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Peter Z. Takacs, Jeffrey Colbert, and Eugene L. Church

**Instrumentation Division, Brookhaven National Laboratory
Upton, New York 11973-5000**

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Survey of surface roughness properties of synchrotron radiation optics

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Abstract

Measurements of surface roughness were made on a large number of grazing incidence mirrors delivered for use at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. The measurements were made with a WYKO optical profiler using a 2.5X and a 10X objective and analyzed with our PROFILE code to generate an average periodogram representation for each surface. The data is presented in the form of representative profiles with all of the periodogram curves arranged according to figure type. Analysis of the periodograms allows one to compute bandwidth-limited values for RMS roughness and slope, to provide valuable feedback information to manufacturers regarding compliance with specifications, and to predict the performance of the optic at x-ray wavelengths.

Introduction

The performance of grazing incidence x-ray mirrors for synchrotron radiation (SR) applications is critically dependent upon the roughness properties of the reflecting surfaces. We have devoted a great effort over the past few years to develop the capability to measure and understand the effects of surface roughness on the scattering of light from optical surfaces. Mirrors delivered for use at the National Synchrotron Light Source are routinely checked for compliance with roughness specifications with an optical surface profiler capable of measuring surface spatial periods in the range from 3 micrometers to 5 millimeters. Over the past two years, we have amassed a body of data which enables us to make some generalizations about the nature of as-delivered mirror surfaces. The analysis indicates where problem areas may exist in the fabrication process for grazing incidence optics and provides an avenue of feedback from the customer to the manufacturer.

Purpose

The purpose of this survey is to present to the x-ray optics community a compilation of data made from real mirrors, not from test samples produced under fabrication conditions that have little or no bearing on the final process. These optical components range in size from 5 cm long to 70 cm long. The types of surface figures that we have seen include flats, spheres, cylinders, toroids, paraboloids, and ellipsoids. Materials that we have seen include fused silica, ZERODUR, float glass, CVD and REFEL silicon carbide, electroless nickel plate (ENP) on aluminum and copper substrates, copper electroplate, and single crystal silicon. The distribution of figure type as a function of material is indicated by an entry in the appropriate element of Table I. This study is not a parametric study of materials and finishing methods--we had no control over any of the input parameters of figure type, material, polishing method, etc. We have only been able to analyze what has been delivered to us for measurement.

The information that we are able to supply to end users regarding the surface roughness power spectral density can be used to predict the performance of the optic when used at a particular wavelength, angle of incidence, and focal distance. Our method has already been useful in guiding NSLS users in the selection of the best mirror when more than one is available for installation.¹

Surface characterization process

The measurements presented here represent our current capability to measure and understand surface finish problems. One result of our research has been the development of a method to specify surface finish characteristics in a way that is meaningful to users and manufacturers of x-ray optics. This method is based on the work of Church and collaborators who have investigated the use of various surface profiling devices in the measurement of surface microstructure and who have investigated the relationship of surface microstructure to scattering at visible and x-ray wavelengths.²

Measurements reported in this work were made with a WYKO NCP-1000 Digital Optical Profiler using 10X and 2.5X magnification objectives. Details on the design and operation of this instrument have been presented elsewhere (11-13) and will not be reproduced here.

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The instrument measures the surface profile in a non-contact manner over a trace length that depends on the magnification of the microinterferometer objective. The spatial frequency bandwidth of the measurement depends on the objective magnification, the full length of the 1024-pixel detector and the individual pixel size. The practical spatial period sampling interval for each objective is as follows:

10X: 1.3 mm to 2.6 μ m
2.5X: 5.0 mm to 9.8 μ m.

We routinely apply a restoration filter in the frequency domain to the Fourier transformed profile data to correct for attenuation by the objective at high frequencies. The short period limit used in our PROFILE analysis code is determined by the practical effects of MTF rolloff of the objective, the instrumental noise level, and sampling theory considerations.¹⁰

