High performance Fizeau and scanning white-light interferometers for mid-spatial frequency optical testing of free-form optics

Leslie L. Deck* and Chris Evans
Zygo Corporation
Laurel Brook Road, Middlefield, CT. 06455-0448

ABSTRACT

Two specially-designed visible-wavelength interferometers meet demanding performance requirements in the mid-spatial frequency regime for current and next generation free-form x-ray and EUV optics. A Fizeau phase shifting interferometer measures waviness in the spatial frequency range from 0.5 to 10 mm^{-1} and an interferometric microscope measures finer-scale deviations from 1 to 1000 mm^{-1}. Uncertainty analysis and experimental work demonstrate <1-nm system error after calibration and 0.05-nm repeatability for both instruments working in a clean-room environment.

Keywords: Interferometry, phase shifting, metrology.

1. INTRODUCTION

Flare is a significant problem for lithography tools using EUV radiation[1]. Flare is associated with the mid spatial frequencies or *ripple* shown in Figure 1 between 0.5 and 1000 mm^{-1}. Ripple error scatters light into small angles and reduce image contrast. The effect scales as $1/\lambda^2$, making the problem 340 times worse at 13.4nm compared to 248nm. Consequently, ripple measurements for EUV optics are particularly important and require metrology tools with very high sensitivity and broad response across the mid-spatial frequency region.

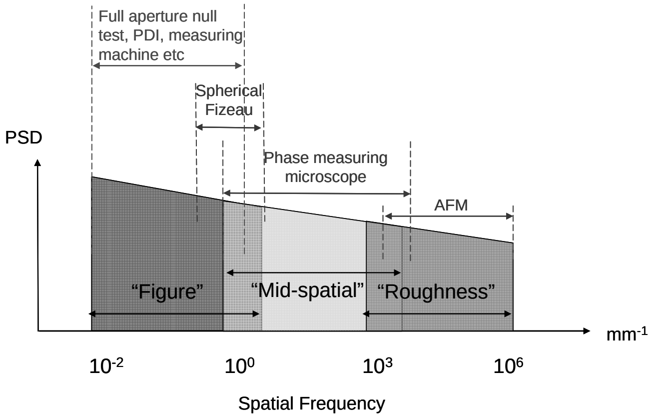


Figure 1: In precision optical fabrication, mid spatial frequencies span the range approximately from 0.5 and 1000 mm^{-1}.

Interferometers are the ideal tool for these demanding vertical and lateral resolution requirements. [2] [3] Here we propose and evaluate two interferometers[4] that together cover the spatial frequencies of interest. A Fizeau interferometer accommodates the spatial frequency regime between 0.5 and 10 mm^{-1} and an interferometric microscope covers the range from between 1 and 1000 mm^{-1}. Measurement techniques include detailed reference surface calibration, optimization of the instrument transfer function, and retrace error correction. Preliminary experimental work demonstrates the excellent repeatability, on the order of 0.05 nm, required for this application.

---

* email: ldeck@zygo.com

2. METROLOGY TOOLS

The Fizeau interferometer of Figure 2 (left) is a large aperture non-equal path system using a coherent HeNe laser. The fixed magnification optical system provides optimum imaging over the 8mm nominal field of view for part slopes up to 1 mrad. A reference sphere focuses the collimated light and the test surface is oriented so that the surface region of interest is nominally perpendicular to the converging wavefront. Light reflected from the test object interferes with light reflected from the reference surface, producing interference fringes which are observed on a charge-coupled device (CCD) with 640x480 pixel density representing deviations of the test surface profile relative to the reference profile. These deviations are determined quantitatively to high precision by phase shifting interferometry[5] (PSI), which calculates the interferometric phase at each location observed by the CCD from an analysis of a number of phase-shifted images by means of a proprietary 13 frame PSI algorithm.[6] The resulting phase surface is converted to a surface of deviations using the known wavelength as the length scale. Combining the known reference profile with the measured deviations determines the test profile.

