The origin and evolution of the optics specifications for the National Ignition Facility

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ABSTRACT

In the second half of the 1990's, LLNL and others will be designing and beginning construction of the National Ignition Facility (NIF). At more than 10 times the power and size of the Nova laser system, this new laser will be capable of producing the worlds first controlled fusion ignition and burn, completing a vital milestone on the path to Fusion Energy.

In order to optimize the performance of the laser system for a minimum cost, we have been conducting a campaign to properly specify the optical properties of the more than 7,500 large optical components to be deployed in the NIF. The draft optics specifications derived from this effort will be presented. The evolution of these specifications, both in language and in content, will be discussed, specifically transmitted wavefront (both P-V and PSD), scratch/dig, surface roughness, bubbles and inclusions specifications.

Keywords: Specifications, transmitted wavefront, National Ignition Facility, NIF, Power Spectral Density, PSD, high energy lasers

1. HISTORICAL PERSPECTIVE

The laser program at LLNL has focused on the construction of large glass lasers for Inertially Confined Fusion (ICF) for more than 20 years. During that time, little has changed regarding the specification of these optics, in terms of format or content. Now we are embarking on an effort to construct a laser large enough to provide fusion ignition; some 1.8 MJ of UV energy. While little has changed regarding the specification of optics at LLNL since Argus in 1975 (except, of course, regarding damaging inclusions during Nova[1]), the metrology and fabrication capability of the optics manufacturers has improved dramatically, most notably with the advent and promulgation of phase measuring interferometry since 1985. In addition over the same period, we have learned a great deal about the functioning and performance of these large, high energy laser systems. LLNL is currently working with CEL-V in France to re-write the optics specifications for the newer lasers from the bottom up. For historical perspective, however, it is useful to see the evolution of these specifications over the years. What follows is a series of specifications for the most critical element in a large high energy glass laser; the final amplifier slabs. Listed are the specifications for homogeneity, bubbles, inclusions, scratch/dig, and transmitted wavefront, and pertinent inspection guidelines.

1.1 Argus (circa 1975)

The first large glass laser constructed at LLNL for ICF research was the Argus laser. (Elliptical disks, maximum dimension: 398 mm) The optics specifications for Argus for the parameters of bubbles, inclusions, homogeneity, scratch, dig, and transmitted wavefront, were as follows.

1. Homogeneity (reference) to meet wavefront specifications with perfect surfaces: $\Delta n \leq 2.6 \times 10^{-6}$ (Equivalent to $\pm 1.3 \times 10^{-6}$). This tolerance is for reference only, and relates to aperture critical to wavefront distortion (see note 4 below).

2. Bubbles: Bubble and inclusion cross section not to exceed 0.03 mm^2/100 cc. No single bubble is to exceed 200 μm over the area contained within central 141 x 296 ellipse.

3. Scratch and Dig: $\leq$ 30/5 per Mil-0-13830A, Rev H, with a 300 Watt light source, over area contained within central 190 x 361 ellipse, $\leq$ 80/50 between that area and the bevel. Surfaces to be well polished with processes and finish suitable for use under high energy conditions.

4. Wavefront distortion: Over the central 180 mm diameter zone of the clear aperture (defined perpendicular to the beam in an as-use orientation through a drawing), the single pass peak to valley wavefront error at Brewster's angle shall not exceed $\lambda/8$ at 632.8 nm. In addition, the wavefront must be smooth, with slope errors and frequency not exceeding two sinusoidal cycles of $\lambda/8$ double amplitude over this region. The peak to valley wavefront error over the entire 200 mm clear aperture will not exceed $\lambda/2$.

5. Certification: Inspection and test requirements and procedure will be as per LLL MEL 74-001250 "Inspection requirements for glass laser disks" (latest revision) Homogeneity requirement is for reference only; actual values should be supplier and may be measured after disk is finished. Only one Brewster's angle orientation must meet specifications.

1.2 Shiva (circa 1977)

The construction of Shiva followed Argus by several years, during which a group of optical engineers were employed at the lab. This resulted in a clarification of the specifications, but very similar content. (Elliptical disks, maximum dimension: 418 mm). Most noticeably, the wavefront gradient specification has been clarified to language that has been used for all subsequent lasers.

1. Homogeneity: Variation in refraction index will not exceed $\pm 1 \times 10^{-6}$ over the clear aperture, or $\pm 2 \times 10^{-6}$ (presumably, over the rest of the piece)

2. Total Bubble, seed, and inclusion cross section in any 100 cm^3 not to exceed 0.03 mm^2. Longest dimension of single bubble, seed, or inclusion shall not exceed 0.2 mm.

