ACTIVE OPTICAL SYSTEMS

AN037

Beam Reshaping for Directed Energy Applications

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Revision: 9/6/12

1 Abstract

Directed energy weapons and long-range free-space optical communications systems often core and clip Gaussian intensity profile lasers to send them out through Cassegrain (annular) apertures. This causes significant loss to the system which can dramatically impact system size, weight, and efficiency (power consumption). In this application note, we present results from a simple model that shows how phase-based beam shaping can greatly improve the efficiency of the system even in a compact space often with no additional optics.

2 Model Setup

Figure 2.1 shows the experiment we are modeling. A Gaussian intensity profile laser beam reflects from a deformable mirror with Gaussian shaped influence functions. The beam them propagates 1 meter to an annular output aperture. In this plane, the beam is perfectly phase compensated and then focussed to a distance equivalent to a Fresnel number of 20. Then the beam is propagated to the focus (far-field).

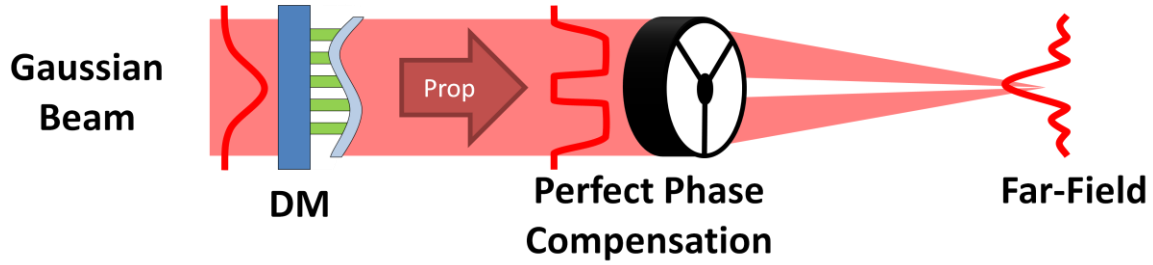

Figure 2.1 - Experimental Setup for Modeling

We worked with a 35-mm diameter 1-micron wavelength beam in this model. A 1-meter propagation of this beam represents a Fresnel number of 306. To properly represent the required angular bandwidth on the mesh (λ/δ), we needed to use a very small sample spacing and many mesh points (~8,192). This modeling was performed in 1D because this number of mesh points exceeded the capability of our current modeling software packages in 2D.

In these models, we varied the ratio of the diameter of the output aperture to the diameter of the central obscuration (called the magnification henceforth) and the number of actuators in 1D across the beam aperture. We were careful to make sure that the sum of the Gaussian influence functions was flat over the

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beam aperture by making the 1/e radius equal to the actuator separation distance. The actuators were evenly distributed over 2.5 times the aperture diameter to make sure the Gaussian edges were well represented.

To find good beam shaping, we used metric AO with a single-parent GESA approach. The metric for these simulations was the power in the diffraction-limited (DL) bucket in the far-field. The DM commands were forced to be symmetric for this model. We monitored the power transmitted through the annular aperture, the increase in power due to the beam shaping, and the power in the diffraction-limited bucket. This modeling approach was chosen as opposed to Gerchberg-Saxton, ray mapping, or Intensity Transport Equation solutions because it gives the user control over the spatial frequency of the results and has been shown to work well both in prior simulations and in the laboratory.[1]

2.1 Optimum Gaussian Beam Size for Power in Diffraction-Limited Spot

Before beginning with these experiments, we wanted to determine the best size of the Gaussian beam in 1D to maximize the power in the diffraction-limited (DL) spot. We created the Gaussian beam field amplitude with the Matlab code,

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E = exp(-1*(x/(sf*w)).^FieldPower);,
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where x is the lateral coordinate, w is the nominal size of the beam set to Dap/2 where Dap is the aperture diameter, sf is a varying scale factor, and FieldPower was set to 2.0 for a Gaussian Beam. This means that when sf=1, the intensity at w is exp(-2) = 13.5% of the peak.

