak to valley 0.45 micron.



(b) Abbe error found by tip and tilt measurement. Peak to valley 0.35 micron.

Fig. 4 Abbe error measurement results.

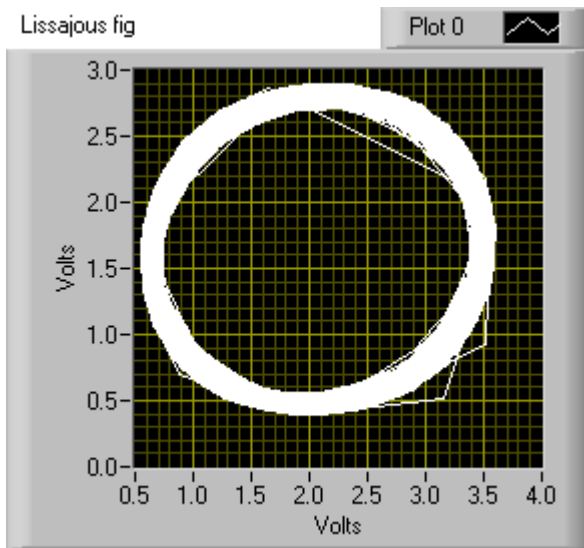


Fig. 5 Lissajous figures of scanning over 1 mm.