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J. K. Lawson, J. M. Auerbach, R. E. English, Jr., M. A. Henesian,
J.T. Hunt, R. A. Sacks, J. B. Trenholme, W. H. Williams,
M.J. Shoup III, J. H. Kelly and C. T. Cotton

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J.K. Lawson, J.M. Auerbach, R.E. English, Jr., M.A. Henesian,
J.T. Hunt, R.A. Sacks, J.B. Trenholme, W.H. Williams
Lawrence Livermore National Laboratory
Livermore, CA 94551

M.J. Shoup III, J.H. Kelly, C.T. Cotton
University of Rochester, Laboratory for Laser Energetics
Rochester, NY 14623

Abstract

The performance of the National Ignition Facility (NIF), especially in terms of laser focusability, will be determined by several key factors. One of these key factors is the optical specification for the thousands of large aperture optics that will comprise the 192 beamlines. We have previously reported on the importance of the specification of the power spectral density (PSD) on NIF performance. Recently, we have been studying the importance of long spatial wavelength (>33 mm) phase errors on focusability. We have concluded that the preferred metric for determining the impact of these long spatial wavelength phase errors is the rms phase gradient. In this paper, we outline the overall approach to NIF optical specifications, detail the impact of the rms phase gradient on NIF focusability, discuss its trade-off with the PSD in determining the spot size and review measurements of optics similar to those to be manufactured for NIF.

Keywords: optical specifications, ICF, solid-state lasers, phase gradient

1.0 NIF OPTICAL SPECIFICATIONS

The National Ignition Facility (NIF) represents the first solid-state laser system for inertial confinement fusion designed at Lawrence Livermore National Laboratory to have a focusability requirement placed upon it. Because of the diversity of missions that NIF will pursue, the focusability requirement actually represents a range of performance requirements. The most demanding of these is the Stockpile Stewardship Program (SSP) requirement with its goal of 500 TW inside of a 250 micron diameter focal spot. Designing NIF to meet this requirement has led us to critically examine a series of optic quality metrics.

The optic quality metric that we found most closely tied to the focusability of a laser system was the wavefront root-mean-squared (rms) gradient. The magnitude of the local wavefront gradient is analogous to the concept of ray angles in geometric optics. The distribution of gradients determines the basic focal spot characteristics. Further, if we assume the distribution of wavefront gradients on an optic is Gaussian, then a series of optics each contributes to the distribution of gradients for the system. The system distribution will then also be Gaussian and the focal spot determined by the root-sum-squared (rss) addition of the individual optics rms gradients.

Using this simple formalism, one can calculate an approximate rms gradient specification for individual optics in a laser system required to produce a specified spot size. Our initial calculations[1] indicate that a lambda/75/cm @ 633 nm (84 Å/cm) rms gradient would be required for the NIF. We have performed detailed calculations to verify this estimate, in particular for the NIF SSP mission. In these calculations, we control the high spatial frequency character of the wavefront consistent with measurements of high quality optics (i.e., 1.7 nm rms wavefront roughness in a $33\text{mm}>\lambda>2.5$ mm spatial wavelength region). The result shows that a rms gradient of 75 Å/cm is adequate to produce 500 TW inside of a 250 micron focal spot at the NIF designed operating point (see Figure 1).

The primary difficulty that we have experienced when using the gradient magnitude stems from the fact that the wavefront seems to contain two types of statistical distributions. While the lowest spatial frequency wavefront distortions ($\lambda > 33$ mm) follow approximately a Gaussian distribution, measurements of real optics do not show the rapid fall-off in spatial frequency content that a classical Gaussian distribution does. Instead, high spatial frequency wavefront distortions exhibit approximately a power law dependence that has been described previously in detail[2]. In order to model the Gaussian portion of the wavefront distortions, we low-pass filter the wavefront measurements and calculate the rms gradient of the filtered measurement. A power-spectral density (PSD) specification controls the power law behavior of the wavefront distortions over that spatial frequency region.