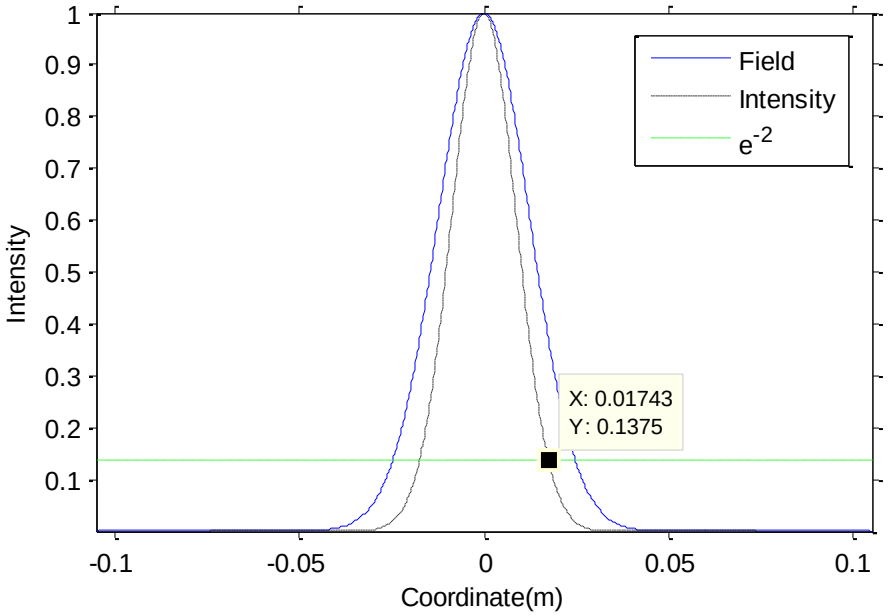

Figure 2.2 – Nominal Gaussian Beam Definition for w=17.5 mm

We varied the scale factor (sf) in the field definition above and examined the ratio of power in the diffraction limited spot to the total laser input power. Figure 2.3 shows the results for different Cassegratin aperture magnifications. In these experiments we determined that the peak in this curve varied with magnification (1.04, 0.97 and 0.93 for magnifications of 6, 8, and 10 respectively), but was always near 1.0, so we used a nominal beam size (1/e2 intensity radius) of Dap / 2.0 for this study going forward.

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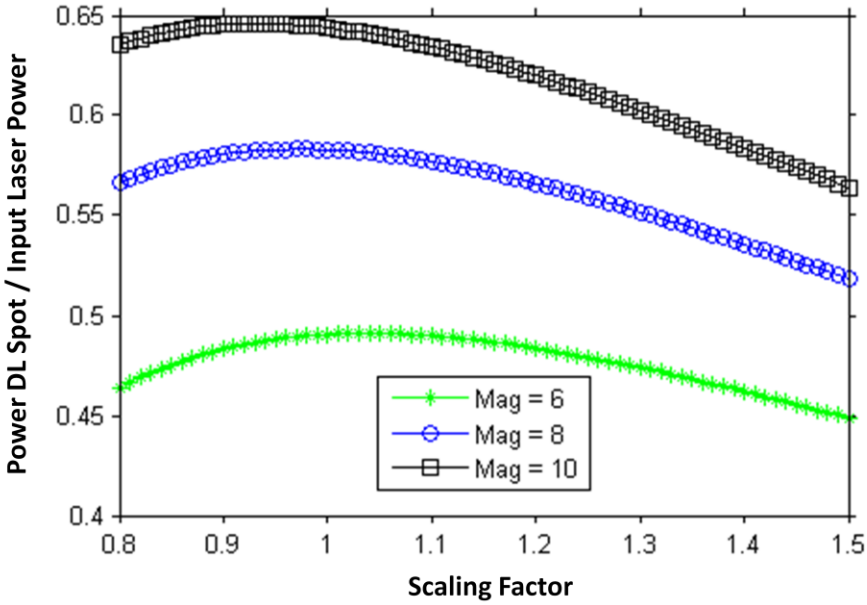

Figure 2.3 - Power in the DL spot vs. Input Laser Power vs. Gaussian Beam Size Scale Factor

3 2D Optimum Beam Clipping

We repeated this study with a 2D Gaussian and annular (Cassegrain) aperture. Figure 3.1 illustrates the results of this study. The optimum clipping radius was significantly lower in 2D than it was in 1D. Table 1 summarizes the optimal results numerically. In both cases, the size scale factor was a multiple on the radius of the exp(-2) intensity.