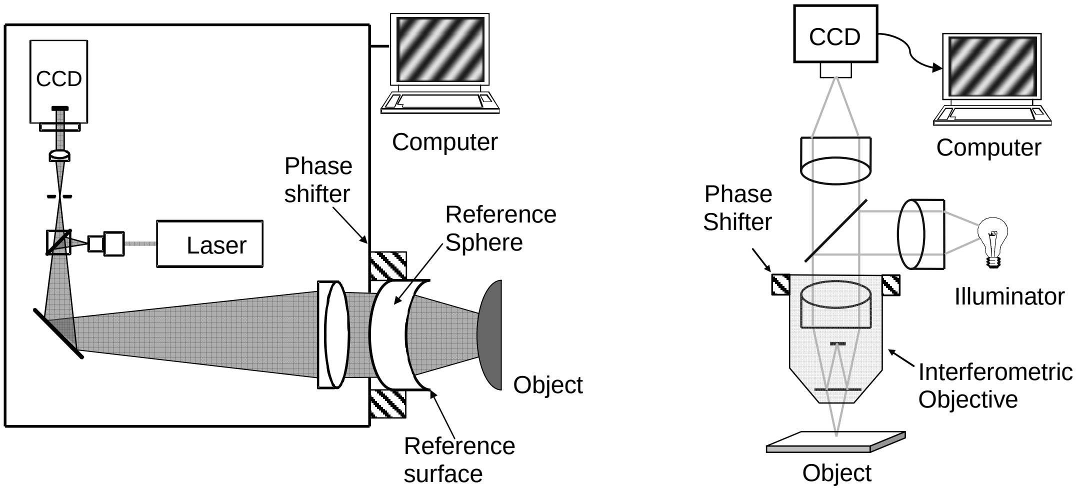


Figure 2: The large aperture Fizeau interferometer (left) and the interferometric microscope (right).

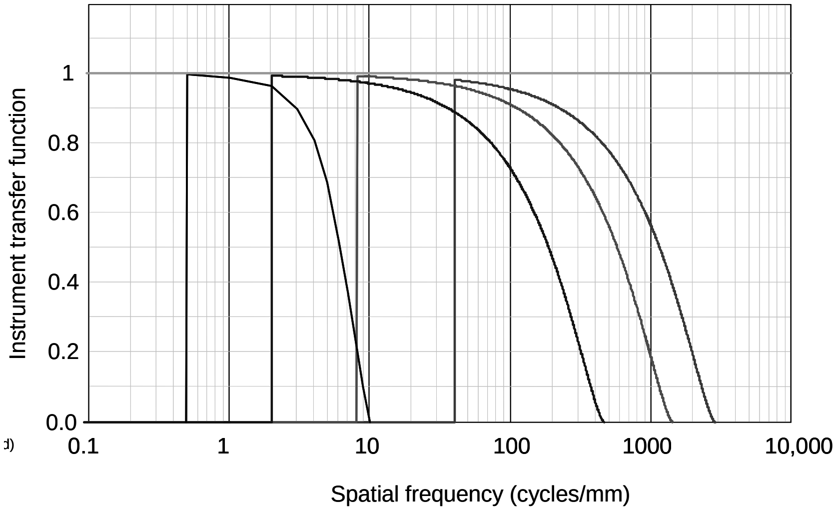


Figure 3: The theoretical transfer functions for a laser Fizeau (left-most curve) and 3 interference microscope objectives (right to left: 100X, 20X and 5X) span the full spectrum of mid spatial frequencies.

The interferometric microscope in Figure 2 (right), designed to cover the spatial frequency regime between 1 and 1000 mm^{-1}, uses scanning white light interferometry[7] (SWLI). A high intensity LED with a mean wavelength of 550nm and a spectral width of 80nm FWHM illuminates the interference objective, reflects off the test and reference surfaces, is recombined and directed toward a 1 Mpixel CCD camera. Interference is observed only when the optical path length of the reference and test wavefronts are the same, which by design also coincides with optimal focus. CCD images are acquired while the phase shifter scans through the surface and the data is converted to a surface of deviations via a spectral analysis of the temporal interference pattern.[8] The physical length scale is determined by the precise motion of a capacitive-feedback phase shifter

Since the desired spatial frequency band is too large to cover with a single objective, the band is split into 3 separate sub-bands that are individually covered with 3 objectives. Each sub-band is further limited by only accepting spatial frequencies between three cycles/aperture and 70% of the instrument transfer function (except the 100X, whose upper limit is extended to 50% ITF). Figure 3 shows the expected spatial frequency coverage obtained with the two instrument.[9] Enough sub-bands are taken so that the final sub-band widths still provide enough overlap to diagnose transfer function mismatch.