A flow diagram of the measurement process for a single mirror is indicated in Fig. 1. A series of profile measurements is made over a representative area of a mirror surface. The raw profile is detrended to remove piston, tilt and curvature. The resultant data set [Z] contains the residual roughness of the surface. Each profile is Fourier-transformed into the frequency domain to produce the periodogram corresponding to that profile. The inverse filter (MTF^{-1}) is applied to each periodogram to produce the restored periodogram (PR). Then all of the restored periodograms are averaged together to produce a single "surface average" periodogram, which is a statistical estimate of the true surface power spectral density (PSD). The surface average periodogram is then used in the computation of various statistical properties of the surface over the appropriate bandwidth-limited range. Typical quantities that can be computed are the RMS average surface roughness, $\langle \sigma \rangle$ and the RMS average slope error, $\langle m \rangle$. It must be understood that these quantities depend critically on the exact bandwidth used in the integration of the PSD curve. Specifying a $\langle \sigma \rangle$ RMS value without specifying a minimum and maximum spatial period or frequency is totally meaningless. An extreme example of the importance of specifying the bandwidth is illustrated in Fig. 2 for measurements made on a piece of thin (1/8 inch thick) float glass. Fig. 2(a) presents typical profiles for this surface with the profile made along the "float" direction (F) and transverse to the float direction (T). One can see that the profile in the F-direction is extremely smooth and flat, while the T-direction profile contains a rather pronounced, well-defined low frequency periodicity greater than one millimeter. The RMS roughness values over the full bandwidth also reflect this difference: $\langle \sigma \rangle = 2.86\text{\AA}$ for the F-direction, $\langle \sigma \rangle = 17.17\text{\AA}$ for the T-direction. But if one integrates the T-direction average periodogram over the spatial period range from 1 mm down to the short period cutoff at 9.8 μ m, the new value of the RMS roughness over this bandwidth is $\langle \sigma \rangle = 2.92\text{\AA}$, which is nearly identical to the F-direction value. Inspection of the periodogram in Fig. 2(b) shows that the two curves coincide for spatial periods shorter than 1 mm, so the result of the calculation is not surprising. What is remarkable is that this surface appears totally isotropic at spatial periods shorter than 1 mm, while exhibiting such anisotropic behavior at the low spatial frequencies. Additionally we can calculate the RMS slope error over selected bandwidths for this surface. Over the range from 5 mm to 1 mm spatial periods, the $\langle m \rangle$ value for the T-direction is 3 microradians, while for the F-direction it is about 1 microradian. Indeed, laying a straightedge along the maximum slope in the T-profile results in a value for this particular profile of about 5 microradians, which agrees very well with the RMS average of 3 microradians over ten profiles and periodograms.

Figure 1. A flow diagram indicating the generation of an average surface periodogram (PR) from a series of surface profile measurements on a particular mirror.

We have attempted to present a large body of data consisting of many variables in a way that would be meaningful and easy for intercomparison. Unfortunately, a problem with the focus of the 2.5X objective adds another degree of complexity to the intercomparison problem and makes it difficult to visualize the "true" periodogram. In the initial stages of installing the 2.5X objective on our WYKO profiler, the position of the reference surface was changed and the condition of zero path difference in the microinterferometer no longer coincided with the condition of focus at the detector array. Most of the 2.5X profiles and spectra were taken with the objective in the out-of-focus condition. This is illustrated in Fig. 3, in which three sets of measurements are presented for three different surfaces taken at different times with the 2.5X objective. The upper curve is the in-focus condition in each case, while the lower curve is the out-of-focus condition. The periodogram for the out-of-focus condition starts to diverge from the in-focus curve at a spatial frequency of about $0.01 \mu\text{m}^{-1}$, which is a $100 \mu\text{m}$ period. All spatial periods shorter than these are attenuated by varying degrees. This is the behavior one would expect for the modulation transfer function of a defocused optical system.¹⁴ We have not included the defocus attenuation of the higher frequencies in our inverse filter because it would result in the amplification of too much system noise, since the attenuated signals for most smooth surfaces fall rapidly into the system noise level at the higher spatial frequencies. The reader should beware that, in viewing the following periodogram curves, the 2.5X curves are usually in the out-of-focus condition and should avoid making generalizations based on the presented shape of the spectrum. In those few instances where we have data on the same surface with the 10X objective and the in-focus 2.5X objective, the spectra overlap very well in the appropriate frequency region.