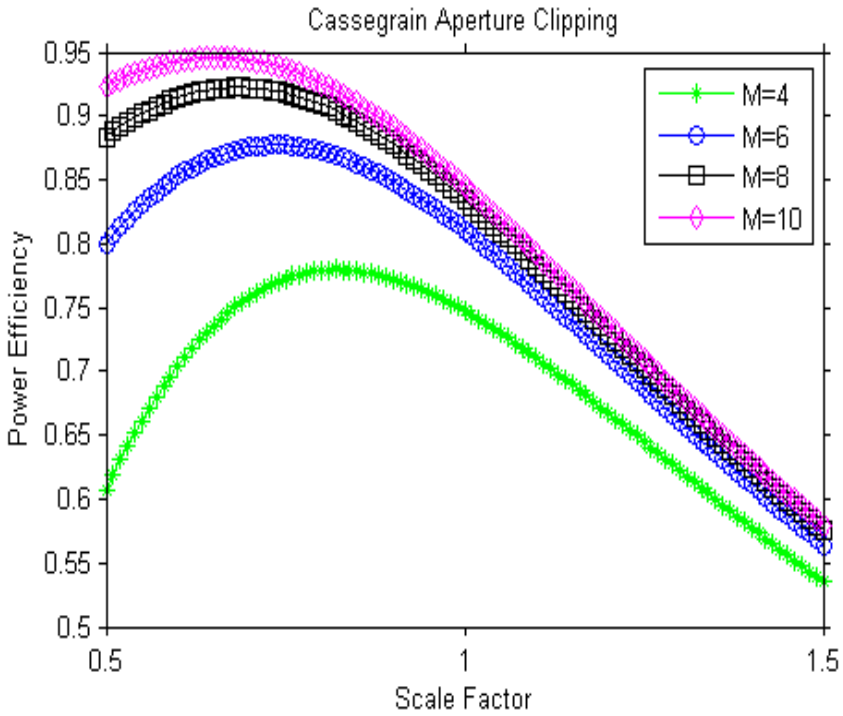

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Figure 3.1 - Results on Optimal Clipping of a 2D Gaussian beam. Scale Factor = 1 means clipping at exp(-2) intensity radius

Table 1 – Summary of Optimal Results from Annular Clipping of 2D Gaussian Beam

Mag	Efficiency	Best Size Factor
4	0.78	0.82
6	0.88	0.74
8	0.92	0.69
10	0.95	0.65

4 1D 35-mm Beam, 1 m Propagation Results

For this set of runs, the magnification was 6, 8, and 10, and the number of actuators across the beam was 19, 33, and 41. Figure 2.1 shows an example final result from the M=8 Nact=33 case. In this case, a low-frequency shaping phase with an amplitude of only about 0.6 waves over the Gaussian aperture was needed to shape the beam (top-left curve). The resulting phase in the shaped plane is larger in amplitude (about 15 waves) but is still very low spatial frequency (bottom left plot). The shaped field does not have a hard null in the center, but dramatically reduces the clipped power. For this case, we see an improvement in the power in the diffraction-limited spot by a factor of 1.17.

