A Step-Height Standard for Surface Profiler Calibration*

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Abstract

We report on the design and fabrication of an all-silicon test pattern that is very useful for assessing the performance of all types of profiling instruments. We present examples of results obtained from applying this method to various kinds of profiling instruments, including a WYKO TOPO 3D system, Micromap Promap 512 profilers, a ZYGO Maxim 3-D system, and scanning probe AFM systems. We also present the results from a measurement of the BRDF of the step with a TMA CASI scatterometer to show the utility of the step as a potential calibration standard for scattered light measuring instruments.

Introduction

We have developed a standard artifact and a test method that is useful for calibrating the performance of both optical and mechanical profiling instruments, and also of BRDF scatterometer instruments. We have found that commercially-available step height standards are inadequate for assessing the performance of optical profiling instruments and are especially difficult to use in measuring the performance of stylus profiling instruments. Quantitative information on the roughness of smooth surfaces requires precise knowledge of the transfer function of the measuring system. An out-of-focus optical system or a dull stylus can give distorted results and mask the true properties of the surface. Optical systems that incorporate changeable objective lenses are especially susceptible to focus errors. Even optical systems that are perfectly aligned attenuate the true amplitude of high frequency surface spatial frequencies.

Our method for profiler calibration involves the measurement of a high-quality step and then computation of the power spectral density (PSD) function of the measured edge. The magnitude of the deviation from the ideal inverse-square power law spectrum of the step is a direct measure of the transfer function of a linear measurement system. The ideal power spectrum of a sharp edge should have an inverse-square dependence on spatial frequency. But because the transfer function of every optical system attenuates the high spatial frequencies, the observed PSD function of the measured step deviates in a predictable way from the ideal inverse-square function. An analogous departure from ideal behavior occurs with stylus profilers, whose transfer function characteristics depend, among other things, on the radius of the tip and the height of the step.

Rationale for a Step Artifact

A step height artifact is a useful item to use in calibrating the performance of surface profiling instruments. It is useful as a check on the height calibration of the measurement transducer and data analysis system. However, measurement of the height of a step only gives one a small piece of information about a system's performance. A surface profiling instrument provides information not only about the height of steps on a surface, but contains information about the surface texture over a wide range of surface spatial frequencies. If the measurement system behaves as a linear system, then the height calibration factor can be considered the DC or zero frequency response function of the system. Knowledge of the DC calibration factor is, however, not sufficient to fully characterize the performance of the system at higher spatial frequencies - what is needed is a method to calibrate the transfer function of the measurement system at all spatial frequencies within the instrument bandpass. The step height artifact provides a means to fulfill this calibration need in a simple manner, and can also be used as a calibration artifact in systems that measure scattered light.

The property of the step that makes it useful for calibrating the system transfer function is that it has a well-known power spectral density function.¹ The PSD of a step is an inverse square function of the spatial frequency: $S_1(f) \approx 1/f^2$. The procedure, then, is to measure the profile of a suitable step artifact, producing a set of digitized numbers corresponding to the height data sampled at uniform intervals along the surface, and then to compute (i.e. "estimate") the PSD function of the data, comparing the result to the ideal spectrum expected for the ideal step. Any deviation from the expected $1/f^2$ spectrum is a reflection of the actual system transfer function. The results of the measurement can be used as a diagnostic tool to assess the current performance of the instrument, to see if it is performing as expected, or to provide information to allow one to correct the spectral content of the data for the usual system attenuation at high frequencies. This process, which is called restoration filtering, is easily done in the frequency domain by point-by-point division of the Fourier transform of the surface profile by the measured system transfer function.¹⁻⁵ The restored profile can thus be used in comparing measurements made by different instruments on the same surface, eliminating the bias caused by non-unity transfer functions.⁵

Other forms of profiler calibration artifacts can be generated, but none are quite as versatile as a step. A delta-function is mathematically the simplest function to use in probing the instrument response function of a linear system, but it is a practical impossibility to approximate a physical artifact that would be useful as a delta function. It is also not possible to construct a delta-function-like artifact that would give a useful answer for the DC height calibration of the instrument. A sinusoidal artifact is useful as a calibration artifact, but it provides transfer function information only at one particular spatial frequency. Presumably a number of sinusoidal artifacts would be needed to approximately characterize the transfer function of a system over its full bandwidth. Sinusoidal artifacts are not very easy to make and usually contain errors in amplitude and period that are difficult to characterize. A high quality, very sharp, single step artifact is, in contrast, very easy to make using standard photolithography techniques. It has a unique property in that the frequency spectrum of the measured step exactly covers the entire range of the measuring instrument, regardless of scan length or magnification. This means that the same step can be used to calibrate a large number of different profiling instruments, or a single profiling instrument with multiple configurations, such as one with an assortment of different magnification objectives. It is not necessary to have different steps to cover different spatial period regimes. It may be useful to have steps of different heights to use with instruments of differing vertical sensitivity, and as a check on possible non-linear measurement effects.