3. Quality of surfaces shall meet or exceed 30/10 scratch/dig per Mil-0-13830A, Rev H, with a 300 Watt light source.

4. Single pass peak to valley wavefront distortion at 0.6328 μm at Brewster's angle shall be less than $\lambda/8$, with a gradient less than $\lambda/22$/cm over the clear aperture, and less than $\lambda/40$/cm over 90% of the central 147 mm. (presumably diameter area)

5. Inspection: Testing shall be per LLL MEL 74-001250. Provide interferograms of wavefront distortion. Indicate proper orientation relative to serial number. Record measured scratches and digs - size and location.

1.3 Novette (circa 1980)

Novette optics specifications saw a tightening of the Shiva specs in terms of allowable slope errors and spatial variances in homogeneity, and are more or less the same everywhere else. The bubbles specification was changed to a fractional area spec. rather than an area per volume spec. (Elliptical and segmented disks, maximum dimension: 629 mm)

1. Homogeneity measured at 0.633 μm for Brewster's angle: PV $\leq \lambda/6$, gradient $\leq \lambda/30$/cm over the clear aperture.

2. Total Bubble, seed, and inclusion cross section in any 100 cm^2 cross-section measured normal to the disk not to exceed 0.3 mm^2. Longest dimension of single bubble, seed, or inclusion shall not exceed 0.25 mm.

3. Quality of surfaces shall meet or exceed 30/10 scratch/dig per Mil-0-13830A, Rev H, with a 300 Watt light source.

4. Single pass peak to valley wavefront distortion at 0.6328 μm at Brewster's angle shall be less than $\lambda/6$, with a gradient less than $\lambda/30$/cm over the clear aperture with the disc oriented in the direction of use.

5. Inspection: Testing shall be per LLL MEL 74-001250. Provide orthogonal interferograms of wavefront at Brewster's angle, record max. PV and slope. Indicate proper orientation relative to serial number (this call-out actually achieved through a sketch). Record measured scratches and digs - size and location.

1.4 Nova (circa 1986)

The Nova specifications were functionally the same as those for Novette, which became the standard for ICF optics for more than a decade. These specifications here are for the re-melt in 1986, with the note for metallic inclusions added. (Elliptical and segmented disks, maximum dimension: 629 mm)

1. Homogeneity measured at 0.633 μm for Brewster's angle: PV $\leq \lambda/6$, gradient $\leq \lambda/30$/cm over the clear aperture. (This specification was given as well, corrected for angle of incidence, for normal incidence testing. I list only the use angle specification for ease of comparison.)

2. Total Bubble, seed, and inclusion cross section in any 100 cm^2 cross-section measured normal to the disk not to exceed 0.3 mm^2. Longest dimension of single bubble, seed, or inclusion shall not exceed 0.25 mm.

3. Quality of surfaces shall meet or exceed 30/10 scratch/dig per Mil-0-13830A, Rev H, with a 300 Watt light source.

4. Single pass peak to valley wavefront distortion at 0.6328 μm at Brewster's angle shall be less than $\lambda/6$, with a gradient less than $\lambda/30$/cm over the clear aperture with the disc oriented in the direction of use.

5. Inspection: Testing shall be per LLL MEL 74-001250. Provide orthogonal interferograms of wavefront at Brewster's angle, record max. PV and slope. Indicate proper orientation relative to serial number (same as Novette call-out). Record measured scratches and digs - size and location.

6. No disk shall contain a total of more than 10 metallic or other damaging inclusions within the clear aperture volume. Any such particles must be separated by at least 25 mm. It shall be a manufacturing goal that the average number of damaging inclusions per disk in any order of 10 or more disks shall not exceed 2. A maximum of one particle per disk may grow to ≤ 0.5 mm largest dimension, when irradiated as specified. ($\lambda = 1.064$ μm, 7 J/cm^2, 8 ns, 100 shots)

1.5 Beamlet (circa 1991)

The Beamlet laser was constructed after an extended hiatus in laser manufacturing for ICF at LLNL of about 7 years. In the interim, the Omega Upgrade laser was constructed at the laboratory for laser energentics in Rochester. The specifications for Beamlet, however, were based upon the Nova specifications rather than Omega. The Beamlet was the first laser constructed using the NIF-style multi-pass architecture, rather than the master oscillator/power amplifier (MOPA) chain of prior lasers. The aperture was square, rather than round, driving the amplifiers to be rectangular slabs, rather than disks. (Maximum Dimension: 906 mm corner to corner).

