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Power Spectral Density Specifications for High-Power Laser Systems

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ABSTRACT

This paper describes the use of Fourier techniques to characterize the transmitted and reflected wavefront of optical components. Specifically, a power spectral density, (PSD), approach is used. High power solid-state lasers exhibit non-linear amplification of specific spatial frequencies. Thus, specifications that limit the amplitude of these spatial frequencies are necessary in the design of these systems. Further, NIF optical components have square, rectangular or irregularly shaped apertures with major dimensions up-to 800 mm. Components with non-circular apertures can not be analyzed correctly with Zernicke polynomials since these functions are an orthogonal set for circular apertures only. A more complete and powerful representation of the optical wavefront can be obtained by Fourier analysis in 1 or 2 dimensions. The PSD is obtained from the amplitude of frequency components present in the Fourier spectrum. The shape of a resultant wavefront or the focal spot of a complex multi-component laser system can be calculated and optimized using PSDs of the individual optical components which comprise the system. Surface roughness can be calculated over a range of spatial scale-lengths by integrating the PSD. Finally, since the optical transfer function (OTF) of the instruments used to measure the wavefront degrades at high spatial frequencies, the PSD of an optical component is underestimated. We can correct for this error by modifying the PSD function to restore high spatial frequency information. The strengths of PSD analysis are leading us to develop optical specifications incorporating this function for the planned National Ignition Facility (NIF).

Keywords:
power spectral density, PSD, optical component specification, wavefront, Fourier analysis

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1. INTRODUCTION

Specification of the optics in a laser system plays a critical role in the subsequent system performance. In high power solid-state laser systems, phase modulations in the beam caused by imperfections in the optics are transformed into intensity modulations and undergo non-linear gain when they occur at certain spatial frequencies[1]. Surface roughness of the optics also causes scatter and divergence in the laser beam. These are critical aspects of the system performance. In order to meet NIF performance and cost goals, the design of this laser system will push current laser technology to the limits of performance[2]. Specification of the optics must include information about the amplitude of spatial frequency of the phase errors present, in addition to more conventional information such as surface roughness and figure error.

Optical specifications have been experiencing a revolution over recent years, due partially to increased performance requirements and partially by increased measurement capability. X-ray optics and other applications requiring tight control of surface roughness have driven the development of analytic techniques specifying, in detail, aspects of surface roughness and scattering behavior[3]. Standards now being proposed will not specify surface roughness in terms of a single number, but instead use the 2D PSD function[4-5]. These analytic techniques have a broad basis of applicability. Our study to optimize the performance versus cost of proposed solid-state laser systems has determined that specifications based on the PSD are the most effective for controlling mid-spatial wavelength errors (specifically any modulation from 33 mm to 0.120 mm in spatial period). Such errors, commonly generated by cost effective, deterministic finishing techniques, can induce laser damage, as well as cause energy loss and inability to focus the energy on target. We have developed a Fourier technique using the PSD function to analyze high spatial resolution, phase-shifting interferometric data from prototypic optics. These tools have enabled us to quantify the spatial frequency content of the optical components proposed for the NIF.

2. APPROACH

With the advent of phase-shifting interferometry and high resolution solid-state cameras, the spatial resolution and information content of interferometric measurements has grown markedly over that available from static fringe analysis. The wavefront measurements reported here have been obtained using several phase-shifting interferometers available at Lawrence Livermore National Lab.[6] These instruments provide two dimensional arrays of wavefront information, typically expressed as waves at HeNe (6328 Å), over apertures from approximately 200 microns square to 300 mm square. We use Fourier techniques to analyze wavefront data. There exist in the literature several treatments of Fourier analysis and the power spectral density function for this type of application[3,5,7-8] . Since our approach has been described in detail in a previous publication[9], we will briefly summarize the process by which we go from an optical measurement to the analysis of the PSD.