Data set summary

The data presented in the following figures are summarized in Table I, which is a matrix representation of the range of surface roughness values measured for particular combinations of surface figure and type of material. An entry in the upper half of a box refers to measurements with the 2.5X objective; those in the lower half refer to the 10X objective. If more than one type of mirror was measured, the minimum and maximum RMS roughness values are indicated as an entry separated by a "slash" character. A few of the entries are in brackets - these are measurements on sample pieces and are not real mirrors, but the data is included for illustrative purposes. All other entries, except the ENP/Al (SPDT) paraboloids, are actual finished mirrors made for installation in a beam line at the NSLS. The paraboloid exceptions are unfinished mirrors measured in their as-machined state following manufacture by single-point diamond turning (SPDT).

The total number of data sets represented in this table is 54. Only in four cases were the same mirrors measured both at 10X and 2.5X. Most of the multiple entries are for only two mirrors, so each entry should not be regarded as a significant statistical sample. The numbers presented in the table should not be regarded as the best or even as typical of a particular figure-material combination. It should be completely understood that these measurements are of real mirrors that have been delivered for use at the NSLS in the past and do not indicate what one can get from a manufacturer in the future. Do not assume that these numbers are representative of a particular material-figure combination obtainable from any manufacturer. Much more work is needed to correlate measured roughness with manufacturing method in a systematic way.

Discussion of data

The data set is best presented by looking at all the periodograms for a particular figure type. We start with data for cylinders presented in Fig. 4. Typical profiles for the fused silica and single-crystal silicon cylinders are shown in 4(a), while the ZERODUR and chemical vapor deposited (CVD) silicon carbide (SiC) are shown in 4(b). These mirrors are all segments of cylinders of revolution with various minor radii and are not complete cylinders. In this case the SiC pieces are 30 cm long, while the remainder are all 70 cm long. Superposition of the corresponding periodogram curves reveal two groupings for the cylinders: the very smooth SiC curves are much lower than the other cylinders. This, however, should not be taken as a representative sample of the best that can be achieved with the other materials, since the method of manufacture of the long cylinders was entirely different from that of the SiC cylinders.¹⁵ Data from ENP/Al cylinder is not presented here, but it would lie within the upper grouping.

The next data set in Fig. 5 concerns toroidal mirrors and gratings. Fig. 5(a) shows representative profiles from the three material categories: fused silica, which is the smoothest, ENP/Al, and REFEL SiC. The REFEL material is a reaction-bonded SiC that contains about 20% free silicon in a matrix of SiC grains. During polishing the SiC grains become dislodged and pull out, leaving pits and scratches in the surface which are evident in the profile. The periodogram curves for all of the toroids are presented in 5(b). In this case there are three distinct groupings according to the material type. It should be

noted that the two ENP/Al toroids have identical specifications, but were made and polished by different vendors. The final RMS roughness values and periodogram curves for each are nearly identical, which may be a remarkable coincidence, or it may indicate the best that can be achieved with this material. None of the periodogram curves for ENP/Al from this or any other figure are ever as low as the best fused silica examples.

It should be noted that most of the fused silica toroids are actually toroidal diffraction gratings with grating line densities of 600 lines per mm or greater. The fundamental period of 1.6 μm far exceeds the short period cutoff of each objective and the resultant amplitude at that frequency, even though it is on the order of 100Å to 200Å, does not appear in the periodogram.

Ellipsoidal mirrors are presented in Fig. 6. Only two materials are represented - ENP/Al and one fused silica example. Again there are two groupings in the periodograms in 6(b) - the fused silica periodogram is significantly lower than the others.

Figure 7 is an incomplete presentation of data from spherical mirrors and gratings. All of the fused silica spheres are actually diffraction gratings with radii of curvatures on the order of a few meters. Figure 7(a) illustrates a systematic problem with the optical profiler in trying to measure a surface with a large amount of sag--in this case the sag resulted in about three circular fringes across the 5 mm field of view. If the piezoelectric driver in the objective is not calibrated properly and the total phase shift is greater than $\lambda/4$ across the field of view, the phase-to-height algorithm computes a residual phase error across each fringe boundary.¹⁵ Hence, a smooth surface appears to have ripples in it that are at twice the frequency of the fringe pattern. The computed value of the RMS roughness for the "pseudo" profile in 7(a) is 38.27Å, while the actual surface roughness is on the order of 4Å. This figure indicates that one must always insure that one is operating the profiler in a linear region in order to make a valid measurement. The other material presented in Fig. 7 is again REFEL SiC which was discussed in Fig. 5. The grain structure of the material is evident in this 10X profile. Periodograms of the spherical materials are presented in 7(c). The lower curve is that of the fused silica grating, showing the false, large amplitudes at low frequencies in the "pseudo" profile, while at high frequencies the curve approaches a typical smooth fused silica surface. The two upper curves for the REFEL SiC illustrate the good agreement over the entire frequency range between measurements made with an in-focus 2.5X objective and a 10X objective.