Traditionally, optical performance has been controlled by wavefront peak-to-valley (PV) with possibly a peak wavefront gradient specification added. This type of metrics does not directly determine the performance of an optic or optical system without knowledge of the statistics that correspond to the values of the extrema. When conventional manufacturing techniques are expected, one can effectively use this traditional metric. However, the NIF design team is attempting to draw upon new manufacturing technologies to maintain optic quality while minimizing cost. Statistics associated with these new manufacturing technologies is not well established. Thus, it is critical to use metrics that are direct measures of optic performance. The rms gradient proves to be directly tied to performance and serves as a useful metric.

2.0 MODELING OF THE NIF OPTICAL SYSTEM WAVEFRONT

Since the optical specifications of the NIF laser system are largely based on results of optical propagation modeling of the system, modeling of the wavefront and the optical specifications are closely tied and should be consistent with one another. In both modeling and specifications, we differentiate between spatial frequency regions, since each involves different system performance issues. To deal with the diverse issues, we break the spatial frequency regime into four regions: figure (0 - .03 mm^{-1}), waviness-1 (0.03 mm^{-1} – 0.4 mm^{-1}), waviness-2 (0.4 mm^{-1} - 8 mm^{-1}) and roughness ($\nu > 8\ \text{mm}^{-1}$). Figure determines most aspects of the main focal spot, while waviness-1 effects the tails of the focal spot. Both of the waviness regions effect near-field modulation, while waviness-2 also determines pinhole loading. Roughness also contributes to pinhole loading and has been shown to play a role in filamentation. Each of these regions is controlled in a slightly different fashion. As described in this paper, figure is controlled by a filtered rms gradient specification, while both waviness regions are controlled by a PSD specification. Roughness is controlled only by a rms wavefront specification.

The NIF system wavefront is modeled by adding the wavefront distortion per optic as they are encountered propagating through the beamline to the system wavefront. Each optic's wavefront distortion is constructed by adding the allowable amount in spatial frequency region (see Figure 3). A Gaussian random phase screen whose magnitude is scaled to produce the correct rms gradient models the wavefront figure. The screen is easily constructed by convolving a uniform random distribution distributed from –1 to 1 with a Gaussian expressed by:

$$e^{-((x/s_x)^2+(y/s_y)^2)} \tag{1}$$

For our simulations, we use a $s_x=s_y=4$ cm. The waviness regions are modeled by using PSDs from measured optics. Since the PSD is a measure of the magnitude of the Fourier components of a wavefront, we can choose random phases in the Fourier domain and combine them with the PSD-defined Fourier magnitude to produce an ensemble of equivalent wavefronts, each possessing the same PSD. By measuring the wavefront of an optic at different spatial resolution, we can build up information that exceeds what can be acquired in any single measurement. Currently, our baseline propagation calculations do not add roughness to the wavefront, since it would exceed the resolution of the baseline calculations. Higher resolution, "patch", calculations are done that use wavefront roughness to investigate the onset of filamentation.

3.0 GRADIENT MEASUREMENTS OF LLE DISKS AND BEAMLET SLABS

Specifications, regardless of the method by which they were developed, are pointless unless parts can be manufactured to meet them. Thus, we have set rms gradient specifications not only to meet performance goals, but also consistent with real optics. We have analyzed 180 measurements of LLE Omega Upgrade 20 cm amplifier disks and 5 measurements of Beamlet amplifier slabs in order to see whether the lambda/90/cm filtered rms gradient specification was attainable. LLE disks were manufactured to a similar specification as NIF[3] (see Table 1) and represented a large database of measurements of laser optics recently fabricated. Over 500 disks (>250 20 cm and >250 15 cm diameter) were required for Omega Upgrade. The Beamlet slabs are considerably fewer in number and were manufactured with specifications of $\lambda/6$ PV and $\lambda/30$/cm peak gradient.

We use a standard five-point gradient calculation on the low-pass filtered wavefront measurement. The low-pass filter is accomplished after applying a hanning window (actually, a von Hann window)[4]. The hanning window minimizes the effect of finite sampling, but causes complications in the reconstruction of the filtered measurement. We multiply the filtered near-field by an inverse hanning window (i.e., 1/hanning) to remove the intensity profile associated with the hanning window. This normalization causes us to lose a few percent of the data at the edges of the measurement. This loss is due to the poor signal-to-noise that occurs when multiplying and then dividing by the small values present at the edge of a hanning window.