2.1 FOURIER DOMAIN

For our purposes, we want to express the measurement of the phase retardation of a transmissive optic (or, alternately, the phase retardation due to the surface contour of a reflective optic) in terms of its spatial frequencies. Specifically, we measure a set of N discrete, evenly spaced data points, $\phi(n)$, along a length, l, or a similar array of N_x by N_y measurements, $\phi(m,n)$, over an area, l_x by l_y. The frequency content of the finite scan length is limited to discrete spatial frequencies, ν, less than the Nyquist cutoff frequency. Thus, using standard computational packages[10], we calculate $\Phi(\nu)$, the finite Fourier Transform of $\phi(n)$:

$$\Phi(\nu) = 1/N \sum_{n=0}^{N-1} \phi(n)\, e^{-j2\pi\nu n/N} \qquad (1)$$

and

$$\Phi(\nu_x,\nu_y) = 1/(Nx \bullet Ny) \sum_{m=0}^{N_x-1} \sum_{n=0}^{N_y-1} \phi(m,n)\, e^{-j2\pi(\nu_x m/N_x + \nu_y n/N_y)}. \qquad (2)$$

The effect of the finite sample is mitigated by the use of a windowing function. Specifically, we use a Hanning window in both the 1D and 2D analysis. This broadens (or 'blurs') the resulting width of the spatial frequency structure, but eliminates frequencies generated by the discontinuities at the edge of the sample. We also correct for the loss of signal due to the application of the windowing function, ensuring that subsequent calculations of the PSD and rms phase error retain quantitative information[11].

2.2 PSD

We calculate the PSD using the formula

$$PSD(\nu) = \Phi^*(\nu) \bullet \Phi(\nu) \bullet l \qquad (3)$$

or in the 2D case,

$$PSD(\nu_x,\nu_y) = \Phi^*(\nu_x,\nu_y) \bullet \Phi(\nu_x,\nu_y) \bullet l_x \bullet l_y\,. \qquad (4)$$

While the PSD has the advantage of being a real quantity which expresses the spectral distribution of the wavefront error, it does not possess any relative phase information in the Fourier domain. Thus, specifications based on the PSD do not uniquely specify a given wavefront, but instead an ensemble of wavefronts, each possessing similar spatial frequencies without necessarily being correlated with one another. Since the PSD in our case is the spectral distribution of the wavefront error, we can calculate the rms wavefront error of any spatial frequency band ($\nu_1 - \nu_2$) by integrating the PSD over that band. That is,

$$\mathbf{rms_{1D}\ (\nu_1 - \nu_2) = \sqrt{\left(\sum_{\nu=\nu_1}^{\nu_2} PSD(\nu) \bullet \Delta\nu \right)}} \qquad \mathbf{(5)}$$

where $\Delta\nu = (l)^{-1}$ and, equivalently, for a 2D frequency range ($\nu_{x1} - \nu_{x2}$, $\nu_{y1} - \nu_{y2}$)

$$\mathbf{rms_{2D}\ (\nu_{x1} - \nu_{x2}, \nu_{y1} - \nu_{y2}) = \sqrt{\left(\sum_{\nu_x=\nu_{x1}}^{\nu_{x2}} \sum_{\nu_y=\nu_{y1}}^{\nu_{y2}} PSD(\nu_x,\nu_y) \bullet \Delta\nu_x \bullet \Delta\nu_y \right)}} \qquad \mathbf{(6)}$$

where $\Delta\nu_x = (l_x)^{-1}$ and $\Delta\nu_y = (l_y)^{-1}$.