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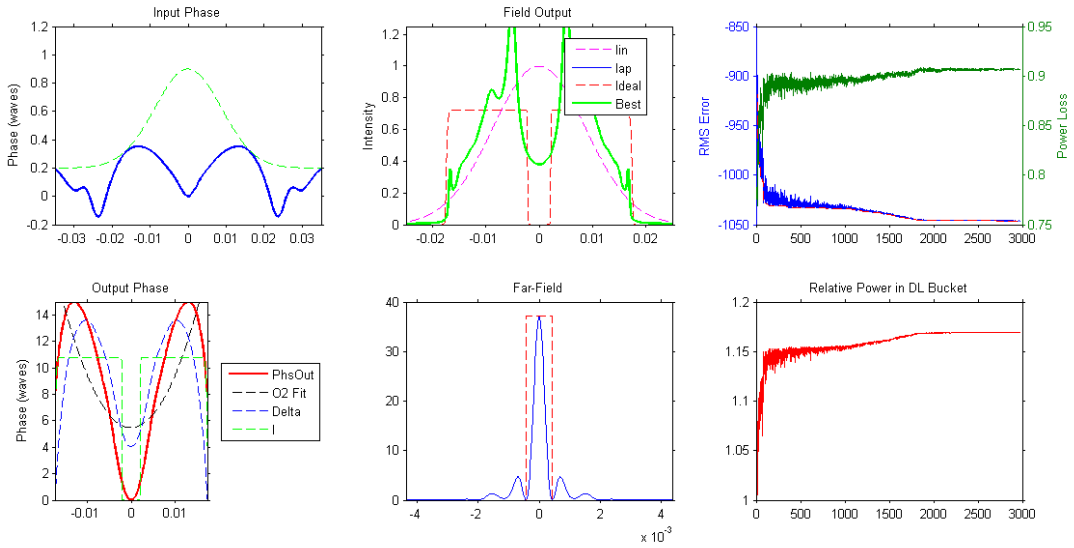

Figure 4.1 – (From top-left proceeding left-to-right then top-to-bottom) Results from the M=8 Nact=33 simulation: the input phase(blue) overlayed with initial Gaussian beam profile; the field at the annular aperture after beam shaping (green); the progress of the error metric(blue) and the power loss (green); the output phase profile(red), the desired annular profile (green), the order-2 fit (dashed black) and the difference between the output and the order-2 fit (dashed blue) ; the far-field intensity pattern(blue) with the diffraction-limited spot size indicated in red; and the power in the diffraction-limited far-field bucket relative to the far-field power without beam shaping.

Table 2 summarizes the results of the simulations including a magnification of 1000, which is the case with no central obscuration. In general, we found a 12% to 25% increase in the power in the diffraction-limited bucket using this approach.

Table 2- Numerical Simulation Results Summary

Actuators 1D	Magnification	DL Power Increase Factor	Aperture Output Ratio After Beam Shaping	Aperture Output Ratio After Beam Shaping	Aperture Output Increase Factor
19	6	1.218576049	0.879834568	0.693501863	1.268683785
19	8	1.146402639	0.896260754	0.756874437	1.184160424
19	10	1.112026486	0.908685839	0.795557628	1.142199894
19	1000	1.044830355	0.993643183	0.953188825	1.042441074
33	6	1.253800844	0.895836721	0.693501863	1.291758205
33	8	1.169278828	0.908969954	0.756874437	1.200952113
33	10	1.127633275	0.918376583	0.795557628	1.154380966
33	1000	1.036281584	0.985449919	0.953188825	1.033845438
41	6	1.255992078	0.894517954	0.693501863	1.289856598
41	8	1.171013682	0.908668591	0.756874437	1.200553945
41	10	1.12949165	0.918844395	0.795557628	1.154968997
41	1000	1.026984661	0.977940851	0.953188825	1.0259676

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5 Comparison of a Circular-Aperture Clipped Gaussian to Circular Top-Hat Beam without Considering the Clip Loss

We compared a circular top-hat beam with a non-annular circular clipped aperture Gaussian beam. For analysis in this section, the Gaussian intensity profile was created with the equation

$$I = \exp\left(-2\left(\frac{r}{r_{ap}} \cdot SF\right)^2\right),$$

where SF was a scale factor and r_{ap} was the aperture radius. The Gaussian intensity profile was hard-clipped at a radius of r_{ap}. The power in each beam shape was normalized. We propagated each of the beams (top-hat and circular aperture clipped Gaussian) to the far field and compared key parameters. Figure 5.1 shows two example clipped Gaussians for two different scale factors, SF.