Examples of plane surfaces are shown in Figs. 8 and 9. Typical float glass and polished fused silica profiles are presented in 8(a). The thin float glass profiles from Fig. 2 are presented again for comparison with the other flats on the same scale. The periodograms in 8(b) do not differ very much for any of these materials. Figure 9 presents profiles and spectra for several CVD SiC plane surfaces which are in various stages of polish. Residual scratches are evident in the incomplete polish in the lower trace in 9(a). They manifest themselves in the upper periodogram curve in 9(b) as a larger amplitude at high frequencies. These curves are not examples of the best that can be achieved with this material, as evidenced by the results for the cylinder mirrors. Recent measurements on new CVD SiC plane mirrors delivered too late to be included in this compilation, show an average < σ > value of about 2.0Å, which is equivalent to the best fused silica surface.

The final figure type to be reported is the paraboloid. This data set consists of measurements made on a set of five off-axis paraboloidal mirrors (designated P1 - P5) that were diamond machined and then post-polished to remove the diamond-turning grooves.¹⁷ A comparison of the surface of a P2 paraboloid viewed at 2.5X and 10X is shown in Fig. 10(a) and (b). The 2.5X profile shows the large amount of low frequency content remaining on the surface after the cosmetic polishing step. This is evident in the periodograms of the P1-P4 mirrors presented in 10(c) as the large amplitude at low frequencies with a subsequent fall-off into the noise level at about 10 μm spatial period. In visible light these surfaces appear to be superpolished to an extremely low scatter finish. This is confirmed by the low value of the amplitude of the spectrum at high frequencies, since the eye is only sensitive to large angle scatter caused by spatial periods shorter than about 10 μm . The RMS roughness values for these spectra integrated over the 10 μm and shorter bandwidth is essentially the noise level of the instrument, i.e., about 1Å RMS in each case. So the experienced eye would classify these surfaces as better than a few Angstroms RMS, when in reality there is a large amount of near-angle scatter that does not show up in a visible light test. Measurements made with the 2.5X objective on two of the mirrors are compared with periodograms from the 10X objective in Fig. 10(d) and show that the amplitudes at the lower frequencies, in the range of millimeter spatial periods, are even greater than the highest 10X values. These measurements have confirmed that the limit on the performance of the NSLS plane grating monochromator is not the source size or monochromator design, but is the near angle scatter (slope error) caused by the low frequency content in the periodogram.¹⁸

For purposes of comparison, profiles and spectra of the unpolished, as-machined ENP/A1 paraboloids are shown in Fig. 11. One notices the large amplitude low frequency undulations in the profiles, sometimes very periodic as in the case of the P5 mirror shown in 11(b). These undulations are many times the tool feed rate, which was on the order of tens of microns. Note the vertical scale change in the final two panels. Periodograms of the five SPDT surfaces are presented in 11(c), showing peaks that correspond to the various frequencies in the machining process and large amplitudes at low frequencies. It is these frequencies that are difficult to remove in the polishing process.

Conclusion

We have presented most of the data available to date on the surface roughness properties of real grazing incidence optical components that have been delivered for use at the NSLS. Through the use of optical profiling techniques and data analysis with our own PROFILE code, we are able to arrive at a statistical estimate of surface roughness based on calculation of the average periodogram for a given surface. We can use this information to predict the performance of the surface under actual operating conditions in SR beamlines. The data presented here should not be construed as being representative of any particular material or figure. There are many other variables that influence the outcome of a particular mirror surface over which we had no control. These data can, however, be used for comparison purposes with future measurements and as a guide to show the direction in which improvements can be made in a particular process. The average periodogram computed from a set of surface profile measurements now forms the basis of a surface finish specification used in procuring optics for the NSLS at Brookhaven National Laboratory.

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Disclaimer

Certain items of commercial equipment are identified in this paper in order to specify the experimental procedure. In no case does such an identification imply recommendation or endorsement by the U. S. Department of Energy.