__2.3 1D vs 2D__

Although the actual calculations are similar in 1D and 2D, certain aspects of the two analyses strongly differ. A 1D profile across a surface samples only a small portion of the surface and is limited by low signal to noise. 2D calculations improve the signal to noise greatly by using all available data to build the Fourier spectrum. The 1D results can be improved by taking multiple profiles and averaging the resulting PSDs. Alternately, we can compute a 1D PSD by integrating over one of the two variables in the 2D PSD, i.e.,

$$\mathbf{PSD(\nu_x) = \int_{-\infty}^{\infty} PSD(\nu_x,\nu_y)\ dy} \qquad \mathbf{(7)}$$

or for discrete sums,

$$\mathbf{PSD(\nu_x) = \sum_{\nu_y=\nu_{y1}}^{\nu_{y2}} PSD(\nu_x,\nu_y)\ \Delta y.} \qquad \mathbf{(8)}$$

This approach only makes sense if either the direction over which the integration is done is perpendicular to the direction of peak modulation or the modulation is homogeneous. We accomplish this by calculating the 2D PSD, determining the orientation of the peak values, and integrating along the perpendicular direction. This result is comparable to the results of the 1D analysis when the 1D profiles are taken along the direction of peak modulation.

While 1D analysis is conceptually easier to understand, actual wavefronts are often not uniformly random or not modulated only along one direction, i.e. cases which can easily characterized by a 1D description. Some of the wavefronts of optics which we are measuring have highly complex structure. Specifications are best made based on a 2D analysis for these types of optics. Alternately, 1D specifications must be based upon the direction suffering the worst modulation. One of the primary drawbacks to making 2D specifications appears to be the limitations imposed by existing commercial software packages for the commonly used interferometers. Until 2D calculations become more prevalent, 2D specifications will require post-processing of the measured data using custom software similar to that which we have written.

3.0 PSD ANALYSIS PROGRAM

The analytic approach outlined above has been incorporated into a computer program written in Interactive Data Language© (IDL) and named PHANALY© (PHase ANALYsis). IDL© is a graphics-oriented language developed by Research Systems, Inc. which incorporates standard image processing tools, such as the Fast Fourier Transform (FFT) and the Hanning window, as integral to the language. PHANALY© makes extensive use of these image processing tools, in addition to IDL©'s array manipulation, algorithms, and widget programming, to produce a user-friendly interface that calculates and displays the PSD for a chosen input file.

3.1 SUMMARY OF THE METHOD OF SOLUTION

PHANALY© reads wavefront files acquired from interferometry measurements of the wavefront either reflected or transmitted from an optical element. The wavefront data format is consistent with that used in Laser Program's propagation modeling effort. The wavefront maps are displayed as a 2D false-color image of the 3D data or as a 3D surface contour. The wavefront has a Hanning filter applied to it prior to the application of a 2D Fast Fourier Transform (FFT). The result of the FFT is used to calculate a 2D PSD. The 2D PSD can be displayed in a choice of graphical representation or can be collapsed to a 1D representation by integrating the PSD over one of the two dimensions. The 1D collapse can be displayed over a range of angles, to sample the variation in 1D behavior. Ranges over which the data is expected to be valid, along with sample specification curves are also displayed with the 1D PSD information. Choices between the different calculations and graphical representations available are presented in a widget-based format that allows simple operation of the program.

3.2 DETAILED DESCRIPTION OF THE PROGRAM

PHANALY© is written in the interactive data language, IDL©, developed by Research Systems, Inc.

For our applications, the input file is a two-dimensional measurement of an optical wavefront, taken either in reflection or transmission using a phase-stepping interferometer. The reflected measurement can be considered a measurement of surface contour of the optic, while the transmitted measurement is a combined effect from the surface contour of two surfaces and the bulk inhomogeneities present in the optic. The input file is assumed to be in one of several allowed formats. The phs format, designed for our propagation modeling analysis, is an ASCII file format that, after specifying a series of pertinent parameters, lists the entire x axis. Then for every value of y, the file lists y and z(x,y). Z is specified in waves at 1.053 microns, while x and y are given in centimeters. Binary ZYGO© and WYKO© data files are also an input option in the program.