3. METROLOGY CONSIDERATIONS

3.1. Measurement definition and requirements

It is good practice to start a metrology problem with a statement of the quantity to be measured – the measurand. Here the measurand is a cloud of 3-dimensional points (one point for each pixel in the CCD) that represents a surface profile, or a parametric (e.g. rms, PV, kurtosis, etc) or spatial analyses thereof. For ripple measurements, the measurand is a bandwidth limited evaluation of the surface profile accomplished through a Fourier analysis. To be capable of measuring angstrom level features, the resolution must be sub-angstrom. The resolution goal is therefore set at 50pm. A first task therefore is to establish how to verify this resolution on the instruments experimentally.

3.2. Instrument repeatability

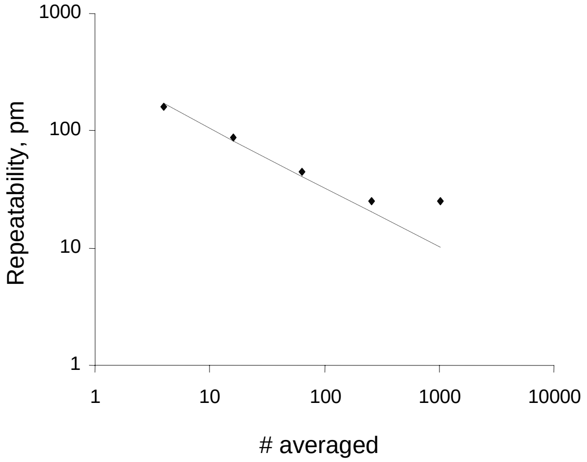


Figure 4: Repeatability of the Fizeau interferometer with a 100mm cavity as a function of averages.

The simplest measure of instrumental performance is repeatability, defined as the “ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement.” [10] The definition notes that the same conditions include “repetition over a short period of time”, implying that longer term (eg thermal) drift is excluded. The definition also notes that repeatability “may be expressed quantitatively in terms of the dispersion characteristics of the indications.” If we knew the true surface shape, then the standard deviation of the differences (for all pixels) from the true value characterizes the uncertainty. As a practical matter it is often very difficult to obtain the true surface profile, so we use instead the profile defined by the average of many measurements. Thus we take the mean plus twice the standard deviation of the rms differences between *N* consecutive measurements of a nulled reference and the average of those *N* measurements, with *N* typically 10, as our estimate of repeatability.

In the case of the laser Fizeau, the theoretical rms uncertainty of a 13-frame PSI measurement with 50% contrast and 8-bit digitization at a wavelength of 633nm is 0.4 nm. Assuming statistically random behavior, 64 averages reduce the rms uncertainty to 50 pm in the absence of other noise sources. Longer cavities introduce additional environmental noise, therefore 256 averages are recommended for cavity lengths of the order 100 mm in a nominal +/-0.05C environment (Figure 4). The directly measured repeatability of the Fizeau (mean plus twice the standard deviation) with an 8mm field of view, tented to reduce atmospheric fluctuations, and a 100 mm cavity was 28pm.

The interferometric microscope follows the theoretical expectations more closely, mainly because of reduced turbulence effects. Figure 5 shows that measurements agree well with the prediction of 64 averages and that the data support the assumption of statistical randomness. The interferometric microscope repeatability depended slightly on the objective used, mainly because each objective had different working distances, but all were less than 50pm.

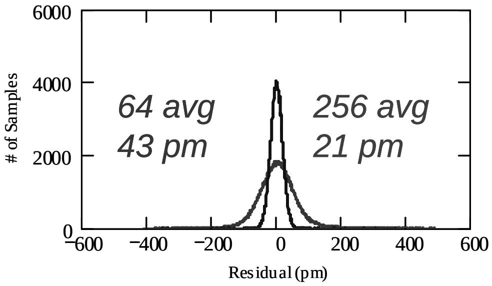


Figure 5: Histogram of pixel residuals from repeated measurements on the microscope indicating the expected statistical behavior.