Power Spectrum of a Step

The spectrum of an ideal step function has a relatively simple form. The "true" power spectral density function of a step has a purely $1/f^2$ functional dependence over all frequencies, but the periodogram estimate of the PSD function is contaminated by high- and low-frequency artifacts that are related to the finite sampling distance, D , and the finite trace length, L . For the case of a step with height H centered along the x -axis, sampled at N equally-spaced intervals separated by a distance D , the periodogram estimate of the power spectral density function is

$$S_1(f_m) = \frac{2D}{N} \cdot \frac{W}{\sin^2(\pi D f_m)} \cdot H^2 \quad (1)$$

where

$$f_m = \frac{m}{ND} \quad (2)$$

is the spatial frequency of the m -th harmonic. W is a numerical factor that depends on the particular data window function applied to the raw height data which is used to suppress spurious ringing in the spectral-estimation procedure. For example, $W = 2/3$ for a Hahn window and $W = 1250/1523$ for a Blackman data window. The window function also distorts the low frequency end of the periodogram slightly, i.e. for the first few lowest harmonics. Note that the frequency dependence in (1) is not exactly an inverse-square, rather it is part of a cosecant-squared function due to high-frequency aliasing in the estimator. If we let the number of samples become large and let the sampling distance get small so that the product

$$ND = L \quad (3)$$

remains constant, equal to the length of the measurement trace, then we can write the spectrum for intermediate values of the frequency in the form

$$S_1(f_m) = \frac{2}{L} \cdot W \cdot H^2 \cdot \frac{1}{f_m^2} \quad (4)$$

This asymptotic form of the discrete spectrum of the step exhibits the familiar inverse-square frequency dependence, which is also the result from the power spectrum computed from the proper Fourier transform of a step over infinite limits in the x -axis. So the results from (1) and (4) tell us that the slope of the PSD curve should begin as $1/f^2$ at low frequencies and then level out at the Nyquist frequency where $m = N/2$ and the sine function becomes unity. Comparing the PSD curve of a step measured with a profiling instrument with the theoretical result above will enable one to assess the calibration of the measuring system.

We should note one interesting consequence of eqn. (4) - the numerical magnitude of each point in the power spectrum contains an inverse dependence on the total trace length, L . This means that if the trace length is changed, the magnitude of the PSD curve will shift in the vertical direction. The same step measured over a different trace length will have a different apparent power spectrum. What is different is only the magnitude of the numbers, not the shape of the curve. The measured power-law shape of the curve still contains all of the information about the system transfer function. If we normalize each PSD curve by multiplying each point by the length of the trace (or equivalently by dividing by the fundamental frequency), we see from eqn. (4) that the result is now an invariant quantity, independent of trace length. $S(f) \cdot L$ now depends only on the square of the step height and has the same values at corresponding frequencies, independent of the trace length or even of the type of profiling instrument. This rather interesting result, which is related to the fractal-like characteristics of an ideal step⁶, allows us to infer the height of a step, which is the zero-frequency term, by computing it from the measured power spectral density value at any other frequency. It also offers us a useful way to compare spectra from the same instrument made with different power objectives or over different scan lengths.

Fig. 1 Scans across the edge on a commercially available step height standard. The variability in the edge height and the surface irregularity are typical of the quality of this type of standard.

Fig. 2 PSD curves for the profiles in Fig. 1. Intrinsic surface roughness contributes to the noise in the high frequency region. A Blackman filter has been used to pre-process the raw data and the restoration filter appropriate for this profiler has been applied to spectra.

