To be presented at: Opitcal Fabrication & Testing (OF&T)
Monterey, CA, 24-28 June (2012)

BNL 96955-2012-CP

MINIMIZING ARTIFACTS IN ANALYSIS OF SURFACE TESTING*

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June, 2012

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Submitted to: OSA Optical Fabrication & Testing, 24-28 June 2012, Monterey, CA

Minimizing Artifacts in Analysis of Surface Statistics

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Abstract: Measurements from interferometers and profilometers contain information about surface figure and finish over a wide range of spatial frequencies. Proper detrending and windowing are necessary to avoid contaminating the true nature of the PSD function.

OCIS codes: (120.4800) Optical standards and testing; (120.6660) Surface measurements, roughness

1. Introduction

Surface texture statistics extracted from the earliest contact stylus profiling instruments were defined over a linear trace along a surface [1]. The early optical profiling instruments utilized linear array sensors that also produced a measurement over a linear trace [2]. Processing techniques were developed for the linear profile data to avoid introducing artifacts that would mask the true statistical nature of the surface [3,4]. Most surface profiling instruments today utilize 2D array cameras that produce areal surface height maps. This work is an attempt to extend the concepts of profile processing to areal measurements in order to provide a basis for standardizing the calculation areal statistics.

2. The method

The usual quantity of interest in characterizing the roughness of a profile or surface is the root mean square (RMS) value. In the spatial domain, this is computed simply from the sum of all the squared residuals over all the data points after removing the mean surface or profile. This number contains implicitly a spatial bandwidth determined by the overall trace length and the minimum sampling period. More useful statistics can be extracted by computing the periodogram estimator of the surface power spectral density (PSD) function and summing over any desired range of spatial frequencies.[3,4] This method allows one to separate high frequency roughness from low and mid-spatial frequency roughness and enables one to have a much better understanding of the nature of the surface. Essential to the calculation of the PSD is detrending to remove the global surface figure terms and the use of a window function in the spatial domain to minimize spectral leakage of edge discontinuities that produce artifacts in the spectrum. These artifacts mask the true nature of the shape of the spectrum at high frequencies where it is most desired to know the correct value of the bandwidth-limited roughness. The use of a window function in the linear profile PSD calculation is well-known [5], but it has not been applied systematically in the calculation of areal PSDs. We illustrate the necessity of applying a normalized 2-dimensional window function to areal wavefront measurements in order to extract RMS roughness numbers with minimum systematic error.

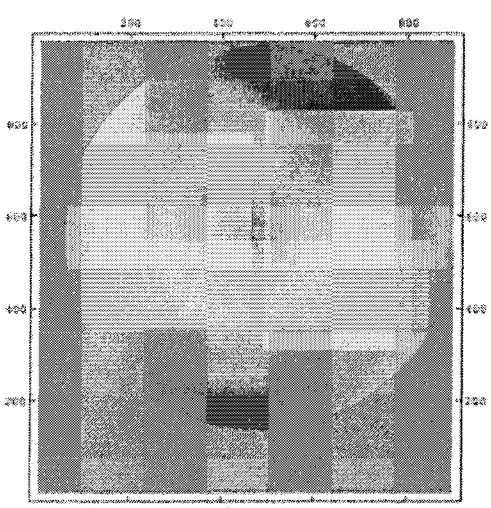

Fig. 1 - Wavefront map from Fizeau interferometer showing underfilled camera array with missing data in center. Data is extracted from the 3 rectangular ROIs..