Table 1. RMS roughness values in Angstroms as a function of material and figure type for real mirrors delivered for use at the NSLS. Measurements made with the 2.5X WYKO objective are entered in the upper half of each box; 10X objective measurements are entered in the lower half. Where applicable, a range of values for a particular entry when more than one mirror was measured is indicated by the minimum and maximum values separated by a slash. Measurements made on test samples are enclosed in brackets.

	Plano	Sphere	Cylinder	Toroid	Paraboloid	Ellipsoid
ENP/Al			40.5	12.3/13.8	30.4/36.0 22.7/29.8	11.6/20.0
Fused Silica	2.6/4.7	4	41.0/83.3	4.3/6.9 2.1/4.4		4.5
Zerodur			16.0			
CVD SiC	10.4/20.3		2.8/3.5			
REFEL SiC		62.1 59.4		59.5		
Float Glass	[2.8/17.2] 3.5/3.7					
Single-crystal Si			25.3/28.6			
ENP on Cu	18.0					
ENP/Al (SPDT)					87.5/399.0	
Cu electroplate (SPDT)	37.2/40.4 [13.6]

Figure 2. a) Profiles of the surface of anisotropic thin float glass at 2.5X magnification. F = parallel to float direction; T = transverse to float direction. The T-direction exhibits a well-defined low frequency periodicity; b) Comparison of the averaged PSD curves for the F- and T-directions. The integrated RMS roughness values over the full measurement bandwidth are $\langle \sigma \rangle = 2.86 \text{ \AA}$ in the F-direction and $17.17 \text{ \AA}$ in the T-direction, most of the power in the lowest frequency components, i.e., at spatial periods greater than 1 mm. Note that at higher spatial frequencies, the shape of the spectra and the corresponding RMS roughness values are nearly identical. The instrumental noise level is nearly flat at a value of about $2 \times 10^{-7} \text{ \AA}^2$, which corresponds to an RMS surface roughness of about 1 \text{ \AA}.

Figure 3. a) Average restored periodograms for a plano SPDT copper surface computed from measurements taken with the 2.5X objective when it was out of focus (lower curve) and in focus (upper curve). The curves diverge only for spatial periods shorter than $100 \text{ \mu m}$. Since most of the roughness power is at longer periods, the correction for being out of focus is negligible for this surface and for other surfaces with similar PSD curves. b) Periodogram for the P2 mirror taken with the 2.5X objective in focus (upper) and out-of-focus (lower), showing the distortion in the shape of the spectrum by the out-of-focus condition. c) Same comparison for the P1 mirror. Harmonics of the fundamental frequency component are more readily apparent in the f^{-3} high frequency tail.

Figure 5. a) Typical profiles of toroidal mirrors and gratings: (Upper) Fused silica mirror with $\langle\sigma\rangle = 4.48\text{\AA}$ RMS; (middle) ENP/Al mirror with $\langle\sigma\rangle = 12.39\text{\AA}$; (Lower) REFEL SiC mirror showing the extremely grainy nature of this material, $\langle\sigma\rangle = 59.53\text{\AA}$. The REFEL profile was made with the 2.5X objective, but only the first 1.3 mm are plotted to allow for comparison with the other data files taken with the 10X objective. b) Periodograms of the toroidal surfaces. A = REFEL SiC mirror; B = Two ENP/Al mirrors of identical specifications made by different manufacturers; C = Five fused silica surfaces, one which is a mirror, the others are gratings with ruling periodicities beyond the high frequency cutoff of the profiler. All of the fused silica pieces exhibit the same basic PSD curve in both slope and magnitude.

Figure 4. a) Typical profiles from a fused silica cylinder mirror 70 cm long with $\langle\sigma\rangle = 83.3\text{\AA}$ (upper trace) and from a single crystal silicon mirror of the same size with $\langle\sigma\rangle = 25.3\text{\AA}$ (lower trace). b) Profile from a ZERODUR cylinder (upper trace) 70 cm long with $\langle\sigma\rangle = 16.0\text{\AA}$; Profile from a CVD SiC cylinder 50 cm long (lower trace) with $\langle\sigma\rangle = 2.86\text{\AA}$. c) Comparison of all the cylinder PSD curves. A = Two fused silica mirrors with $\langle\sigma\rangle$ values of 83.3Å and 41.0Å; B = Two single crystal silicon mirrors with $\langle\sigma\rangle = 28.69$ and 25.33Å; C = ZERODUR mirror with $\langle\sigma\rangle = 16.0\text{\AA}$; D = Two CVD SiC mirrors with $\langle\sigma\rangle$ RMS of 3.49Å and 2.86Å.