Signal-to-Noise Ratio Model Considerations

No real step artifact can ever be mathematically perfect. We have found that the problem in manufacturing a real step is not in producing a sharp, steep edge - rather it is in maintaining a smooth, flat region on either side of the edge. Figure 1 is an example of several traces across a commercially-available step height standard. One can see that in addition to considerable variation of the step height at different positions along the length of the step, the regions immediately surrounding the edge are very irregular and rough. The signal-to-noise ratio for this step, which is defined to be the ratio of the step height to the root-mean-square roughness of the underlying surface, is on the order of 20 to 30. Height standards with such low S/N ratios are not useful in attempting to use the power spectrum of the measurement to assess the performance of the measurement system because they contain too much noise in the high frequency end of the spectrum and mask the true behavior of the system transfer function. The power spectrum of a trace from the commercial step is shown in Figure 2. This spectrum has been restored with the inverse filter appropriate for this profiling instrument.

In order to estimate the S/N ratio required of a step height artifact for it to be useful as a profiler calibration standard, we performed some model calculations with an ideal step, changing the amplitude of the step while keeping the amount of random noise constant. Uniformly-distributed Gaussian noise with $\sigma = 0.1\text{nm}$ was added to steps of varying heights, from 0.1nm high to 100nm high, providing a S/N range between 1 and 1000. The model height profiles are shown in Figure 3, and the corresponding power spectral density functions are shown in Figure 4. Comparing the PSD of the commercial step in

Figure 2 with the model results in Figure 4, one can see that the S/N ratio of the actual step does lie between the 10 and 100 model curves, and that to eliminate the effects of random noise from the power spectrum of the step, the S/N ratio should be no less than about 200 or 300. The result of this exercise is to show that an order of magnitude improvement is needed in the quality of the commercial step standard before it can be used as a profiler system calibration standard.

Fig. 3 - Model steps of heights ranging from 0.1nm to 100nm (not shown), with 0.1nm RMS random noise applied to each. The signal-to-noise ratio ranges from 1 to 1000 for these model profiles.

Fig 4. - PSD curves computed from the individual model profiles in Fig. 3. The random noise level has more of an influence on the spectrum as the S/N ratio decreases. The PSD curve in Fig. 2 lies in the range of 20-30.

BNL Step Artifact

In an attempt to improve upon the quality of commercially available step standards, we have developed a step height standard that meets the requirements imposed by the S/N ratio of the power spectral density function. We have produced steps in optically-polished Si(110) wafers by an anisotropic etching process. The anisotropic etch produces extremely sharp steps with very steep slopes - the etch rate is about 600 times greater in the direction normal to the surface than in the transverse direction.⁷ Our process is such that the etching is done into the Si(110) surface, leaving no thick oxide layers remaining on the surface. The resultant surface is single phase material with no thin films of varying thickness. This homogeneous residual surface is necessary in order to properly calibrate optical profiling instruments which are extremely sensitive to differential phase retardance caused by material properties that change across the surface.⁸ The measured height changes across this surface are produced only by surface topography and not by differential phase retardance.

Fig. 5 - Sketch of BNL step artifact pattern. Lower half is just a single step. Upper part consists of two laminar profile bar patterns of 50μm and 10μm pitch. The material is uncoated Si(110).

The step height pattern developed in our laboratory consists of three parts as indicated in the sketch in Fig. 5. The lower part consists of a single step in the center of a 10mm wide by 5mm high flat region. One half of the region is high; the other half is low. Immediately above the step is a bar pattern with a 50 μm pitch and at the top of the chip is a bar pattern

with a 10 μm pitch. The lower part of the pattern, the single step, is useful for calibrating optical profiling instruments, which can operate with either linear array detectors or area array cameras. The size of the single-step area is large enough so that optical profilers with objectives as low as 1.5x magnification can be used without exceeding the lateral size of the chip. The bar pattern is useful for calibrating stylus profiling instruments. It is often extremely difficult to find a single edge with a stylus profiler. The bar patterns insure that one will find an edge with the probe on the first try, regardless of the lateral position of the stylus on the chip. And the uniformity of the etching process assures that the peak-to-valley height and the edge sharpness of the bars will be exactly the same as the single edge.

A number of prototype step height artifacts have been made in our laboratory. We are still in the process of optimizing the parameters of the lithography process. In order to assess the usefulness of the step as a calibration artifact for various types of profiling instruments, one of the steps was measured on a number of different profiling instruments and the data was returned to our lab and analyzed by our codes.³ The periodogram estimate of the power spectral density is computed for each profile using a Blackman data window and zero-padding the data to the next integral power of 2. Usually several PSD curves are averaged together to give the results appearing in the following plots. The step artifact that was used in most of the measurements in this assessment study had a nominal height of 147nm as measured by our Promap 512 system. We believe that the actual profile of the step is very square and nearly vertical - no evidence for any roundoff or finite slope was seen in any of the measurements by any of the instruments. Scanning electron microscope images of other structures produced in our laboratory by the same anisotropic etching processes have shown the wall structure to be nearly vertical.^{7,9}

Fig. 6 - Averaged PSD curves from measurements on the 147nm step with a Zygo Maxim 3D profiler. Blackman window is used on each profile. Two curves for the 40x objective are: in focus (lower solid) and deliberate defocus (upper dotted). An inverse-square curve is shown for reference purposes.

