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How to model laser beam propagation in OpticStudio: Part 1 - Gaussian beam theory and ray-based approach

Zemax OpticStudio

Also available in **日本語**, **简体中文**

This article is part of the **Modeling Laser Beam Propagation in OpticStudio** free tutorial.

Three tools can be used in OpticStudio sequential mode to model Gaussian beam propagation. They are:

- The ray-based approach
- Paraxial Gaussian Beam analysis
- Physical Optics Propagation

In this series of three articles, we'll discuss how to set up a Gaussian laser source, how to analyze the beam as it propagates through the optical system, and how to optimize for the smallest spot size using these three methods. We'll also discuss when is appropriate to use which methods.

This article is the first of the three-article series describing the ray-based approach to model laser beam propagation.

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Introduction

OpticStudio sequential mode provides three tools to model Gaussian beam propagation:

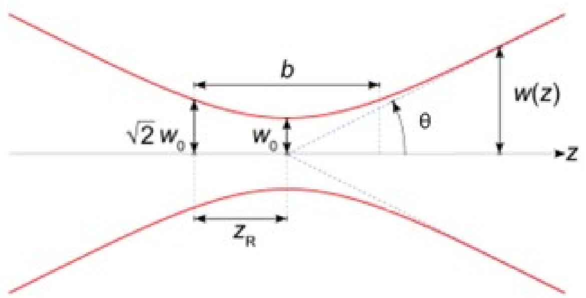
- Physical Optics Propagation (POP). It models laser beam by propagating a coherent wavefront, which allows very detailed study of arbitrary coherent optical beams.

This series of three Knowledgebase articles discuss how to model Gaussian beam using these three methods. In this article we'll introduce method 1 - how to model laser beam propagation using ray-based approach.

Gaussian beam theory

Consider an ideal Gaussian beam with waist w_0. As shown in the schematic below This Gaussian beam can be described using any two of the three parameters:

- wavelength λ
- beam waist w0
- divergence angle θ



The beam size is a function of the distance from the waist. Please note that OpticStudio uses the half width or radius to describe beam width.

$$w(z) = w_0 \left[1 + \left(\frac{z}{z_R}\right)^2\right]^{\frac{1}{2}} \qquad (1)$$

For large distances the beam size expands linearly. The divergence angle θ of the beam is given by

$$\theta = \frac{\lambda}{\pi\, w_0} \quad for\ z \gg z_R \qquad (2)$$

Here, z_R is the Rayleigh range of the beam given by

$$z_R = \frac{\pi\, {w_0}^2}{\lambda} \qquad (3)$$

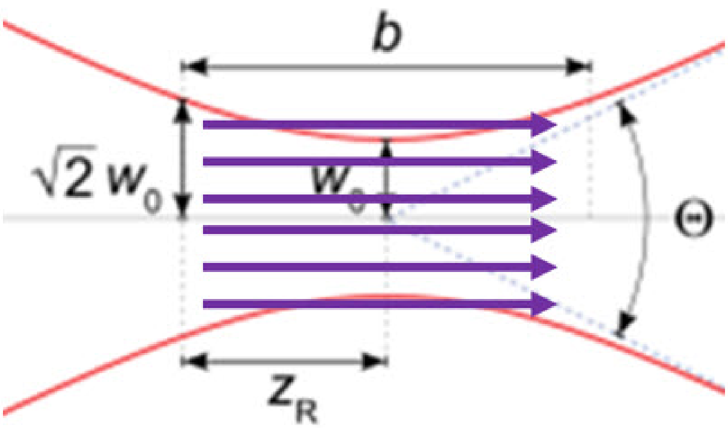
The phase radius of curvature of the beam is a function of the distance from the beam waist, z:

This means that the radius is infinite at waist location z = 0, reaches its minimum of $2z_R$ at $z = z_R$, and asymptotically approaches infinity as z approaches infinity.