Figure 4 displays the result of the rms gradient calculation for the low-pass filtered and unfiltered measurements of the Omega Upgrade 20 cm disks. As shown, the Omega Upgrade disks were well matched to the LLE specification with less than 1% rejection. Similarly, the LLE disks meet the filtered specification used for NIF with only 5-10% rejection. Considering that the disks were not manufactured to this specification, this is encouraging. It suggests only minor adjustments to the manufacturing process should produce acceptable acceptance ratios.

The Omega Upgrade disks form an interesting database, but they do not address issues that are tied to the characteristic size of the NIF optics. To investigate scaling with size, we studied available measurements of Beamlet amplifier slabs. Figure 5 displays the result of the rms gradient calculation for the low-pass filtered and unfiltered measurements of 5 Beamlet slabs. Although this is a limited sampling, each slab met the NIF specification for rms gradient. These slabs were similar in size to the NIF slabs and suggest that the overall size of the optic should not prevent the part from meeting the specification.

4.0 ACKNOWLEDGEMENTS

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	Phase Spatial Filter				
	None		**3.3 cm**		
Specification	**LLE**	**NIF**	**LLE**	**NIF**	**Comments**
Peak-valley phase, Å (waves @ 633 nm)	703 (λ/9)	n/a	n/a	2109 (λ/3)	-
Peak phase gradient, Å/cm (waves/cm @ 633 nm)	211 (λ/30)	n/a	n/a	n/a	LLE: 5% of points can exceed peak
rms phase gradient, Å/cm (wave/cm @ 633 nm)	105 (λ/60)	n/a	n/a	70 (λ/90)	modeling indicates NIF needs 75 Å/cm, minimum

Table 1. Comparison of LLE Omega Upgrade and NIF optical specifications

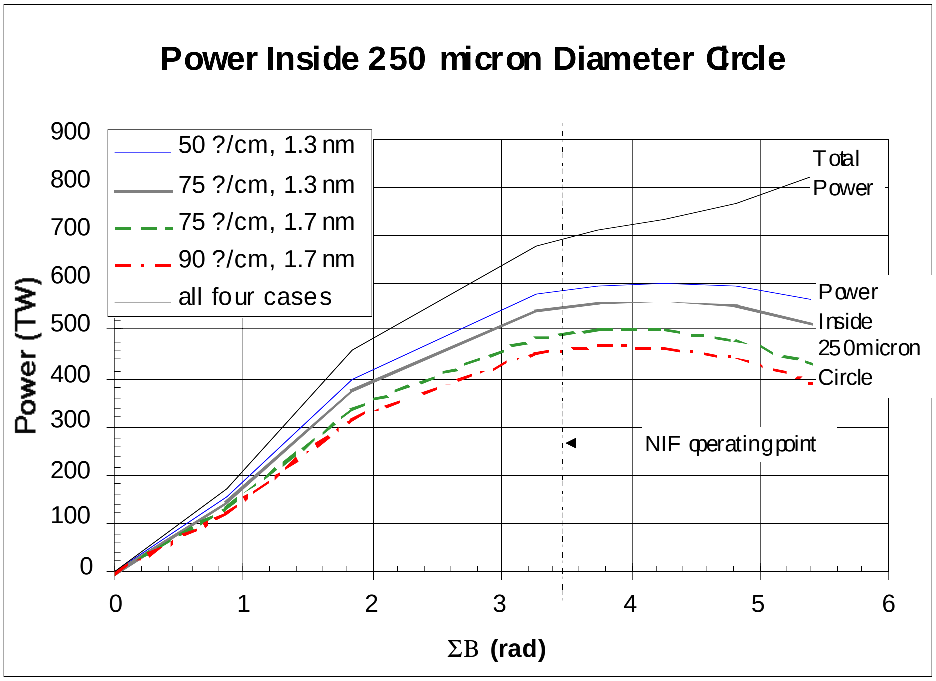


Figure 1. Projected performance for NIF SSP mission (1.8 MJ, 1ns)