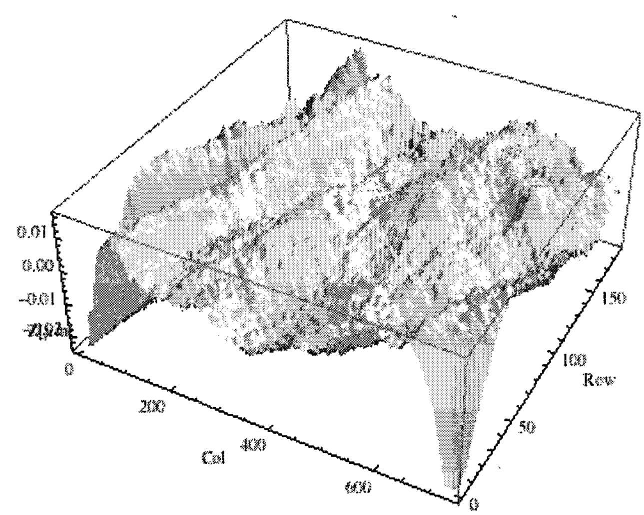

Fig. 2 - Residual surface from the long, narrow ROI below center in Fig 1 after 4th order polynomial detrend. Large edge discontinuities remain around the perimeter of the region.

3. Measurements

Measurements were made of a transmitted wavefront of a lens in double pass mode with a Fizeau interferometer. The data is shown in Fig. 1. There are two main issues with this data. First, the measurement aperture is circular and does not fill the data array completely. Second, there is a hole in the center of the circle that contains missing data points. This creates an annular region of good data points embedded in the full sensor area. In order to use conventional Fourier transform calculation algorithms, we need to mask the full data array and partition it into rectangular regions that exclude the missing data. This requires defining several regions within the annular region that are "representative" of the true surface. That the surface is ergodic and any subregion is statistically the same as any other is an implicit assumption for now.

4. Data processing

The first thing to do to prepare the measured data for statistical analysis is to remove the low-order surface figure and rigid body alignment terms. The Fizeau data file has already been detrended to remove piston, tilt and curvature terms. After extracting the data points from each rectangular region, the data was detrended further by removing a least squares fit 4^{th} order polynomial in x and y. This removes most of the low frequency figure error terms and leaves a residual surface that contains the higher spatial frequencies. An example of the residual surface after detrending is shown in Fig. 2.

Now compute the 2D Cartesian PSD for this residual surface over the rectangular region. We do this both before and after applying a 2D Blackman window to the data. The window is normalized so that the total volume under the window is unity so as not to distort the statistics of the underlying surface. The results are shown in Fig. 3 in 3D plots of the log of the 2D PSD. The unwindowed PSD on the left can be considered as having a rectangular window with constant height applied, identified here as a Rect window. The PSD from the Rect windowed data shows the artifacts induced by the edge discontinuities aligned along the x and y frequency directions. The edges of the height data array do not fold over smoothly to match the other side of the array. The resultant step height discontinuity at the edge introduces the spurious power along the x and y frequency axes. By applying the Blackman window, the edge discontinuities are forced to zero and the resultant PSD is a much better estimate of the underlying "intrinsic" surface roughness.