After being read into the program, the wavefront information is converted from units of waves into units of nanometers. The x and y axes are converted to units of millimeters. Further, the data is checked to insure that there is a mean of zero, i.e., there is no height offset to the data. Any tilt (i.e., uniform slope) is assumed to have been removed from the data at a prior point in time. A 2D Hanning window (i.e. $\cos^2(\pi x/l_x)\cos^2(\pi y/l_y)$, where l_x, l_y are the lengths of the x and y axes) is also applied to the data prior to calculating the FFT. The PSD is calculated by taking the square of the absolute value of the FFT of the data, then multiplying by l_x and l_y. The multiplication is equivalent to division by the spatial frequency bin sizes;

$$\Delta v_x = 1/l_x, \quad (9a)$$

$$\Delta v_y = 1/l_y. \quad (9b)$$

The root-mean-square (rms) of the surface is computed from the surface height data. The rms is also computed over various frequency ranges by summing the PSD over the frequency range.

PHANALY© offers many options in the way that the 2D PSD is displayed. The PSD can be shown as a false-color image on a linear or logarithmic scale, as a contour plot with either linear or logarithmic contours, or as a surface plot with either linear or logarithmic scaling. The color table for the false-color display can be chosen from a variety of options. The PSD can also be displayed versus the radial spatial frequency.

PHANALY© offers the option of reducing the 2D PSD to a 1D representation by an integration over the orthogonal direction as described above. The user is given the choice of multiple plots, spanning the 2D image at chosen angular intervals, or a single 1D plot in the orientation specified. The integration is achieved by using the IDL Riemann function which computes the ray sums along a view vector, P, given an angle, θ, through a 2D array. (This is more properly referred to as a Radon transformation[12].) This 1D representation is equivalent to the average PSD based on all possible 1D lines extracted at that angle from the 2D image, resulting in much higher in signal-to-noise than calculations based on 1D lines extracted from the 2D image.

Superimposed on the 1D representation of the PSD is the range of valid data. Based on Fourier analysis considerations[3], we limit the valid data to between three times the minimum resolvable frequency

$$\nu_{min} = (3 * 2/l) \tag{10}$$

and half of the Nyquist frequency,

$$\nu_x = (1/2 * N/2l), \tag{11}$$

where N is the number of points in the Riemann view vector and l is the length of the view vector. Also plotted on the 1D PSD representation, for reference, is an optical specification for transmissive optics, $PSD_{max}(\nu) = A\,\nu^{-B}$. The coefficient (A) and power (B) of this draft specification can be changed within the program.

In addition to options on the graphical representation of the PSD, the wavefront data can be redisplayed at any time as a false-color image or as a surface plot. The option is also available to sub-section the wavefront data into a smaller array. This option is useful when the data consists of a circular patch of data surrounded by zero or NODATA values. The sub-section option also is useful if a region of the data has an artifact or missing pixels that might confuse the results of the analysis. Sub-sectioning reduces the number of points and the extent of the axes, resulting in an increase in the minimum resolvable spatial frequency and an increase in the size of the frequency bins, but the maximum spatial frequency remains constant.

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4. EFFECT OF INSTRUMENT RESPONSE

Calculations of the PSD described above do not take into consideration the measurement limitations of interferometers. Calculations based only on the issues listed above will show a non-exponential downward trend in PSD with increasing spatial frequency. In fact, the PSD of a given optic at a particular frequency calculated for two measurements at different magnifications will not, in general, give the same magnitude. This behavior is typical of data which do not adequately account for the frequency response of the instrument making the measurement.[13,14]

Currently, we are measuring the optical transfer function (OTF) of the instruments which we are using. Analytically, we know that the OTF will primarily contain contributions from the interferometer optical system and from the detector. The complex (and often proprietary) optical system design of the interferometers makes calculation of the actual optical contribution problematic. Thus, we have chosen to determine the OTF experimentally. To do this, we measure a test pattern of known amplitude and spatial frequency content (an abrupt discontinuity of known height and known transition distance works well[15]). We then compare the Fourier amplitude calculated from the measurement to the Fourier amplitude known from calibration of the test pattern. The OTF(v) is the ratio of these two, i.e.