1. Homogeneity measured at 0.633 μm for Brewster's angle over the clear aperture: PV $\leq \lambda/2$ power, $\lambda/4$ astigmatism, $\lambda/6$ residual, higher order inhomogeneities. Gradient $\leq \lambda/30$/cm over the clear aperture. (Again, an analogous specification was given as well for normal incidence testing.)

2. Total Bubble, seed, and inclusion cross section in any 100 cm^2 cross-section measured normal to the slab not to exceed 0.3 mm^2. Longest dimension of single bubble, seed, or inclusion shall not exceed 0.25 mm. The glass shall be free of metallic or other damaging inclusions except as indicated below.

3. Quality of surfaces shall meet or exceed 30/10 scratch/dig per Mil-0-13830A, Rev H, with a 300 Watt light source.

4. Single pass peak to valley wavefront distortion at 0.6328 μm at Brewster's angle shall be less than λ/6, with a gradient less than λ/30/cm over the clear aperture with the slab oriented in the direction of use. No finishing process shall be used that will produce periodic phase perturbations across the clear aperture. (This last note was added in 1994 for reasons discussed further in section 2.3 below.)

5. Inspection: Testing shall be per LLL MEL 74-001250. Provide orthogonal interferograms of wavefront at Brewster's angle, record max. PV and slope. Indicate proper orientation (done as before, with a sketch). Record measured scratches and digs - size and location.

6. No slab shall contain a total of more than 15 metallic or other damaging inclusions within the clear aperture volume. Any such particles must be separated by at least 25 mm. The average number of damaging inclusions per slab in any order of 10 or more slabs shall not exceed 3. No inclusion may grow to a size greater than 0.25 mm largest dimension, when irradiated as specified. (λ = 1.064 μm, 7 J/cm^2, 8 ns, 100 shots)

2. PROBLEMS WITH NON-LINEAR SYSTEMS

Starting in the earliest days of high energy lasers[2,3], we have been aware that the non-linear refractive index effects were a significant contributor to the wavefront and intensity distribution of the laser system. What follows is a brief synopsis, drawn from the literature, of the salient points of non-linear effects which impact the specification of optics.

2.1 Small Ripple Amplification (SRA)

As has been described by Trenholme[3] and others, any 'ripple', or periodic structure, either in the phase or amplitude of a laser, can be particularly damaging to the performance of a high peak power optical system. This is because certain such periodic structures, of certain spatial frequencies, can see a gain of 10-1000, rather than the normal plane wave gain of 1-2, per amplifier stage. In the case of the Beamlet, NIF and LMJ lasers, it can be shown that[4] the range of phase error spatial periods which will undergo this small ripple amplification are from 33 mm to about 0.12 mm. These spatial periods (or their inverse, spatial frequencies) are referred to here and elsewhere as "mid-spatial scale-length (or frequency) errors", to differentiate them from simple roughness (periods shorter than 0.12 mm) and "figure" errors (periods greater than 33 mm). These mid-spatial frequency errors are also referred to elsewhere as "waviness", or "ripple".

2.2 Controlling ripple error

Historically, the specification on the slope errors in the transmitted wavefront have 'controlled' the source terms to the small ripple amplification. By reading the Argus amplifier specification closely, one can see the logic that leads to this control. While the language is somewhat difficult to interpret, the term "with slope errors and frequency not exceeding two sinusoidal cycles of λ/8 double amplitude" will constrain the power spectrum of the wavefront errors. If the wavefront is constrained to two cycles of error over a 200 mm clear aperture with amplitude λ/8, that is equivalent to a slope specification of (λ/8) / 30 mm, or λ/24/cm. If the periodic error is of a shorter period, but the slope is constrained, the amplitude of the error must drop linearly with period. Since there is no lower bound on the spatial periods controlled in this manner, though, the requirement is assumed to be limited by the spatial resolution of the measuring instrument.

In Nova's case, the highest spatial resolution obtainable over a full aperture measurement, in 1986, was some 20 points. If you assume at least two cycles per measurement and two measurements per cycle, this would automatically band-limit the detection of errors of periods from 240 mm or so down to about 48 mm. Amplitudes of pure sine wave errors over this period range are constrained by the slope specification of λ/30/cm to be less than about λ/4 P-V at 240 mm, to about λ/20 P-V at 48 mm. While this hardly accomplishes the objective of controlling ripple errors, it was the best that could be done at the time.