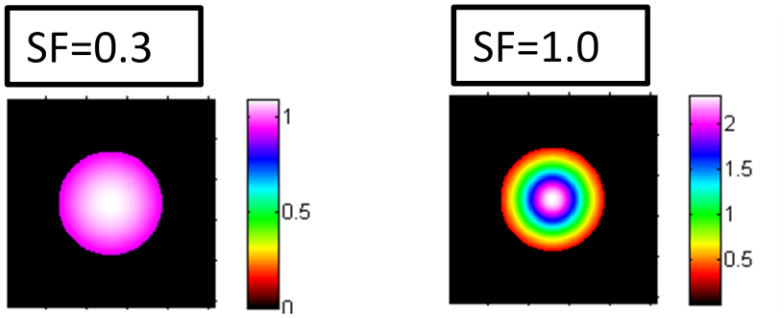

Figure 5.1 - Example intensity profiles for two different scale factors (SF) of the circular clipped Gaussian

Figure 5.2 shows the peak irradiance with respect to the scale factor, SF. In no case was the clipped Gaussian peak irradiance higher than the top-hat beam.

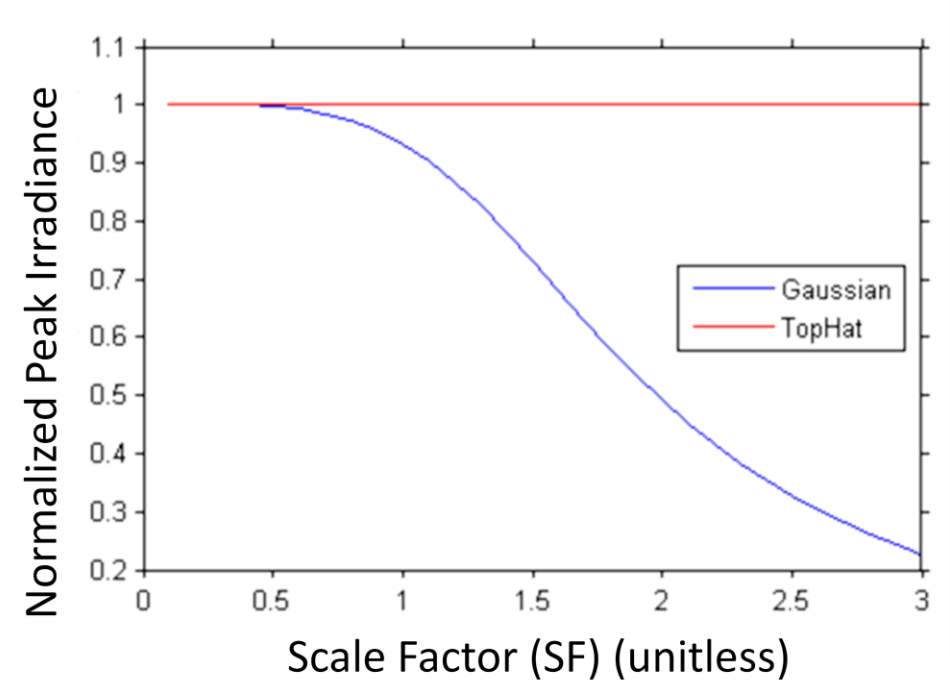

Figure 5.2- Comparison of peak irradiance between Gaussians and top-hat beams

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Figure 5.3 shows a comparison of the power in the diffraction-limited bucket for the two types of beams. The power in the diffraction-limited bucket was significantly higher (93% vs. 84%) for the clipped Gaussian beam. The power peaked at around a scale factor of 1.1.