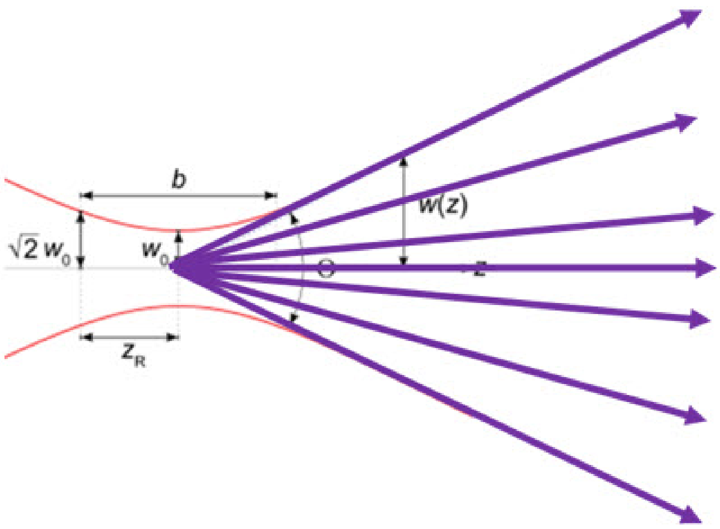
Ray-based approach to model Gaussian beam

Geometrical optics is the modeling of optical systems by tracing rays. Rays are imaginary lines which represent normals to the surfaces of constant phase, or the wavefront (see **"What is a ray?"** for more details). For a paraxial Gaussian beam, within the Rayleigh range, $z < z_R$, the beam size changes very slowly. In this case, beam can be modeled as collimated ray bundle. When far outside the Rayleigh range, $z >> z_R$, beam size changes linearly with propagation distance, so beam can be modeled as a point source. This is shown in the drawings below.

As collimated ray bundle inside z_R

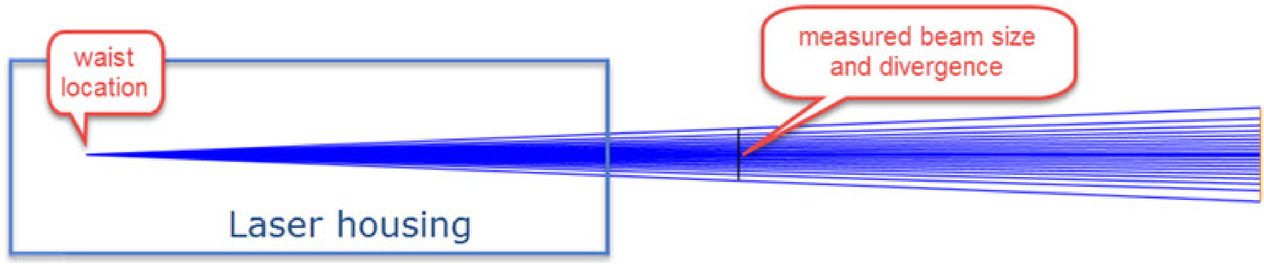


As point source for $z \gg z_R$



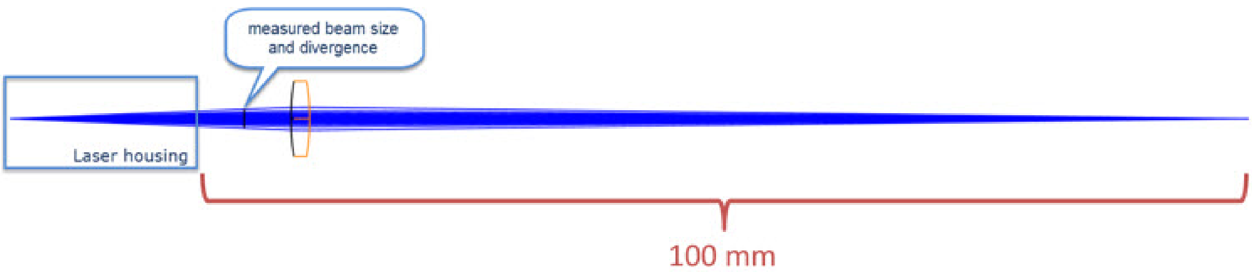
Example

- Nominal Wavelength = 355 nm
- Measured 5 mm from laser output:
  - Beam diameter = 2 mm
  - Measured divergence = 9 mrad



Knowing the wavelength and the far field divergence angle, using equations (1) through (3), the beam waist is calculated to be 0.0125 mm, with a Rayleigh range of 1.383 mm. We will focus the beam using a singlet lens. The goal is to optimize the system, so the beam size is the smallest at 100 mm away from the laser output. We will model this system using ray-based approach first.