3.3. Environment

3.3.1. Vibration

As with all interferometric testing, environmental noise can quickly degrade performance because of the extreme sensitivity of the measurement technique. For the Fizeau interferometer, vibrational distortion will manifest itself as a surface error pattern identical to the fringe pattern but with twice the spatial frequency. For the microscope, the spatial distortion will be more complicated because the fringe visibility is both spatially and temporally local. A phase-shifting interferometer will be most sensitive to vibrations at frequencies near the interference signal frequency, typically near half the frame rate of the imager.[11] The interferometer will experience a vibrational spectrum equal to the product of the spectrum of the floor times the spectral transfer function of the vibration isolators upon which the instrument is mounted.

Specifications on the floor vibrational and acoustical spectrum were set for both instruments to VC-D and NC-30 respectively, which are appropriate for the high quality clean room environment expected for free-form EUV and X-ray optics. Note that the vibrational specifications are meant to bound broad-band noise, large amplitude single frequency tones are assumed to be absent. At the frequencies for which the interferometer is most sensitive (between 10 and 40 Hz), we measure using accelerometers an rms vibrational velocity of ~50nm/sec, or only ~1nm/frame. Even under these conditions, environmental noise will distort the profiles at the sub-nm level. Assuming random vibrations, averaging 64 data sets reduces vibrational errors to acceptable levels.

3.3.2. Turbulence

A fine mesh screen over the interferometers mitigates turbulence by reducing turbulence cell size. Of the two interferometers, the Fizeau is most susceptible to turbulence because of the long cavity length. Tests were performed showing that the statistical behavior of both vibration and turbulence effects were consistent with pure random processes, which once again diminish to acceptable levels with data averaging.

3.4. Reference calibration

The interferometers measure surfaces relative to a reference surface, and so it is necessary to know the reference profile absolutely in order to subtract out reference related features.[12] For the interferometric microscope, averaging many measurements of different positions separated by the surface correlation length of a flat reference artifact calibrates the reference mirror. Typically the average of 100 separate locations provides <50pm reproducibility. The spherical reference of the Fizeau interferometer uses a spherical reference artifact. In this case 400 averages achieve 50pm reproducibility, given the additional effects of turbulence.

3.5. Focus

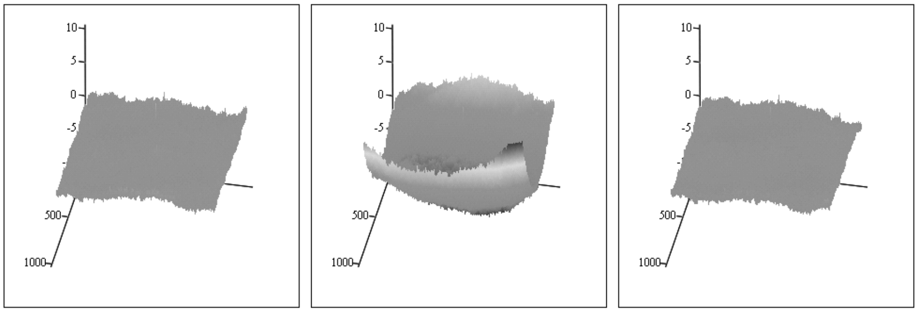
Focus error can produce hundreds of pm of diffraction induced distortion with spatial frequencies that depend on the spatial frequency of the feature imaged. Focus for the Fizeau interferometer is currently performed by manually focusing on a sharp edge of an object set in front of the test surface, since the test surface generally has no features adequate for focusing. This has proven inadequate for the high precision of the intended application and we are considering a more deterministic procedure.

The interferometric microscope enjoys a more forgiving focus behaviour. Data acquisition occurs when the optical path lengths experienced by the reference and test wavefronts are the same, which by design occurs at the best focus position. Thus the profile derived from the SLWI signal is at the best focus conditions for every pixel in the field of view automatically.[13]

3.6. Retrace error

All interferometric systems for which a mismatch between test and reference wavefronts exist, suffer from a phenomenon known variously as propagation error, ray-mapping error, shearing error or retrace error. Retrace refers to errors produced when the test and reference wavefronts traverse different paths through the system optics, typically due to relative shearing of the two wavefronts occurring from local slope mismatch or defocus. These errors can couple strongly to optical fabrication imperfections, making a-priori quantitative error prediction/correction difficult.