Fig 7. - "Normalized" PSD curves, i.e. PSD functions multiplied by the trace length, L, lie along the invariant line described by equation (4), which is unique for each step height.

Measurements

The power spectral density functions from a series of measurements made on the step with a Zygo Maxim 3D instrument are shown in Fig. 6. Measurements were made with 5 different magnification objectives, ranging from 2.5x to 40x. One can see the overall shape of each PSD curve follows the result of eqn (1), except at low spatial frequencies where the effect of the Blackman window causes the curve to first rise above the $1/f^2$ asymptote and then curve downward at the lowest frequencies. We can view these PSD curves in another way by multiplying each by the trace length, L, and then plotting the function $S(f) \cdot L$ vs. frequency. These "normalized" spectra are shown in Fig. 7. One can see that they indeed do lie along the invariant line represented by the constant coefficients in Eqn. (4).

A similar set of measurements with the step artifact was made using a Wyko TOPO 3D profiling instrument with objective magnifications ranging from 1.5x to 200x. The results of the PSD curves computed from several line profiles selected from each measurement frame are shown in Fig. 8. The normalized spectra, multiplied by the trace length, are shown in Fig. 9. Again, all of the profiles lie along the same invariant line and exhibit varying amounts of attenuation at high frequencies, as they should, since, for different objectives, the Nyquist frequency of the data array is not always the same fraction of the transfer function cutoff frequency.

Fig. 8 - Averaged PSD curves from measurements with a Wyko TOPO 3D profiler with Blackman window applied.

Fig. 9 - "Normalized" PSD curves for the Wyko measurements.

Fig. 10 - The effects of deliberate defocus with a Micromap Promap 512 profiler on the apparent edge shape. The 40x objective focus was stepped between ± 5 fringes. Positive fringe direction means the objective is closer to the surface. The phase reconstruction algorithm causes an apparent reversal of high and low as the overshoot near the edge goes over the $\lambda/4$ limit at the -5 fringe position.

Fig. 11 - PSDs calculated for the defocused Promap profiles. The curve labeled "focus" shows the normal high frequency attenuation expected for this objective. The uppermost dashed curve corresponds to the phase-reversed -5 fringe profile.

Defocus Effects

The effect of a deliberate defocus of the optical system on the measured power spectrum of the step was investigated with a Micromap Promap 512 instrument with a 40x objective. Measurements were made after deliberately defocusing the surface by increasing the distance to sample (negative fringes) or decreasing the distance (positive fringes) up to a maximum of 5 fringes in either direction. Figure 10 shows the measured height profiles from each focus setting in the narrow region within a few microns around the edge. One can see that the apparent slope of the edge changes with focus setting, becoming sharper as the distance to the sample increases (negative fringes). The power spectra for each of the conditions also confirms this behavior: the high frequency tail of the curve is higher for the negative fringes and lower for the positive fringes. This is a rather unexpected result, since we would expect that defocus in the optical system would degrade the optical transfer function to reduce the high frequency content in both cases.¹⁰ The odd curve in Fig 10 is a result of a $\pi/2$ phase ambiguity during the surface reconstruction from the intensity measurements. The step artifact is nearly $1/4$ wavelength in height at the 552 nm wavelength used in this measurement. As the edge became sharper in the field of view, as a result of increasing the distance between the sample and the objective, a slight amount of ringing at the bottom of the edge occurs. The ringing makes the apparent height of the edge exceed the $1/4$ wavelength limit, and the phase reconstruction algorithm interprets the entire row as being the inverse of what it should normally be. This is an extreme example of a non-linear optical system effect.