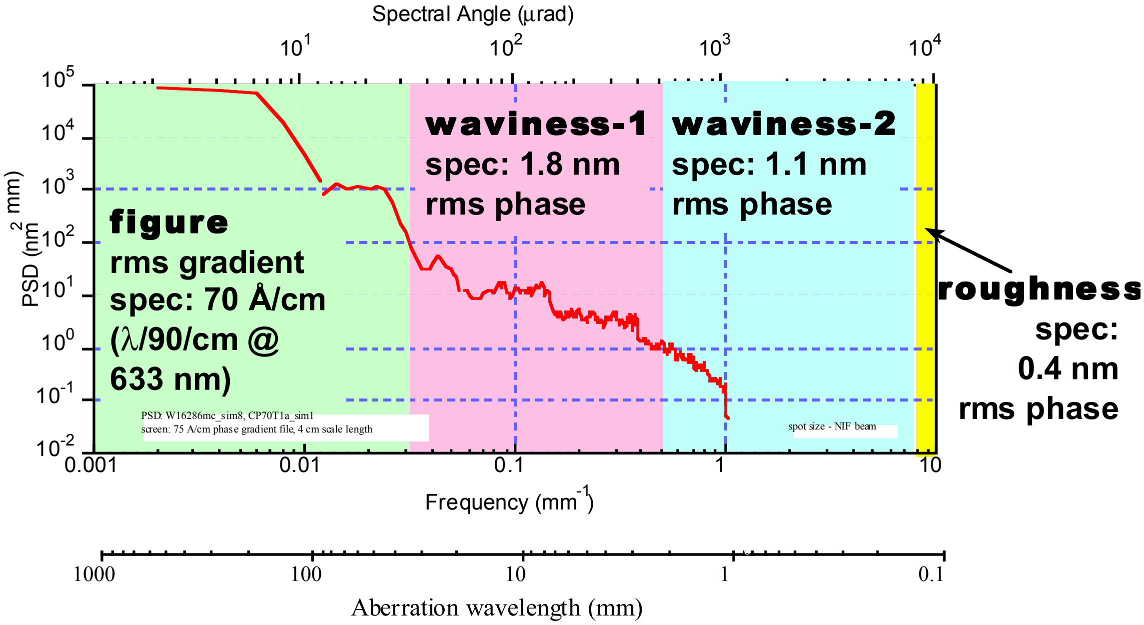
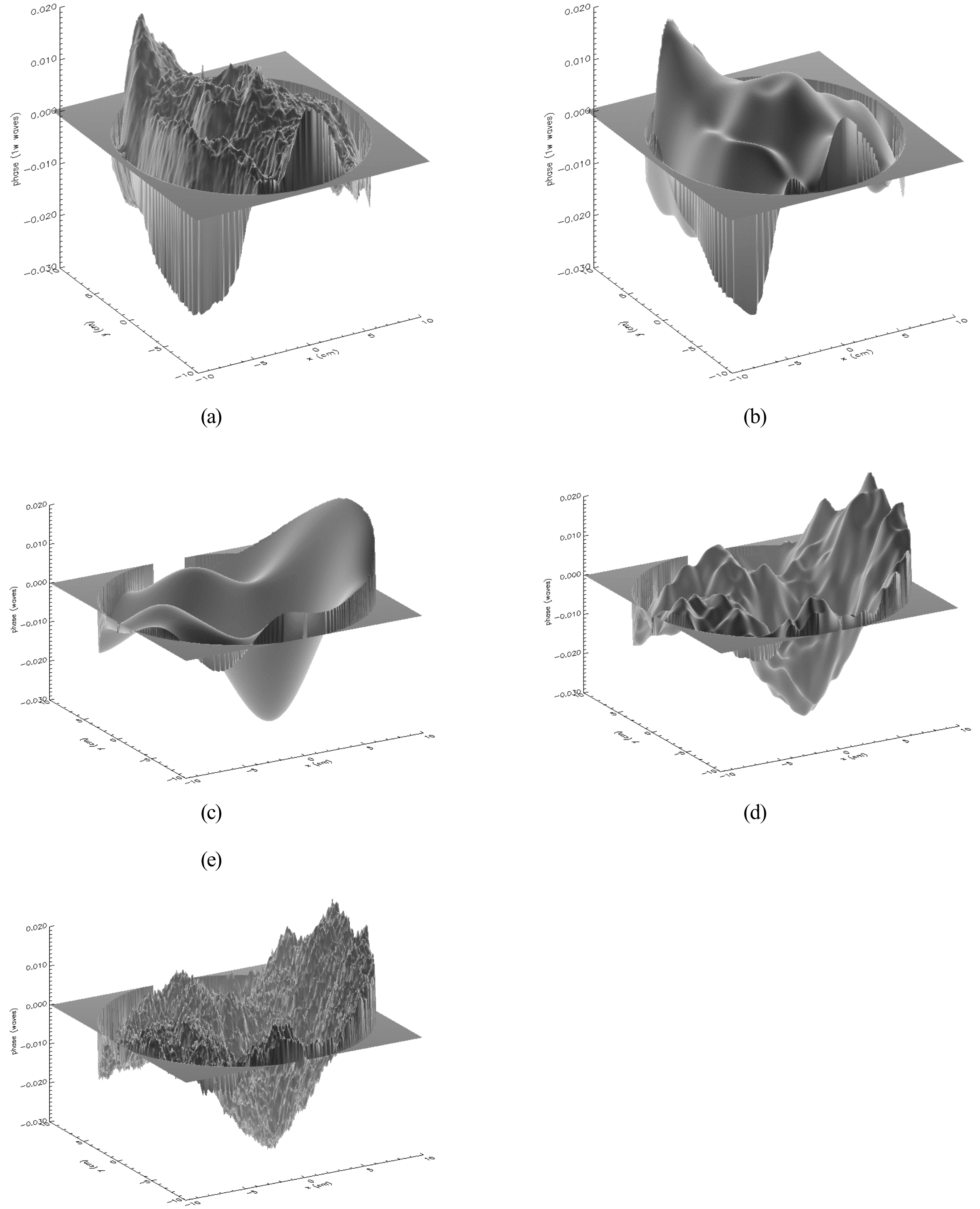