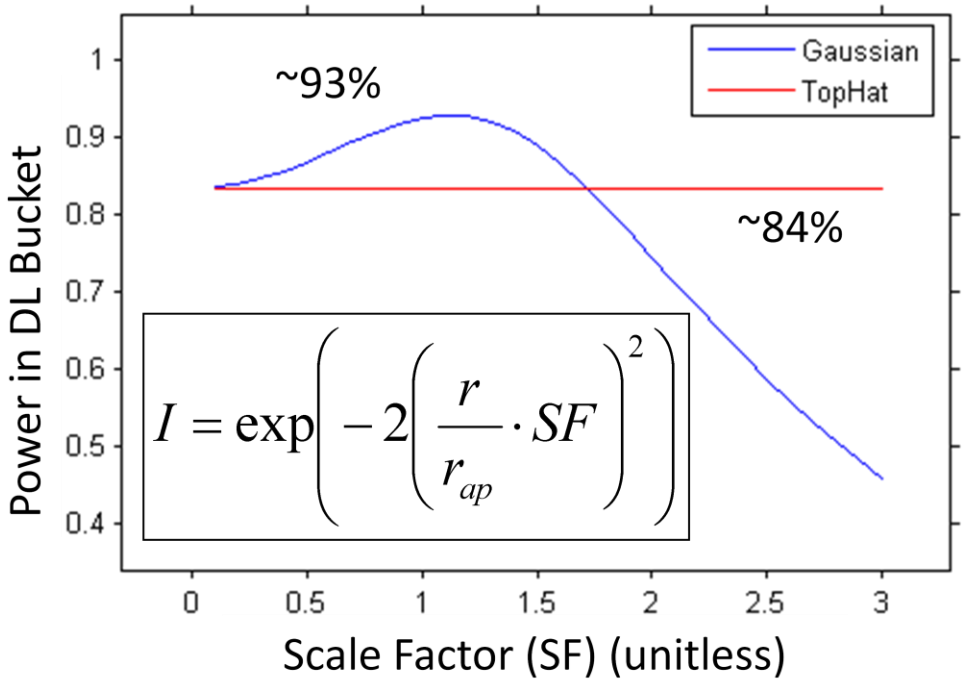

Figure 5.3 - Comparison of circular-aperture clipped Gaussian and top-hat beam power in the diffraction limited bucket

5.1 Comparison of Top-Hat to Circular-Aperture Clipped Gaussian Including the Clip Loss

Figure 5.4 shows a comparison of the power in the diffraction-limited spot including the Gaussian clip loss. We were surprised to find that even with the clip loss of the aperture, the clipped Gaussian had significantly more power in the diffraction-limited bucket than the top-hat beam. We are currently working to obtain a secondary verification of this result because it is so surprising. The effect has been attributed to the high-angle scatter from the edge which is more significant for the top-hat than for the clipped Gaussian due to the reduction in power at the edges of the clipped Gaussian. The peak was around a scale factor of 1.4. Figure 5.5 shows the near-field and far-field results of the wave-optics simulation which was implemented on a 256x256 mesh. It is clearest on the log intensity cross-section that the energy in the top-hat beam is much higher outside the diffraction-limited spot.

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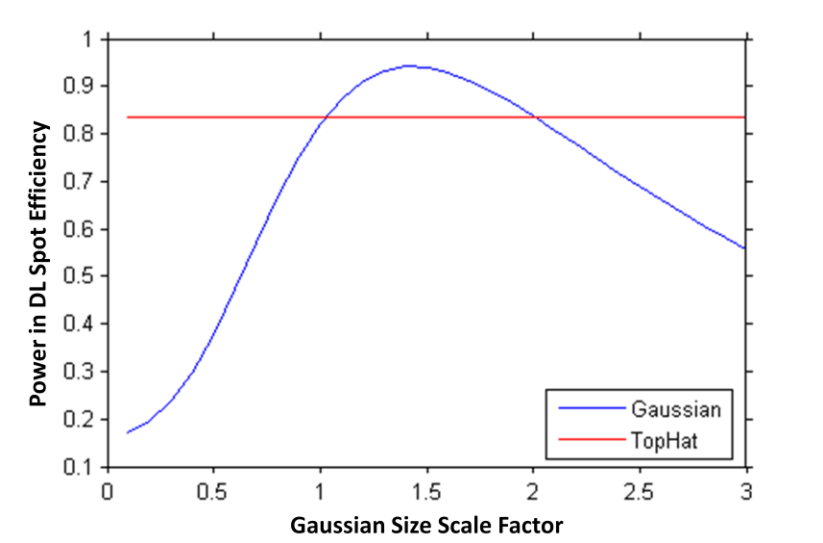