2.3 Beamlet and ripple error

If we do the same analysis of the spatial frequencies controlled by the gradient specification, applied to Beamlet, we get a similar answer. The full aperture interferometer capabilities of the industry, after almost a decade, were no better in 1991. Thus, the gradient specification could only control errors of spatial periods from 220 mm to 44 mm, with corresponding pure sine error amplitudes of $\lambda/4$ to $\lambda/20$ P-V, respectively. Referring again to the spatial periods which undergo small ripple amplification, the Beamlet is particularly sensitive to errors with spatial periods from 33 mm to 0.12 mm. Thus, the laser was sensitive to errors in the optical components which were not actually measured, and hence controlled by the wavefront specification.

During the activation of the Beamlet, unacceptably high modulation was observed in the near-field intensity distribution which could be traced to optics which were made using small tool and diamond turning processes[5]. When the offending optics were removed, the near-field modulation dropped to acceptable levels. As a result, LLNL began a campaign to re-finish several of the optical components, the amplifier slabs being one of them. To assure that no periodic errors would be introduced by the re-finishing process, a note was added to specify that "No finishing process shall be used that will produce periodic phase perturbations across the clear aperture".

For future ICF lasers, we wish to make use of the advent of full-aperture, high spatial resolution, phase measuring interferometry to control these ripple errors in all of the optics. To that end, we have elected to control the phase errors using a PSD and RMS specification, versus spatial frequency, which is described in detail in section 3.

2.4 Holographic imaging of hot spots[6]

Another consequence of non-linear effects is that of the holographic imaging of hot spots in the laser beam, potentially threatening downstream optics. Again, the reader is referred to the sited literature for a detailed discussion; however for our purposes, the problem can be summarized as follows. Suppose there is an obscuration in the beam, such as is caused by a bubble suspended in a glass element. Such an obscuration causes a radial pattern to occur in the intensity of the beam as a result of simple diffraction. When in a non-linear optical system, this can result in the creation of a holographic lens, which will cause the beam to come to a focus further down stream. Such re-imaging could result in hot spots in the wake of contamination or defect sites, effectively limiting the maximum safe operating fluence of the laser system.

Hunt et. al.[6] describe the consequences of Gaussian and circular scatters, for a given laser condition which closely corresponds to the design regime for both the NIF and LMJ lasers. On both Nova and Beamlet, experimental evidence has been obtained that indicates such degradation of downstream optics does in fact occur. Historically, we have limited the maximum acceptable diameter of such a scatterer (e.g. bubbles, inclusions, digs, and damage spots) on a new or re-finished optic to between 100 and 250 μm. While an analysis is needed here regarding life time and maintenance of the new, larger laser systems, for now we have retained the same conditions for specifying these parameters.

3. SPECIFICATION EFFORTS AT LIVERMORE

As a consequence of our experiences with the Beamlet optics described in section 2.3, we have begun an effort to revitalize the large optics specifications to be used in future ICF lasers. This effort, underway for almost a year, involves three principal activities; Metrology, Modeling and Analysis, and Drawings and Standards. Each of these efforts is discussed in brief below, and in more detail in the following 3 papers in this proceedings.

3.1 Metrology

The first step in specifying future laser systems is establishing a more complete understanding of what optics have been made for ICF lasers in the past. To this effect, we have begun a campaign to scrutinize more thoroughly the optics currently deployed on the Beamlet laser. Focusing first on wavefront and roughness, we have compiled an extensive database of phase screens of various apertures and resolutions

for many of the Beamlet components. These phase screens serve a dual purpose; first, the give us a benchmark of the 'state of the art' against which to compare the specifications and future optics components manufactured using different techniques. Second, they serve as source files for the efforts to model high energy laser performance.

3.2 Modeling and Analysis

Taking the metrology data described above, we have obtained insight into the optics themselves through the creation of multi-decade, 1-D and 2-D power spectral density (PSD) plots of the various phase screens. This has allowed us to understand the properties of the Beamlet components within the context of high energy lasers. We have run computer simulations of the Beamlet laser based on real phase screens as source terms. Where necessary, we have fused data in the Fourier domain for similar optics over various scale-lengths, and generated synthesized phase screens which combine several decades of spatial ripple and figure resolution. By comparing the predictions of the model of Beamlet with the actual laser performance, we hope to validate the model. A model of the NIF laser system can then be constructed using the same approach, and the phase errors can be magnified or mitigated for performance comparisons. This forms the basis of the cost-benefit analysis alluded to above.