Discounting some types of optical imperfections, retrace error generally produces relatively low spatial frequency distortions for the anticipated departures. For example, Figure 6 shows the measurement of a reference flat using a 20X objective in the interferometric microscope. Figure 6A measured with zero tilt, 6B with 21mrad of tilt (over 50 fringes) and 6C is 6B with just cylinder removed, indicating that the assumption of low spatial frequency deformations is justified.



A B C

Figure 6: Measurement of a flat with a 20X objective on the interferometric microscope shows that the system errors have a low spatial frequency. (A) was measured with zero tilt, (B) was measured with 21 mrad of tilt and (C) is Figure (B) with just cylinder removed. The horizontal scale is in pixels and the vertical scale is in nm.

Thus our strategy for handling retrace error is to band-limit the spatial frequency sub-bands by removing the lowest spatial frequencies via software, thereby preferentially removing the distortion due to retrace.

This works very well for the microscope, but the situation is different for the Fizeau. We have found that the shearing of higher frequency optical defects on the internal optics in the instrument can produce a distortion contribution with a magnitude similar to that of low order aberrations. The low frequency errors are more amenable to compensation,[14] but the higher frequency distortions are difficult to correct.

Figure 7 shows the results for the same test performed on a Fizeau interferometer, zoomed up 6x and masked to an 8 mm aperture. Here the total system error and the rms of the residuals are essentially identical. It is clear from the rms of the fit to the lowest 36 Zernikes, that low spatial frequencies contribute only about half of the total rms residual. A significant fraction of the residual error is due to shearing of high frequency artifacts in the internal optics of the interferometer.

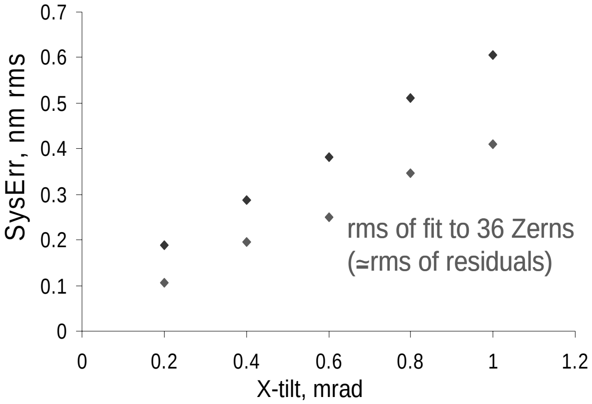


Figure 7: The uncompensated system error in a laser Fizeau as a function of part tilt is <1nm but is dominated by high frequencies, unlike the microscope. The lower data series is the Zernike fits.

3.7. Instrument Transfer Function calibration

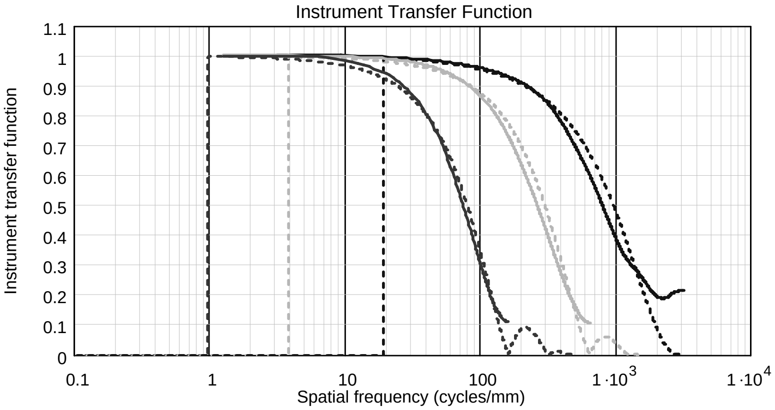


Figure 8: Comparison between measured (solid) and theoretical (dashed) results for the (left to right) 5X, 20X and 100X interferometric microscope objectives demonstrates good agreement when using a step height artifact to evaluate ITF.