As shown in the earlier section, when using rays to model Gaussian beam, we need to know if the propagation is within the Rayleigh range or outside Rayleigh range. This can help us decide if we should use a point source or a collimated ray bundle to model the beam. In this case, we know the beam waist location is inside of the Laser housing. Using equation (1), with the calculated beam waist 0.0125 mm and Rayleigh range 1.383 mm, we can manually calculate the beam propagation distance z from its waist, around 111.1 mm, when the beam hits the measurement location. Since this propagation distance is much larger than the beam Rayleigh range, $z >> z_R$, we can then model the beam using a point source.



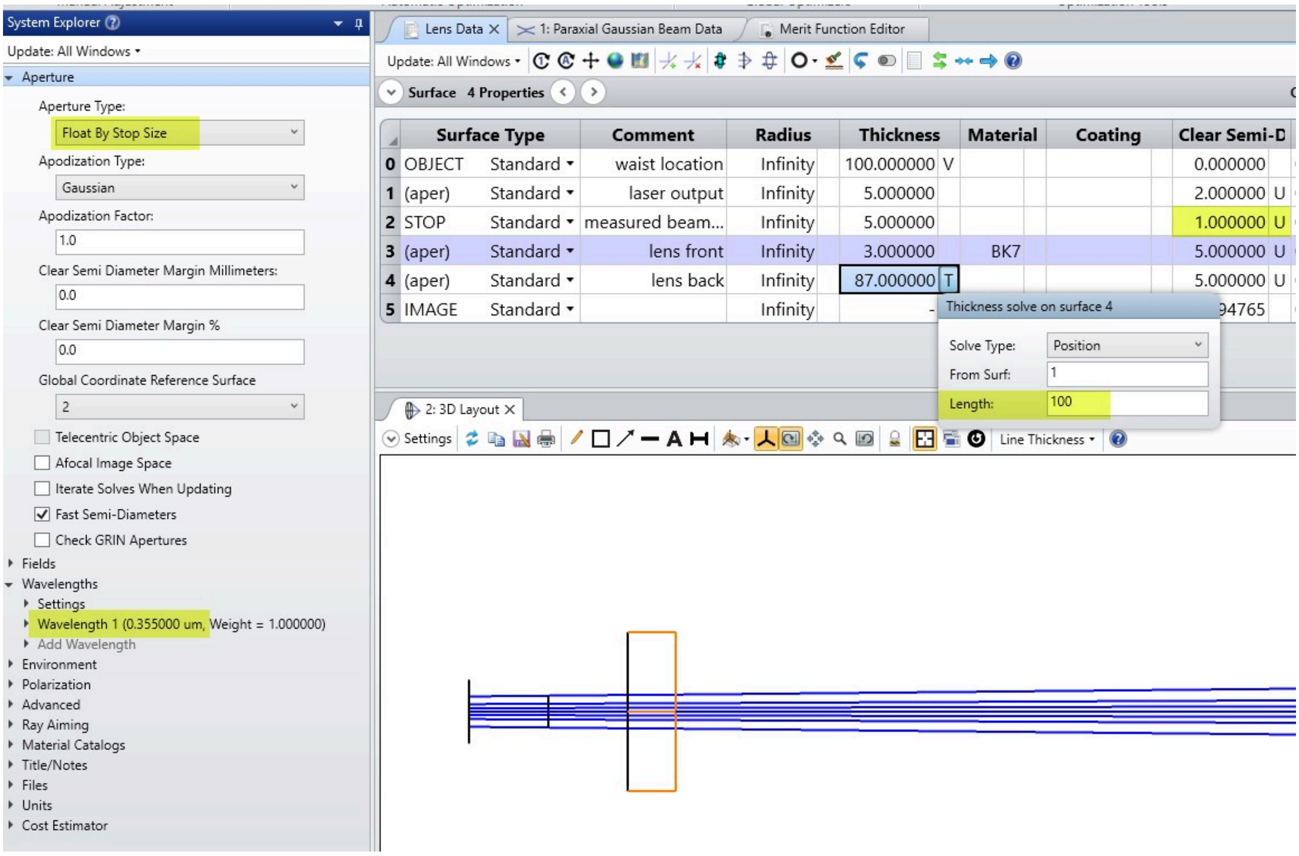
To set this up in OpticStudio:

In the **System Explorer**:

- Enter the wavelength 0.355 um into **Wavelengths**.
- In **Apertures...Aperture Type**, enter Float By Stop Size.
- In **Apertures...Apodization Type**, enter Gaussian, and **System Explorer...Apertures...Apodization Factor,** enter 1.0. In geometric ray tracing, the apodization factor can be used to produce a Gaussian type amplitude variation in the pupil to simulate illumination of the entrance pupil by a laser beam. Setting the apodization factor G=1.0 creates a Gaussian amplitude distribution where the beam intensity decreases to $1/e^2$ at the edge of the pupil. This means the beam width or radius is set to be the same as the semi-diameter of the entrance pupil.

face.

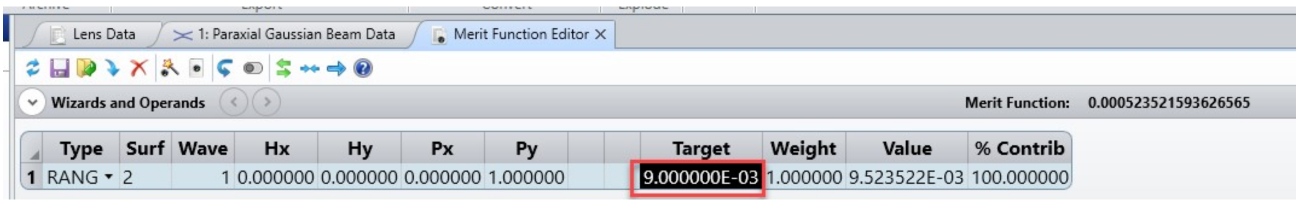
- Surface 1 is the laser output face.
- Surface 2 is the STOP surface and 5 mm away from surface 1. This is the dummy surface where beam size and divergence angle were measured.



- Using beam size equation (1), the waist location can be calculated first, and then the object plane can be set at the waist location.
- Alternatively, we could also make OpticStudio find the waist location for us, which is what we will do here. The Object Thickness value is 100 mm as a first guess. Set it as a variable.
- The Semi-Diameter value on the STOP surface 2 is 1 mm, to match the given 2 mm laser beam diameter.

This is the file “1_rays start.zmx” which can be found in the Download section of this article.