3.3 Drawings and Standards

In parallel with these activities, LLNL plans to specify optical components for the National Ignition Facility according to ISO 10110, the new international standard for preparation of optics drawings. This new standard, in the final stages of adoption by the international optics community, will become widely accepted and used in the U.S and around the world. The standards represent a fairly comprehensive language for describing optical components. There are a number of practical issues that we must address in implementing this new standard. The foremost is knowledge and understanding of the standard itself, both by our staff and by the optics vendors. By means of in-house training, explanation to vendors, and practical application to existing drawings, we are beginning to understand the standard and its implications.

4. PSD BASED OPTICS SPECIFICATIONS

The Power Spectral Density, or PSD, is a powerful and compact expression of wavefront structure[7], expressing the contour of the wavefront "phase surface" in terms of Fourier components. Elson and Bennett[8] have described problems which may exist in measurement practice and in some codes currently used for calculation of PSD's, specifically in terms of normalization, and give a mathematical formulation for the accurate computation of a "smoothed" surface PSD. This section is meant to explain, in fairly simple terms, how to create a PSD specification, and assumes rudimentary understanding of the function and how to generate it. The reader is referred to the literature sited[7-9] for a more complete discussion of these calculations, as factors of two are easily lost in the normalization unless care is taken, and such an in-depth treatment is beyond the scope of this work.[10]

The PSD, which is expressed versus spatial frequency, typically on a log-log plot, is a physically significant figure-of-merit for expressing the wavefront shape. In addition to allowing access to the periodic functions present in a given wavefront through the appearance of peaks in the PSD, this function also directly yields the average squared roughness of the wavefront for any frequency band for which data is available.

In 1-D, the magnitude of the PSD for a given frequency, v_i, is given by:

$$PSD(v_i) = (A(v_i))^2 / (\Delta v)$$

where $A(v_i)$ is the discreet Fourier amplitude at the frequency v_i.

The units of PSD are $(length)^3$. For consistency with the move towards scientific units[11], and to keep the order for 'typical' errors moderate, we use the units of $(nm)^2$ x (mm), where the spatial frequency is given in inverse mm.

It can be shown[8] that the "area" under the PSD curve in any frequency interval is equal to the square of the RMS wavefront error of the original line-out over the same frequency interval. This is because the integral of the discreetly valued PSD can be written as a sum of the square of Fourier amplitudes per frequency interval times the frequency increment, which is exactly the square of the RMS error. Thus:

$$RMS^2 = (\Delta v) \, {}^*\Sigma_v \, [PSD(v_i)]$$

The bandwidth of a PSD calculation is directly related to the length of the scan and the number of pixels per scan line. In addition, the range over which such a calculation of the PSD is considered valid is dependent on several factors such as the number of samples required per period and the number of cycles per measurement, as well as the fidelity of the measurement instrument versus spatial frequency.