$$\mathbf{OTF}(\nu) = \Phi(\nu)_{\mathbf{measurement}} / \Phi(\nu)_{\mathbf{known}} \quad . \qquad \mathbf{(12)}$$

Previous investigations have shown that deconvolution of the OTF from the data is effective and can be used to join measurements made over different apertures into one extended profile[3].

We are also investigating a technique for producing phase objects with a prescribed PSD, such as a constant Fourier amplitude with increasing spatial frequency. This approach will circumvent the signal-to-noise limitations encountered with using a step discontinuity, whose Fourier terms decrease in magnitude as $(1/\nu)$ with increasing spatial frequency.

5. RESULTS

To date, we have made hundreds of measurements of optics on phase-shifting interferometers. From this data we have calculated the PSD's for various types of optics. The properties of these surfaces have been modeled and incorporated in our laser performance modeling. We use the phase information from the interferograms to create simulated optics that are the correct dimension and have the correct spatial frequency signatures. One interesting case that we have investigated is the effect of phase modulation evident in a amplifier slab from the Beamlet laser system[16] (a physics prototype of the NIF laser system). This slab exhibits strong periodic phase ripple at a spatial period close to 5 mm. Unfortunately, there is a peak in the non-linear gain spectrum for NIF near 5mm spatial period. Simulations of the NIF laser chain that used data from this slab showed unacceptable intensity modulation. In contrast, other slabs showed little if any similar structure. Simulations of NIF performance using data from these alternate slabs appear acceptable. Thus, initial optical specifications for NIF laser slabs have been drafted that would fail the offending slab, but would pass other Beamlet slabs.

We have tested the veracity of our PSD-base phased aberrations by comparing the results of our laser performance models with measurements on the Beamlet laser system. Recent experiments have provided a measure of the spatial frequency distribution present in the Beamlet laser chain. By blocking the central focal spot (which corresponds to the main, unperturbed beam), we obtain Schlieren data, a measure of how the beam is being effected by phase errors and other perturbations. Detail about these features is usually obscured in focal measurements of the beam due to the strength of the central focal spot and limited dynamic range. Initial results of the comparison between the Schlieren data and model predictions are in very good qualitative agreement. We are working on understanding the limitations of the laser performance model and improvements needed to bring the data and predictions into quantitative agreement. We need to understand the origin of the spatial frequencies (i.e., phase aberrations which we can measure off-line), the way the various elements add (constructively or destructively) and the effect of non-linear gain on certain spatial frequencies in order correctly model Beamlet performance.

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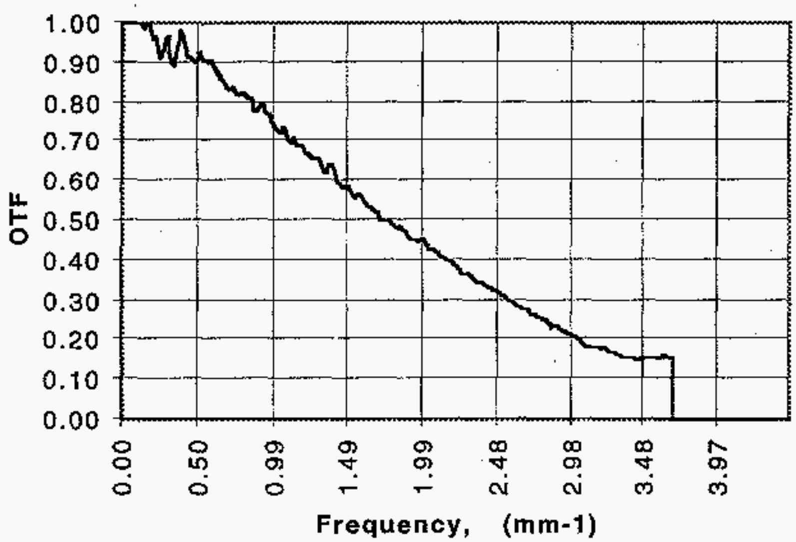


Figure 1. Optical transfer function (OTF) computed from a measurement of a reflective step made on a Wyko phase-shifting interferometer.