Scanning Probe Measurements

Measurements were also made on the step with scanning probe microscope profilers. Figures 12 and 13 show results from a Wyko SPM system using the atomic force mode over different scan lengths. The profile in Figure 12 is a segment from a 40 μm long trace across the 50 μm bar pattern part of the step artifact. Figure 13 is a segment from a 2.5 μm long trace across the same region of the bar pattern. One can see that the high, or unetched, side of the pattern is very smooth and flat, even at the extreme lateral magnification of the short trace length. The low, or etched, side of the pattern appears significantly rougher than the unetched side. However, the edge appears extremely sharp, and the actual slope of the edge (which is highly exaggerated in the vertical direction on this plot scale) is most likely a result of the actual shape of the stylus tip. The bar pattern edge is thus a good, easy-to-use diagnostic tool for assessing the quality of the probe tip in the AFM. The length-normalized PSD curves for the two AFM measurements are shown in Fig. 14. There is significant departure from the ideal $1/f^2$ spectrum, especially the high frequency end of each. The gradual fall-off in the mid-frequency range for each spectrum is probably a result of the finite tip shape and the fact that the step height is relatively large compared to the actual AFM tip radius. Non-linear effects in the system response function resulting from the non-vanishing tip size are more readily seen with large amplitude steps such as this one.¹¹ The fluctuations in the two spectra at high frequencies are probably a result of the residual surface roughness, mainly from the etched region of the pattern.

Fig. 12 - Measurements made with a Wyko SPM in atomic force mode on the 50 μm bar pattern. Curves are displaced both horizontally and vertically to show the edge sharpness.

Fig. 13 - Wyko SPM measurements at a slower scan rate provide higher resolution across the edge. The observed edge profile is most likely the shape of the stylus tip.

Fig. 14 - "Normalized" averaged spectra for the Wyko SPM measurements on the 147nm step. Departure from a $1/f^2$ curve is most likely a result of the tip radius on this relatively high step.

Fig. 15 - Measurements made with a DI Nanoscope III AFM with a stand-alone head on the 50μm bar pattern at 3 scan rates: 1Hz, 5Hz, and 10 Hz. Slight oscillations at the top right edge in the fastest scan rate are induced by the rapid flyback to the beginning of the scan line.

Fig. 16 - High-resolution scans over 2μm length made with the Nanoscope III AFM at the 3 scan rates. Periodic structure in the 1 Hz scan (lowest height curve) is a scan artifact. Structure in the edge is most likely caused by a problem with the tip: a measurement with this tip a few weeks earlier showed no structure in the edge.

Fig. 17 - PSD curves for the individual profiles in Figs. 15 and 16. The deviation from the inverse-square power law caused by the probe tip structure is evident at spatial periods shortward of about 2μm.

Measurements were made on the bar pattern with a Digital Instruments Nanoscope III AFM with a stand-alone head. Measurements were made over 2 different scan lengths: 45 μm and 2 μm, and at 3 different scan rates for each length: 1 Hz, 5 Hz, and 10 Hz. The scan rate refers to the rate at which each row in the image is scanned. The 45 μm long scans shown in Fig. 15 are practically identical, although the fastest scan rate shows ringing at the start of each scan row, which is a result of oscillations in the stylus caused by the rapid flyback and direction change that have not had the opportunity to damp out before the start of the next scan row. The 2 μm long scans shown in Fig. 16 show considerable structure across the edge. This is probably a result of damage or deterioration of the tip, since scans made with this same tip on the same step artifact a few weeks earlier show no excess structure. The unaveraged spectra from the 3 individual long scans, shown in the upper left in Fig. 17, are nearly identical over the low frequency range, which is as expected since the heights in the profiles are nearly

indistinguishable. The fastest scan rate curve shows some excess high frequency component because of the ringing. The spectra start to deviate from the $1/f^2$ curve at the frequency corresponding to about a $2\text{ }\mu\text{m}$ spatial period. Power spectra from the $2\text{ }\mu\text{m}$ scans are shown on the lower right of Fig. 17. One can see the considerable influence of the structure in the apparent edge on the details of the individual spectra.

Fig. 18 -

BRDF measurement of a 97nm high step made with a TMA CASI scatterometer instrument. A slit aperture was used to collect all of the light scattered out of the plane of incidence. As expected, away from the near-angle specular region the BRDF follows the inverse-square power law over 5 decades in intensity.