4.1 Defining a PSD specification

The prototype optics used in the Beamlet demonstration project, with a few exceptions already mentioned, are believed to be acceptable, or nearly acceptable, for the NIF production. In writing the first revision of the specifications for the NIF, therefore, we chose to define those specifications based on currently available optics. The technology to be used to fabricate the optics for the larger laser system, must be substantially lower in recurring costs than the technology used to fabricate the Beamlet optics. Such a change in technology can be expected to change the PSD of the resultant parts. Thus it is important at this juncture to define a specification which will assure us of 'same quality' optics, to be used by the vendors in qualifying their new processes. The next step may be to begin loosening or tightening this specification based on further modeling or experimentation, or both.
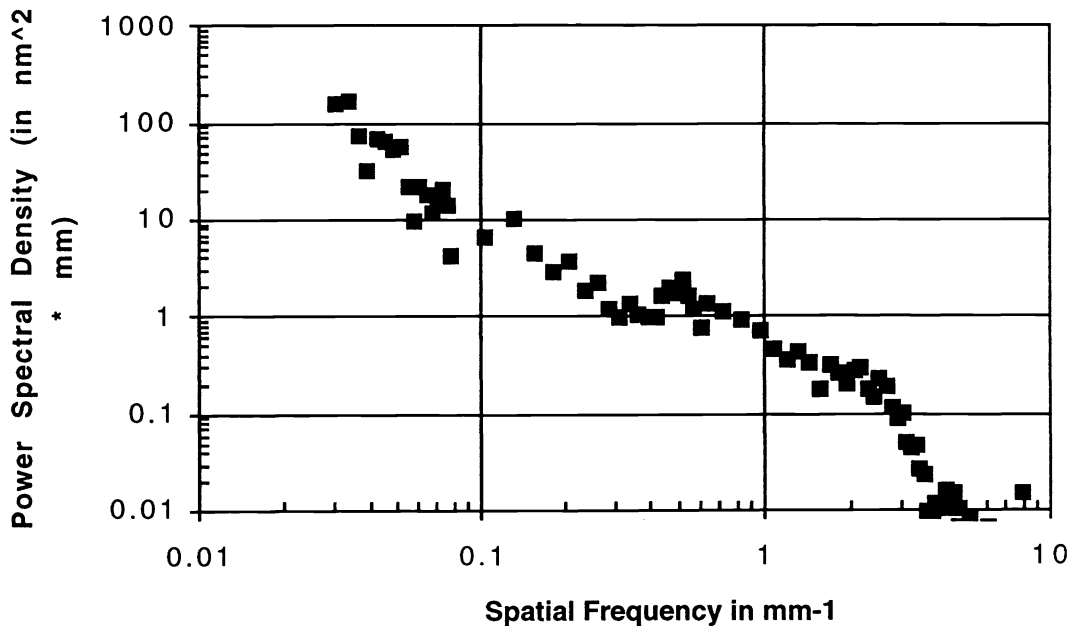

Figure 1. A sample measured PSD for an amplifier slab

In figure 1 we see a log-log plot of a PSD versus spatial frequency. Avoiding for the moment arguments about measurement techniques and data valid ranges, if we use a straight line to bound the values on this PSD, we effectively place a limit on the amplitude of modulations over the specified range of frequencies. The slope of the line which properly bounds the PSD will be determined by the process which created the optic. In our case, the slope of such a bounding function is about -1.5. This means that the specification on

the PSD is dropping at a rate of one and a half decades per decade of frequency. Obviously such a bounding function need not be continuous; it may make sense to have lines of different slopes over different regions of the frequency domain. We record this specification as follows:

When plotted log-log, for spatial periods from 33 mm to 0.12 mm, the maximum value of the PSD shall be less than the line described by the equation:

$$PSD \leq Av^{-b} \qquad \text{for } 0.03 \text{ mm-1} \leq v \leq 8.5 \text{ mm-1}$$

$$\text{where} \qquad A = 1.05$$
$$b = 1.55$$

with v given in mm^{-1} and PSD given in (nm)$^2 \cdot$ mm.

For clarity's sake, we include the graphical representation. The maximum permissible value of the PSD is represented by the uppermost line shown in figure 2.

Several other parameters need to be described explicitly in the notation or understood through some other specification being applied. For instance, it is prudent to specify the exact instrument used for the measurement, since different instruments have different sensitivities and bandwidths, and the aperture to be used for the measurement. In our case, we specify the PSD to be measured over a 100 mm patch and a 7.5 mm patch. Since we are not sampling the entire area of the part, we must also specify how many patches must be measured, and where they lie. To eliminate possible discrepancy in the calculation, we will provide the algorithm to be used to calculate the discreet PSD, the number of line-outs used, and will specify the orientation of the line-outs.

One of the most critical concerns regarding using Fourier analysis as an acceptance criterion is that of the validity of the data, versus frequency. Following Church's approach[12], but being even more conservative, we assume data is valid only within a smaller bandwidth of frequencies than is strictly allowed by calculation. In our case, we require at least 8 samples per cycle for high frequencies and 3 cycles per measurement for the low frequencies. This results in data valid in a given measurement, based on a line-out of length L, over the range of frequencies $3 / L$ to $n / (8 \cdot L)$, where n is the number of pixels in the measurement.