Figure 2. Spatial frequency regions used in modeling and specifications.



(a)

(b)

(c)

(d)

(e)

Figure 3. Synthesis of an optical wavefront
(a) Measurement of LLE slab H20025A,
(b) Measurement low-pass filtered at 33 mm spatial wavelength,
(c) Random Gaussian phase screen simulating filtered measurement
(d) Random Gaussian phase screen with waviness-1 noise added
(e) Random Gaussian phase screen with waviness-1 and waviness-2 added

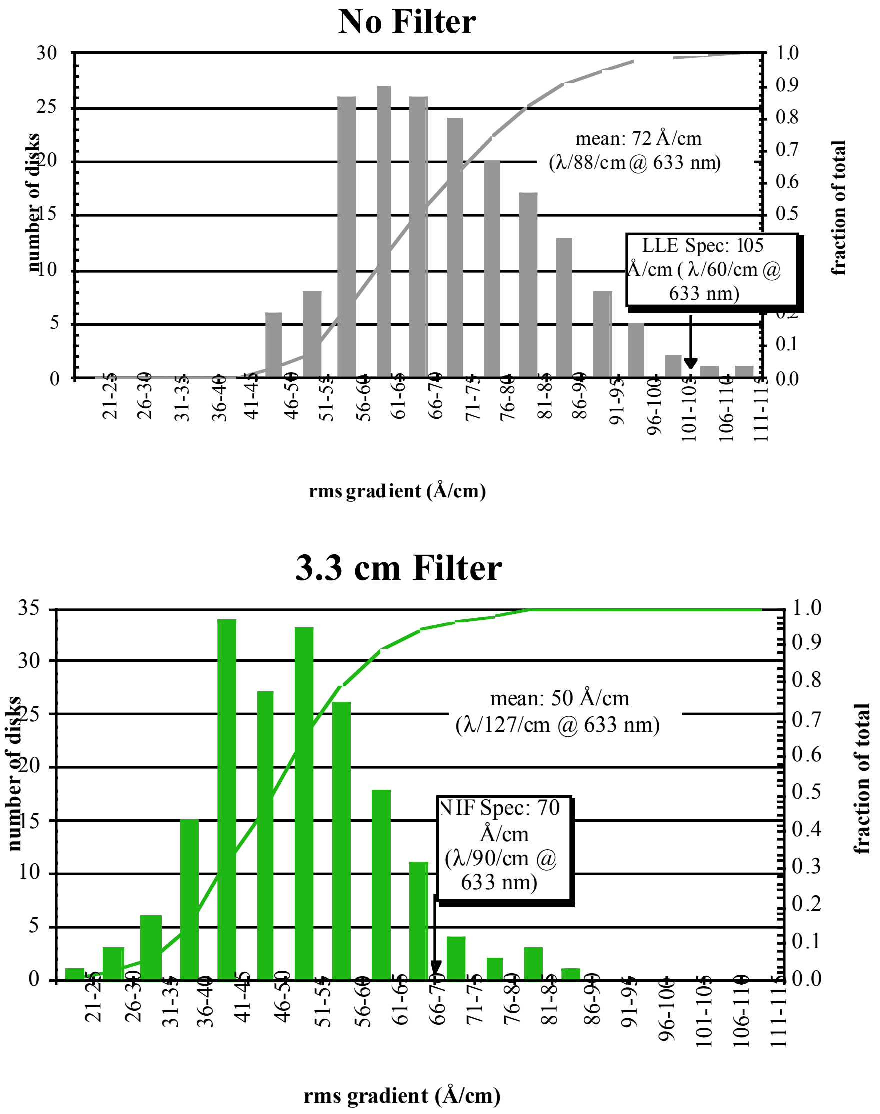


Figure 4. RMS Gradient distribution of 180 LLE Omega Upgrade 20cm disks with and without low-pass filtering.

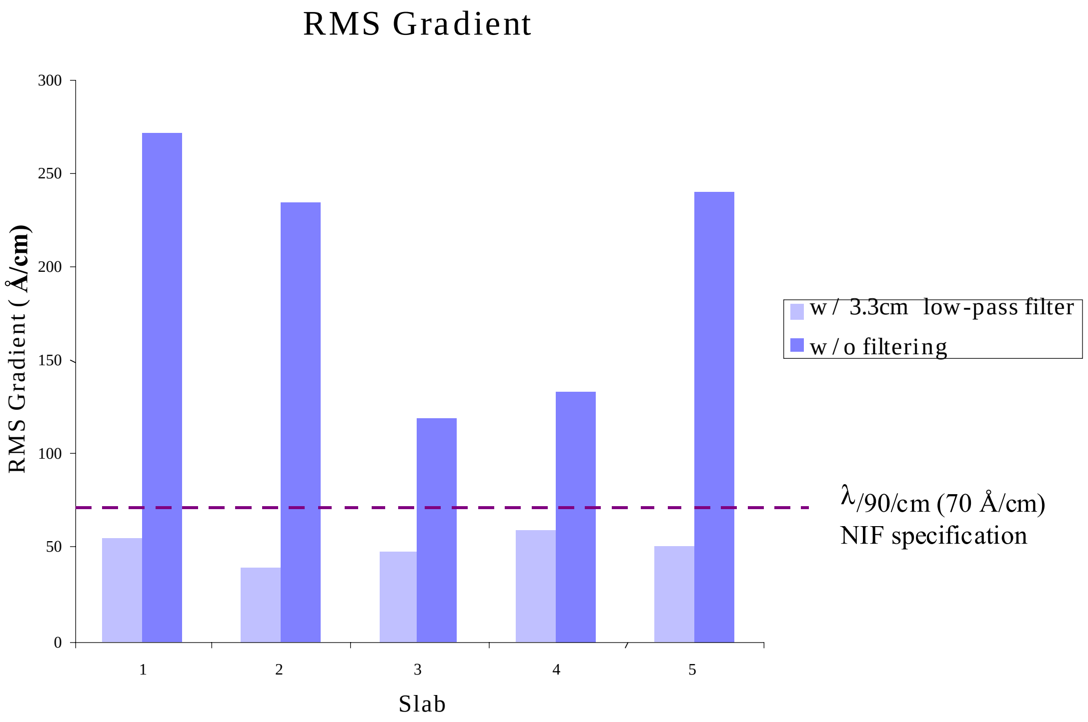


Figure 5. RMS Gradient distribution of Beamlet slabs with and without low-pass filtering.

5.0 REFERENCES

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