BRDF Measurement

The usefulness of the step artifact extends beyond the realm of the profiling instrument - it is also a useful item to use in calibrating BRDF scattered light measuring instruments. Since the amount of light scattered from a surface is directly related to the power spectrum of the surface roughness, it is reasonable to expect that the light "scattered" from the step artifact should also be directly proportional to the inverse-square power spectral density function of the step. We have confirmed this result by measuring the BRDF of a step artifact on a TMA CASI scatterometer. The BRDF measurement of a 97nm high step at a wavelength of 633nm is shown in Fig. 18. The beam diameter on the sample was about 2mm and the detector had a slit aperture in front of it to collect all of the light scattered out of the plane of incidence. The BRDF for a step illuminated by a Gaussian beam with a width, σ_0 , can be calculated from simple Fresnel-Kirchhoff scattering approximation for angles far from specular direction to be

$$\text{BRDF} = \frac{1}{(2\pi)^{5/2}} \cdot \frac{\cos^2 \theta_i}{\cos \theta_s} \cdot \frac{\sin^2(\beta H)}{\sigma_0 \lambda} \cdot \frac{1}{f^2} \quad (5)$$

where

$$\beta = \frac{\pi}{\lambda} (\cos \theta_s + \cos \theta_i) \quad (6)$$

and the spatial frequency is related to the angles of incidence and scatter through the grating equation

$$f = \frac{1}{\lambda} (\sin \theta_s - \sin \theta_i) \quad (7)$$

One can see from equation (5) the inverse-square dependence on spatial frequency of the scattered light, which is actually observed in the measurement in Fig. 18. A detailed analysis of the measurement is currently in progress to confirm that the absolute intensity of the scattered light agrees with the values of the other variables in equation (5), in particular the width of the illuminating beam, the step height and the angle of incidence.

Conclusions

The examples presented in this paper have demonstrated the step height artifact to be a useful diagnostic tool in assessing the performance of various types of profiling instruments. The key feature of the present artifact is that the underlying surface is both very smooth and flat. This makes it possible to compute the power spectral density function from the measured step and compare the result to the ideal PSD function with a minimum of distortion from errors in the substrate. The step artifact is useful in calibrating the vertical scale factor (the DC component) and also to measure the system transfer function attenuation at higher spatial frequencies. We have also demonstrated that the step is useful as a calibration artifact for BRDF scatterometer instruments, using the principle that the distribution of light scattered from any surface is directly proportional to power spectrum of the surface topography. We are continuing our analysis of the scatterometer result to develop the necessary connection between the incident beam parameters and the observed scattered power distribution.

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References

1. E.L. Church and P.Z. Takacs, "The optimal estimation of finish parameters," *Proc. SPIE* **1530**, 71-85 (1992). BNL 47567
2. E.L. Church, J.C. Dainty, D.M. Gale, and P.Z. Takacs, "Comparison of optical and mechanical measurements of surface finish," in *Optical Testing and Metrology II*, C.P. Grover, ed., *Proc. SPIE* **954**, 189-199 (1989). BNL 44892
3. E.L. Church and P.Z. Takacs, "Use of an optical-profiling instrument for the measurement of the figure and finish of optical-quality surfaces," *Wear* **109**, pp. 241-257, (1986), BNL 37800
4. E.L. Church and P.Z. Takacs, "Instrumental effects in surface finish measurement," in *Surface Measurement and Characterization*, J.M. Bennett, ed., *Proc. SPIE* **1009**, 46-55 (1989). BNL 44686
5. E.L. Church and P.Z. Takacs, "Effects of the optical transfer function in surface profile measurements," in *Surface Characterization and Testing II*, J.E. Grievenkamp and M. Young, ed., *Proc. SPIE* **1164**, 46-59 (1989). BNL 45542
6. E.L. Church, "Fractal surface finish," *Applied Optics* **27** (No. 8), pp. 1518-1526, (1988), BNL 41043
7. D.L. Kendall, "Vertical etching of silicon at very high aspect ratios," *Ann. Rev. Mater. Sci.* **9**, pp. 373-403, (1979)
8. E.L. Church and S.R. Lange, "Structure effects in optical surface metrology," in *Surface Characterization and Testing*, *Proc. SPIE* **680**, (1986). BNL 39216
9. J.B. Warren, "Material consideration in the microfabrication of grating microstructures for use in a laser-powered linear accelerator," *Mat. Res. Soc. Symp. Proc. Vol. 76*, pp. 129-133, (1987)
10. H.H. Hopkins, "The frequency response of a defocused optical system," *Proc. Roy. Soc. A* **231**, pp. 91-103, (1955)
11. E.L. Church and P.Z. Takacs, "Effects of the non-vanishing tip size in mechanical profile measurements," in *Optical Testing and Metrology III: Recent Advances in Industrial Optical Inspection*, C.P. Grover, ed., *Proc. SPIE* **1332**, 504-515 (1990). BNL 45578

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