Figure 6. a) Typical profiles for ellipsoidal mirrors: (Upper) Fused silica with $\langle \sigma \rangle = 4.49\text{\AA}$ RMS; (Lower) ENP/Al with $\langle \sigma \rangle = 18.62\text{\AA}$ RMS. b) Periodograms of ellipsoidal mirrors, all at 10X magnification: A = Four ENP/Al surfaces with $\langle \sigma \rangle$ values that range from 12Å to 20Å RMS; B = Single fused silica ellipsoid with $\langle \sigma \rangle = 4.49\text{\AA}$.

Figure 7. a) "Profile" of a smooth spherical grating surface at 2.5X with a radius of curvature of 3.71 meters. The low frequency structure is an artifact of the measurement process, owing to the small value of the spherical radius. (See text for discussion.) The "roughness" value in this profile is computed to be $38.27\text{\AA}$, while the actual surface exhibits a $4\text{\AA}$ roughness. b) Profile of a rhodium-coated REFEL SiC sphere with a 1 km radius of curvature at 10X magnification, $\langle \sigma \rangle = 59.41\text{\AA}$. The grain structure of the material is readily apparent. c) Upper two curves are periodograms of the REFEL SiC sphere taken with the 2.5X and 10X objectives. The agreement in the frequency range of overlap is excellent. Lower curve is for the fused silica grating, which exhibits large amplitude at low frequency, owing to the phase error artifacts.

Figure 8. a) Typical profiles of plane surfaces at 2.5X magnification: A = Fused silica, $\langle\sigma\rangle = 4.70\text{\AA}$; B = Thick float glass, $\langle\sigma\rangle = 3.63\text{\AA}$; F = Thin float glass (parallel to float direction), $\langle\sigma\rangle = 2.86\text{\AA}$; T = Thin float glass (transverse to float direction), $\langle\sigma\rangle = 17.17\text{\AA}$. b) Superposition of several float glass and fused silica periodograms at various magnifications. All exhibit the same basic shape and general amplitude level characteristic of superpolished surfaces.

Figure 9. a) Profiles of CVD SiC plane surfaces at 2.5X magnification: (Upper) $\langle\sigma\rangle = 11.6\text{\AA}$ RMS; (Lower) Incomplete polish, $\langle\sigma\rangle = 19.28\text{\AA}$ RMS. b) Periodograms of SiC plane surfaces. A = Two different mirrors with an incomplete polish, PSD curves are nearly identical; B = Three flats with a more complete polish with RMS roughness levels around $11\text{\AA}$.

Figure 10. a) Profile of a polished ENP/Al P2 paraboloid at 2.5X. b) Profile of the same paraboloid at 10X. c) Periodograms of the four P1 - P4 paraboloids, showing the similarity among all the curves. The average roughness ranges from 25Å to 30Å for this data set. The P2 mirror exhibits some high frequency structure that manifests itself by an upturn in the spectrum at high frequencies. d) Comparison of periodograms of the P1 and P2 polished paraboloids taken with the 10X objective (A) and the 2.5X objective (B). The falloff at frequencies greater than $10^{-2} \text{ } \mu\text{m}^{-1}$ in curve (B) is caused by the out-of-focus 2.5X objective. The agreement at low frequencies is quite good. RMS roughness values over the appropriate bandwidth limits for P1 and P2 at 10X are 25.8Å and 29.8Å, respectively, and at 2.5X are 30.4Å and 36.1Å.

Figure 11. a) Profile of an unpolished "as machined" ENP/Al P2 paraboloid, $\langle \sigma \rangle = 91.2\text{\AA}$. b) Profile of an unpolished "as machined" ENP/Al P5 paraboloid, which shows large periodic fluctuations in the residual diamond machining tool marks. Note the change in vertical scale; $\langle \sigma \rangle = 399\text{\AA}$. c) Periodograms of the 5 ENP/Al paraboloidal mirrors. Note change in vertical scale for comparison to previous figures. P1 and P5 exhibit large amounts of low frequency periodicity, as evidenced by a nearly flat amplitude spectrum at low frequency.