Returning to the NIF requirements, we can define two measurements which span the frequency range of interest. Since our range of interest is 33 mm to 0.12 mm, if we assume a 512 x 512 detector array and a 512 sample line-out, and assume the 'data valid' range for a given measurement as described, we must assign a scan length of 99 mm or greater (to meet the 3 cycles per measurement requirement at 33 mm period). In addition, a second measurement can be defined based on the highest spatial frequency required, 8.3 mm-1. Using the criteria of 8 samples per cycle, we know that the pixel size for this second measurement must be 0.015 mm or less. The result is the following two measurements to evaluate the PSD over our required bandwidth:

	scan length	# of pixels	v_0 to v_{max}	data valid freq.	data valid period
measurement 1	100 mm	512	0.01 mm^{-1} to 2.6 mm^{-1}	0.03 mm^{-1} to 0.64 mm^{-1}	33 mm to 1.56 mm
measurement 2	7.5 mm	512	0.13 mm^{-1} to 34 mm^{-1}	0.4 mm^{-1} to 8.3 mm^{-1}	2.5 mm to 0.12 mm

4.2 Defining an RMS

The above specification controls only the highly periodic functions present on the optic. If we were to use it alone, we could conceivably get the maximum PSD value at all points in the mid-spatial frequency spectrum, which is not our intent. The other key parameter for this specification is the area beneath the PSD curve which, as was described above, is equivalent to the square of the RMS wavefront error. It is necessary to describe such an RMS requirement in terms of specific frequency ranges.

Since one can simply sum the values of the discreet PSD times the frequency increment and take the square root to determine the RMS error, an RMS wavefront requirement translates directly into an equivalent area beneath the curve of the PSD. One could draw another line, the square root of the area beneath which would be indicative of the RMS error, given in nm. This is also shown in figure 2. Notice that we have drawn the line bounding the top of the area to be parallel to the peak PSD line from section 4.1. As mentioned before, such a pictorial representation is sufficient, but not very precise. Adding an explicit notation regarding the RMS wavefront over a given frequency range removes confusion. In our case, the following notation is used:

$$RMS_1 \leq 1.8 \text{ nm} \qquad \text{for } 0.03 \text{ mm}^{-1} \leq v \leq 04 \text{ mm}^{-1}$$

$$RMS_2 \leq 1.1 \text{ nm} \qquad \text{for } 0.4 \text{ mm}^{-1} \leq v \leq 8.3 \text{ mm}^{-1}$$

For demonstration, these RMS values are shown graphically as the square root of the area beneath indicated lines in figure 2.
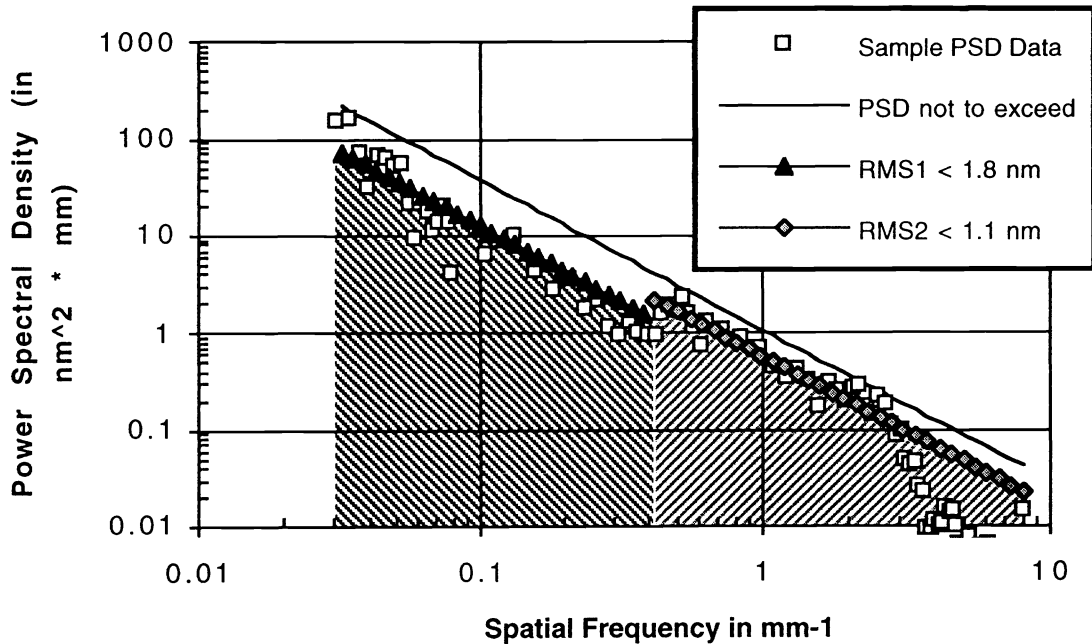

Figure 2. Sample graphical representation of a specification for PSD and RMS.