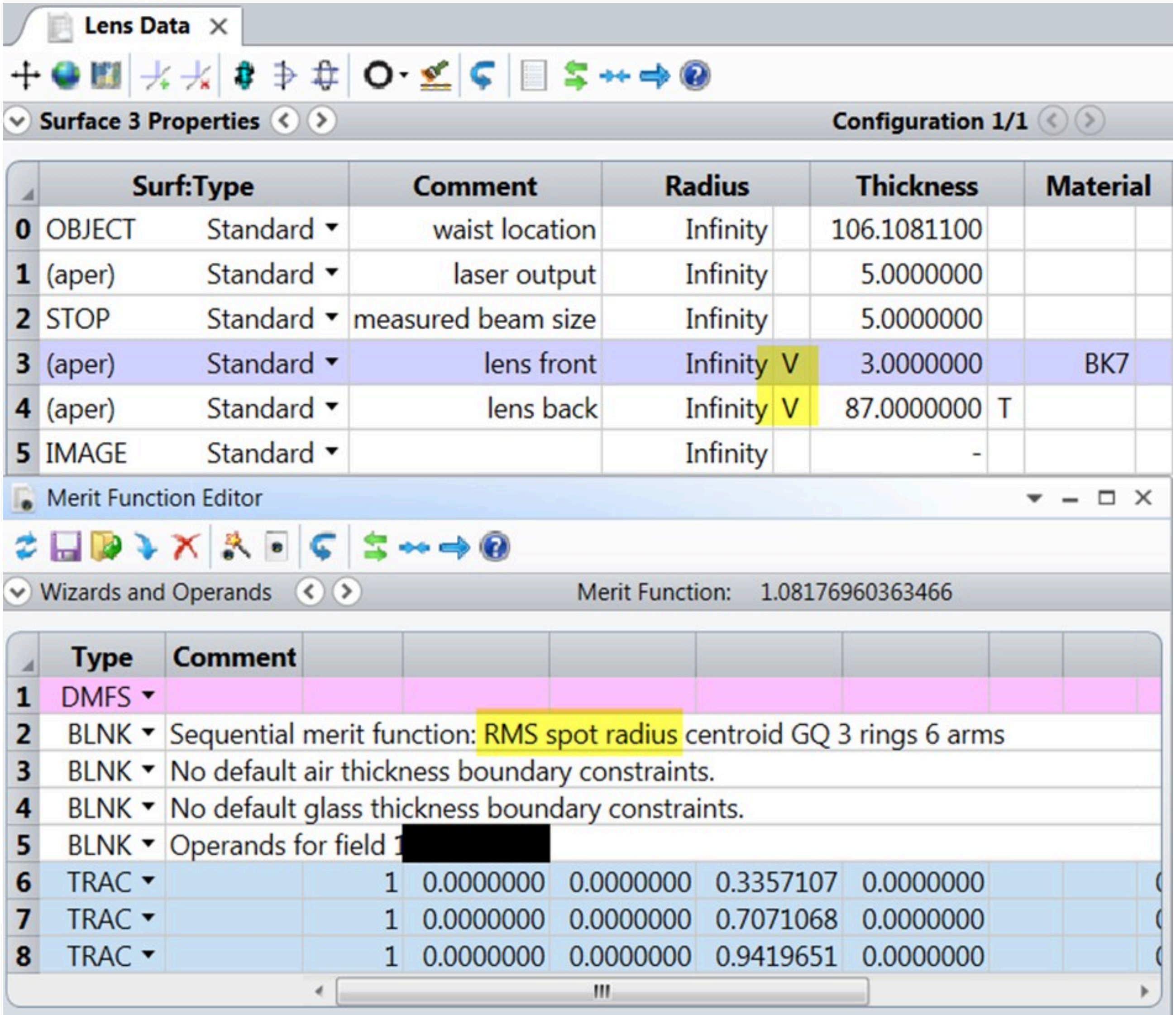
The beam divergence is 9 mrad, measured at surface 2. This information can be entered in the Merit Function Editor using operand RANG, as shown below. RANG returns the ray angle in radians with respect to the local *z* axis of the specified surface. Set the Target to 9 mrad, and the Weight to 1.0.



Now optimize. Object Thickness becomes 106.108 mm. The marginal ray hits surface 2 at 9 mrad angle.