Figure 5.4 - Comparison of Power in the Diffraction-Limited Bucket of a Top-Hat beam to Clipped Gaussian including the Gaussian Clip Loss

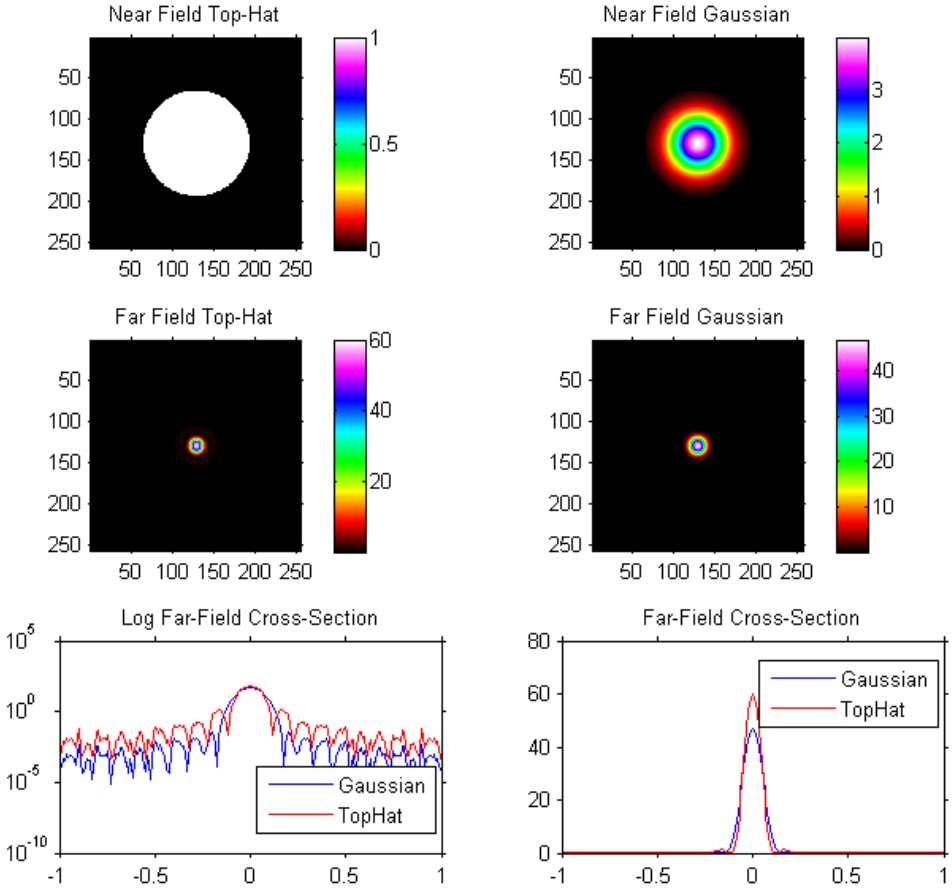

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Figure 5.5 - Comparison of top-hat and circular-aperture clipped Gaussian for a scale factor of 1.4.

6 Conclusions

We have shown that beam shaping can significantly increase the efficiency of a typical directed energy system for a very low cost compared with a comparable increase in laser output power. Although we have presented this result as if a DM were being used, it is clear to us that since the phase required for beam shaping will not change significantly over time and the amplitude of the necessary phase profiles is somewhat large, it would be preferable to manufacture a fixed optic through methods like diamond turning, MRF, or micro-machining.

7 References

[1] J. D. Mansell and B. G. Henderson, "Evaluation of polymer membrane deformable mirrors for high peak power laser machining applications", SPIE Proc. Vol. 7816 (2010).

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