5. THE USE OF ISO 10110

In addition to significantly altering the method of controlling figure and ripple errors, we have decided to bring the drawings into conformance with international optical drawing standards. While the ISO 10110 standard for optics drawings notations is still in draft form[13], we have selected it as the most appropriate notation standard for an international project of this size, bypassing entirely the ANSI and DIN drawing standards. This is in keeping with the directive from government (Circular A-119 from OMB, Oct. 20,1993) to adopt international standards.

There is currently no ISO standard for transmitted wavefront; however the description of the PSD shown in section 4 (i.e. point slope formula) resembles the ISO standards for using PSD specifications for surface texture[11]. We intend to participate in the creation of a transmitted wavefront standard, and will try to influence its language to be consistent with our new large optics specifications.

Following the same methodology described at the beginning of section 4, we intend to revise the scratch/dig, bubbles and inclusions specifications to first cover the optics as they are currently being

manufactured, and then later to modify these specifications as necessary to achieve the required laser performance, according to a cost-benefit analysis to be performed as part of the Title I engineering for the NIF.

Since another paper in this proceedings[14] documents the translation process we have applied for the case of the lenses, I will simply describe the specifications to be used for the amplifier slabs, so that we may compare their notation to the specifications listed in section 1.

5.1 Scratches and digs

Traditionally, we have specified scratches and digs using the Mil-13830A Rev H standard. Translating the 30/10 scratch/dig requirement used in Beamlet and other lasers to ISO 10110, we get the following requirement:

5 / 1x0,25 ; L 1x0,060 ; E1,0 (ALL Ø50) Note: Edge chips shall be polished out.

Per ISO 10110 Part 7, "Surface Imperfection Tolerances".

5.2 Bubbles and Inclusions

Our bubble specification for Beamlet is an area per unit area specification, which translates easily into ISO 10110. The metallic inclusion requirement, however, must be preserved through a note, since there is no equivalent ISO specification:

1 / 5x0,25 (ALL Ø110) (sub-aperture indication)
1 / 15x0,25 (full aperture indication) Note: No disk shall contain more than 15 metallic or other damaging inclusions within the clear aperture volume. Any such particles must be separated by at least 25 mm. The average number of damaging inclusions per slab in any order of 10 or more slabs shall not exceed 3. No inclusion may grow to a size greater than 0.25 mm largest dimension, when irradiated as specified. ($\lambda = 1.064$ μm, 7 J/cm^2, 8 ns, 100 shots).

Per ISO 10110 Part 3, "Material imperfections - Bubbles and inclusions".

6. CONCLUSIONS

We have embarked upon a path to take LLNL ICF optics drawings into the 21st century, through a re-investigation of our traditional optics specifications based on modeling and metrology, and through a conversion to the international standard for optics drawings indications. This will result in a conversion to specifications which more precisely define the optics requirements that are pertinent to the laser performance. Ultimately, this conversion process will result in a more optimum balance between laser performance and laser cost, to obtain the most cost effective NIF optical system.

While these changes result in a significant difference in form, the new optics specifications are intended to describe optics which were successfully manufactured for Beamlet. The most significant change in form is in the transmitted wavefront specification, which has gone from a P-V and gradient specification and a complete ban on periodic functions, to a PSD based specification.

7. ACKNOWLEDGMENTS

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7. See, for example, J. M. Bennett and L. Mattsson; "Scattering Theories and Surface Statistics", Chapter 4 in <u>Introduction to Surface Roughness and Scattering</u>, published by OSA: ISBN 1-55752-108-5, 1989.

8. J. M. Elson and J. M. Bennett, "Calculation of the power spectral density from surface profile data", Applied Optics, Vol. 34, No. 1, p. 201 (1995).

9. D. J. Janeczko, "Power spectrum standard for surface roughness: Part 1", SPIE Vol. 1165, <u>Scatter from Optical Components</u>, pp. 175-183, 1989.

10. See also, J. K. Lawson, et. al., "Specification of optical components using the power spectral density function", later in this proceedings.

11. Notice that these units ($nm^2 \cdot mm$) for the 1-D PSD are inconsistent with the units used in the ISO standard for PSD specification of texture, which are μm^3. In the absence of the transmitted wavefront standard, I have chosen to use the units most appropriate for optical problems, and will try to prevail upon the ISO committee to do likewise when units for a transmitted wavefront PSD are selected.

12. E. L. Church et al; "Direct comparison of mechanical and optical measurements of the finish of precision machined optical surfaces", Opt. Eng., Vol. 24, No. 3, May/June 1985.

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14. See R. E. English, et. al., "Implementation of ISO 10110 optics drawing standards for the National Ignition Facility", later in this proceedings.