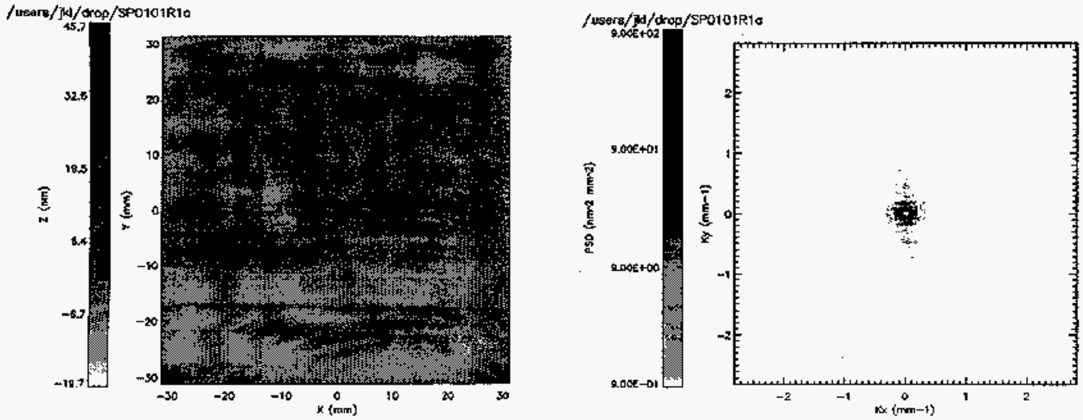
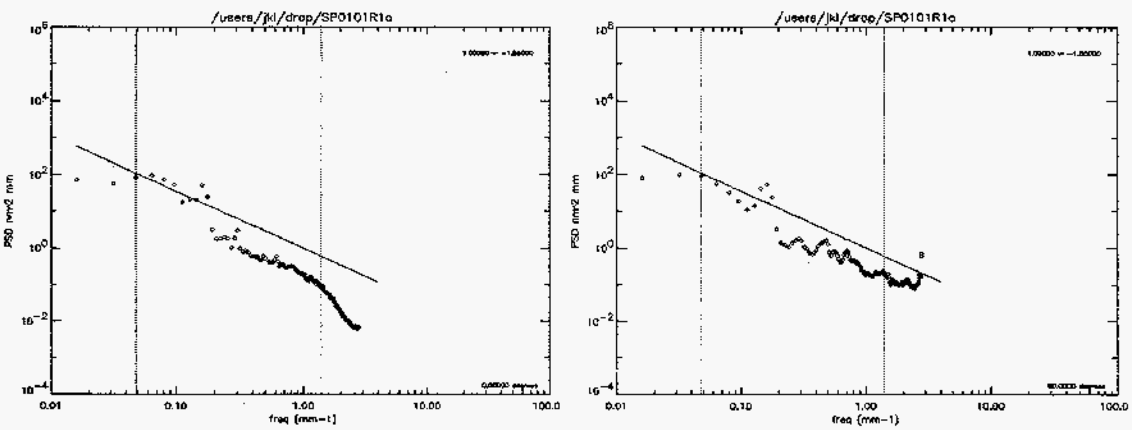


Figure 2. The measured surface contour of a fused silica optic finished with a small-tool process and its PSD.



(a) (b)

Figure 3. The 1D PSD extracted from the 2D PSD shown above, (a) along the x-axis and (b) along the y-axis.

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