The power spectrum for small surface deviations from null can be corrected for instrumental sensitivities by dividing each spatial frequency component by its corresponding instrument transfer function (ITF), which describes the instrumental measurement sensitivity for a particular spatial frequency. Each spatial frequency sub-band measurement is corrected using the measured ITF, and the ITF is determined from the ratio of the measured power spectral density (PSD) to the true PSD [15] of an artifact with known spatial frequency content. The artifact is a 40nm step standard, a height optimized for good signal to noise while obviating diffraction artifacts and nonlinear behavior that can occur with larger steps. The step is coarsely aligned to the grid and we average the PSD's calculated from each of the 1-D perpendicular profiles. Results reported in Figure 8 show good agreement with theory using this technique.

4. CONCLUSIONS AND FURTHER WORK

These preliminary results show that with the proper care, a combination of a visible-wavelength laser Fizeau and a white-light interference microscope successfully cover the mid-spatial frequency metrology requirements for EUV and other demanding applications for which ripple error in the optics is of high importance. Our measurements show 0.05-nm repeatability in clean room conditions, while measurements of system error and ITF show that <1nm global uncertainty is achievable, with <0.1 nm a realistic goal once system errors are compensated in software.

On the balance we have found that the white light interference microscope is the more powerful of the two tools for the largest range of spatial frequencies encompassed by ripple, in part because of the focus properties of the tool, the incoherent illumination and the very small cavities. However, the laser Fizeau is promising as a bridge to the overall figure measurement, provided that we work to contain air turbulence, focus errors and coherent noise.

Our next step will be to perform a series of demonstration measurements on optical surfaces of interest, including EUV aspheric mirrors.

REFERENCES

---

[1] J.E. Bjorkholm, “EUV Lithography – the Successor to Optical Lithography?” Intel Technology Journal (1998) , www.intel.com/technology/itj/q31998/pdf/euv.pdf

[2] K. Freischlad, “Interferometer for optical waviness and figure testing,” Proc. SPIE 3098, 53-61 (1997)

[3] C. Saxer, K. Freischlad, “Interference microscope for sub-angstrom surface roughness measurements,” Proc. SPIE 5144, 37-45 (2003)

[4] Multiple domestic and foreign patents pending.

[5] J. Greivenkamp and J. Bruning, “Phase Shifting Interferometry”, Chap. 14, of “Optical Shop Testing”, 2nd Ed., J. Wiley pub, edited by D. Malacara.

[6] P. de Groot, “Measurement of transparent plates with wavelength tuned phase shifting interferometry,” Appl. Opt. 39(16), 2658-2663 (2000)

[7] L. Deck and P. de Groot, “High-speed non-contact profiler based on scanning white light interferometry,” Appl. Opt. 33(31), 7334-7338 (1994)

[8] P. de Groot and L. Deck, “Surface profiling by analysis of white-light interferograms in the spatial frequency domain,” J. Mod. Opt., 42 (2), 389-401 (1995)

[9] P. de Groot and Xavier Colonna de Lega, “Interpreting interferometric height measurements using the instrument transfer function,” Proc. International Workshop on Automatic Processing of Fringe Patterns (Stuttgart, September 2005, to be published).

[10] ISO International Vocabulary of Basic and General Terms in Metrology, Geneva, 2nd Ed 1993

[11] P. de Groot, “Vibration in phase shifting interferometry,” J. Opt. Soc. Am. A, 12(2), 354-365 (1995)

[12] C. Evans, R. Hocken, W. Estler, “Self Calibration: reversal, redundancy, error separation and absolute testing,” CIRP Annals, 45/2 (1996)

[13] S. Chakmakjian, J. Biegen and P. de Groot, " Simultaneous focus and coherence scanning in interference microscopy " Technical Digest, International Workshop on Interferometry, 171 (Riken, Japan, 1996).

[14] Evans C. J. “Software based improvements in the accuracy of measurement of aspherics using a Fizeau interferometer” Proc. Optical Fabrication and Testing Workshop, 1994

[15] C. Wolfe, J. Downie, J. Lawson, “Measuring the spatial frequency transfer function of phase measuring interferometers for laser optics,” SPIE, 2870, 553-557 (1996)