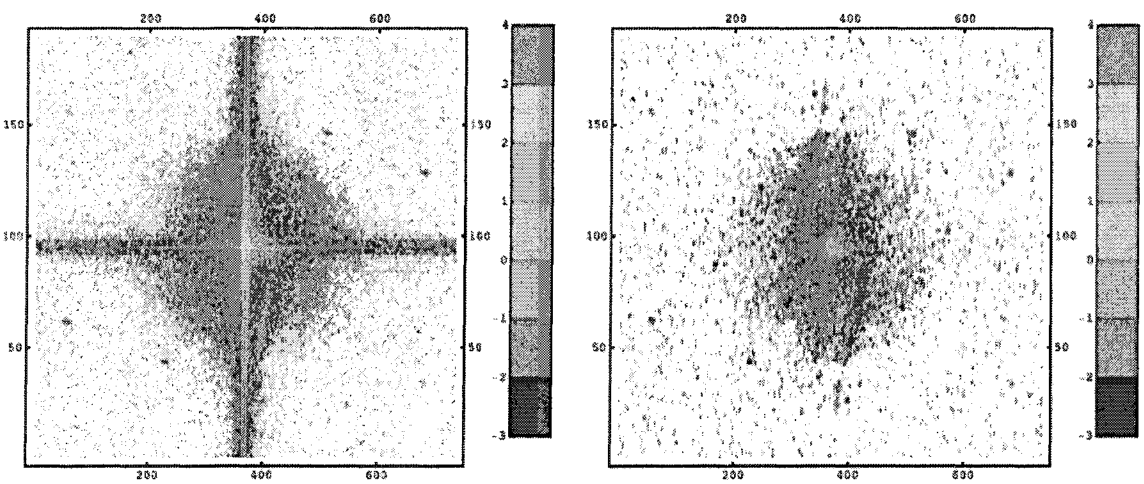

Fig 3 - Cartesian PSD for region shown in Fig. 2 (left) without a window applied, and (right) with a 2D Blackman window applied. The Blackman window reduces the contamination caused by discontinuities between the beginning and end of each row and column. Vertical scale is log PSD in units of μm^4.

The PSD functions in Fig. 2 are computed by a conventional DFT in the Cartesian coordinates of the camera array. What we are interested in is midspatial frequency surface roughness over a particular bandwidth, averaged over all directions. We can see from the 2D PSD on the right that the roughness has some directional component, but if we assume anisotropy, we can integrate over all azimuthal angles and generate an equivalent radial PSD function, which is a single curve. This makes extracting surface statistics much easier. By performing a numerical integration, the Cartesian 2D PSD is converted into the 2D radial PSD, rPSD, shown in Fig 4.

Two sets of 3 curves are shown in Fig. 4, plus the average of the 3 as the heavy lines. These curves correspond to the rPSDs for the 3 data regions, with and without the Blackman window applied. The heavy curves are generated by first interpolating each rPSD to a uniform frequency grid, then averaging the interpolated curves. The RMS can now be computed from each averaged curve over any desired bandwidth by integrating the area under the curve.

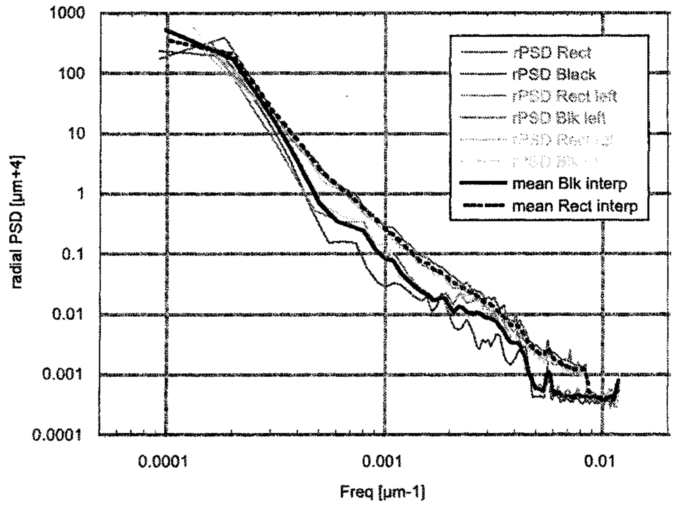

Fig. 4 - Radial PSD curves for each of the 3 regions in Fig. 1, both with and without a Blackman window applied. The windowed curves are always below the unwindowed curves.

Note that the Blackman windowed curves lie below the Rect windowed curves. This is due to the spurious power introduced into the spectrum by the edge discontinuities that are not filtered out by the Rect window. Step edge discontinuities produce excess $1/f^2$ noise, which adds to the underlying spectrum at high frequencies. When this power is removed by Blackman windowing, the "true" surface spectrum is revealed at a lower level.

For this particular lens, we are interested in the RMS midspatial frequency error over the 5mm to 100µm bandwidth, which coincides with almost the entire spatial frequency range of the measurement. From the averaged curves, the RMS over this bandwidth is **0.74nm** for the Rect windowed data and **0.38nm** for the Blackman windowed data. The specification for this lens is for an RMS roughness not to exceed 0.5 nm. Without the Blackman window applied, the RMS roughness exceeds the limit and the lens fails. With the Blackman window applied, the RMS roughness is within the tolerance and the lens passes. This shows the necessity of proper data conditioning and windowing in computing statistical quantities from measured surface profiles. Improper data conditioning and PSD computation could result in significant economic consequences if a good part is rejected because of artifacts introduced into the data.

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