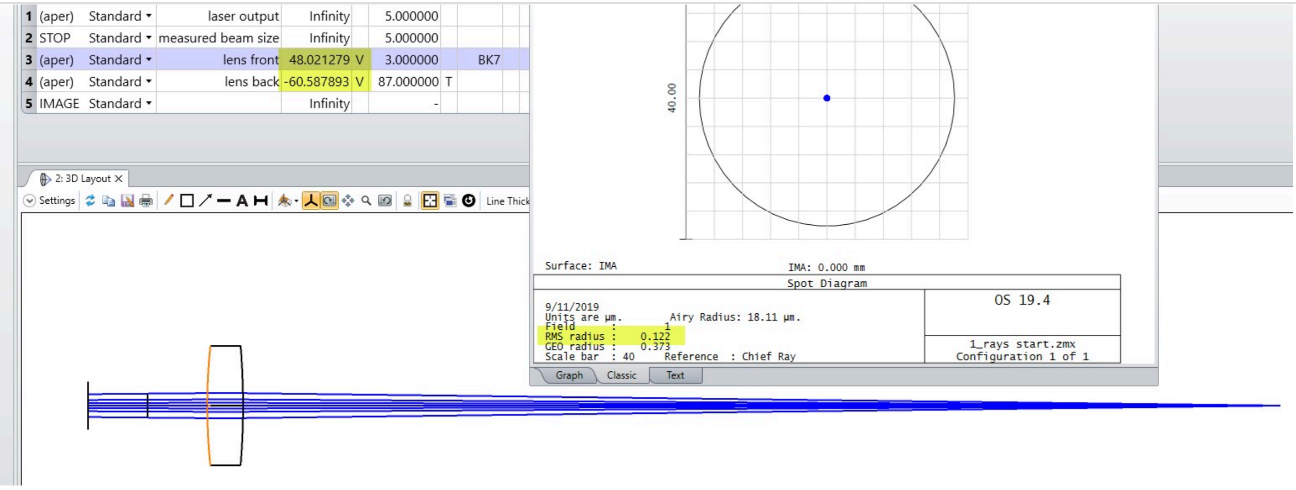
Next is to optimize the singlet so it focuses the beam down to the smallest spot 100 mm away from the laser output face surface 1.

- Set the front and back radii of the singlet as variables.
- Set up the Merit Function Editor using Optimization Wizard and choose RMS spot radius as Image Quality criterion.



After a quick local optimization run, the spot size decreases from initial 1.086 mm to 0.122 µm which is much smaller than the Airy disc radius 18.11 µm, reported by OpticStudio in the Standard Spot Diagram analysis window. This indicates the system is now diffraction limited. It is important to remember that in diffraction cases the RMS/Geometric spot radius is not a good measure of the real beam size (whether it is Gaussian or not) as it does not account for the effects of diffraction. OpticStudio provides other tools to study diffraction effect, for example the Fast Fourier Transform (FFT) PSF and Huygens PSF, as well as the Physical Optics Propagation (POP) tool. We will not discuss the FFT and Huygens PSF in this series, but we do describe how to use POP as a tool to focus this beam in part 3 of this series.

This file "1_rays optimized.zmx" can be found in the article Download section.

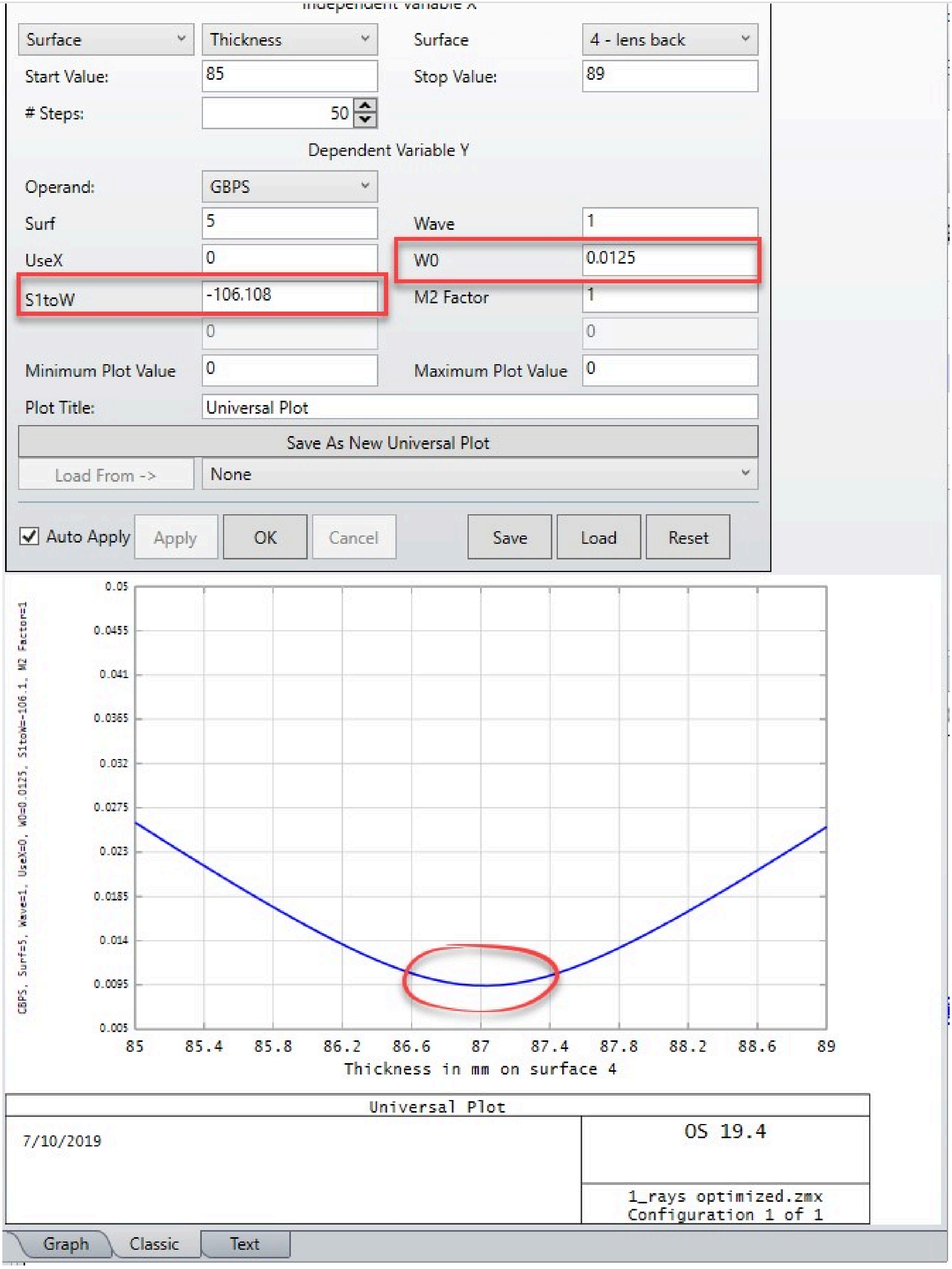


Validation of the ray-based approach

Above we used pure ray-based approach to optimize the singlet lens so that the beam size is the smallest at 100 mm away from the laser output. As we know the laser beam diffracts as it propagates through the space, which cannot be modeled by ray-based approach. While we know that the focused spot size reported by the ray based calculation is not accurate in this case, this does not mean the result of our optimization to find the location of the best focus is invalid.

To find out how agreeable this result is when launching a coherent laser beam into the system, we can do a quick comparison using the Paraxial Gaussian Beam analysis tool under **Analyze…Lasers and Fibers…Gaussian Beams…Paraxial Gaussian Beam. A** full description of this tool can be found in part 2 of these three-article series.

Here, we'll only look at the Paraxial Gaussian Beam results using 1D Universal Plot under **Analyze…Universal Plot…1D.** This plot shows the computed paraxial Gaussian beam size as a function of the image plane location.



In the plot, you can see the smallest Gaussian beam size occurs at a back focal distance around 87.020 mm, which turns out to be very close to our current back focal distance. This suggests the image location found by ray-based optimization yielding the smallest geometrical spot size also results in the smallest Gaussian beam size computed by the Paraxial Gaussian Beam tool. In other words in this system the smallest spot location found by ray-based approach agrees well with the location of the smallest Gaussian beam size.

Beam analysis to model Gaussian beam

KA-01849

Associated files

download example (.zip)

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