

Lesson 30: Understanding Gaussian Beams

Background:

Lasers, which are frequently used as light sources for all kinds of optical systems, produce a beam that is usually very small in diameter. The intensity of such beams is nonuniform, following a Gaussian profile in the ideal case, hence the name, and deviating from that profile in a characteristic manner in most real cases. There are two issues that must be accounted for when designing and analyzing systems with this kind of illumination: the shape of the profile and the fact that beams of very small diameter exhibit strong diffraction effects as they propagate.

Gaussian Beams in SYNOPSIS

As with most sophisticated features of the program, we aim at getting accurate results with as few complications as possible. For this reason, the program addresses the peculiar properties of such beams in a novel fashion.

The main issue is the fact that, if the beam diameter is small, diffraction plays a role all along the beam. Rays going through normal lenses, on the other hand, where the beam diameter is much larger than the wavelength of the light, follow straight lines to a very good approximation, and we can then deal with “rays” of light. That is not the case with Gaussian beams, as long as the beam is very small. Then the path of a light ray is *curved* and requires special attention in ray tracing.

Consider the following system:

```
RLE
ID OBG DEMO
OBG .15 2
UNI MM
WA1 .6328
1 TH 50
2 RD -2.55 TH 2 GTB S
BK7
2 CAO 2
3 CAO 2
3 RD -55 TH 100
4 RD 100 TH 2 PIN 2
5 TH 50 UMC
4 CAO 10
5 CAO 10
7
AFOC
END
```



Following the rules for this kind of beam, the object is declared type “OBG”, with a waist on surface 1 and a radius of 0.15 mm. We are concerned with rays out to a point that is twice the $1/e^{**2}$ point, according to the third word on the OBG line. The marginal rays shown in the picture above originate at that point in the beam. For this example we have also included two simple lenses, to expand and then recollimate the beam.

If we took the beam at surface 1 to be exactly collimated, the ray intercept on surface 2 would be the same as on surface 1. But that would be incorrect, since diffraction enlarges the beam by the time it gets there. To account for this effect, the program considers the beam at the waist to be slightly curved, just enough so that a *real ray*, traced from surface 1, hits surface 2 at about the same place as the diffracted Gaussian beam, and with the same divergence angle. From that point we can treat a diffracting beam with the usual raytracing methods, provided diffraction thereafter is minimal. How accurate is this trick?

Ask for a beam trace, which evaluates the beam everywhere according to paraxial Gaussian beam theory.

SYNOPSIS AI>BEAM

ID OBG DEMO 33262 13-MAY-13 14:16:08

GAUSSIAN BEAM ANALYSIS

SURF	BEAM RADIUS	WAIST LOCATION	WAIST RADIUS	DIVERGENCE
1	0.150000	-7.5157030E-15	0.150000	0.001343
2	0.164341	-7.368983	0.005965	0.022287
3	0.208892	-6.563589	0.006332	0.031811
4	3.389933	-357.899054	0.014036	0.009472
5	3.408876	-2087.561971	3.406641	5.9127598E-05
6	3.408985	-2137.561971	3.406641	5.9127598E-05
7	3.408985	-2137.561971	3.406641	5.9127598E-05

SYNOPSIS AI>

Notice that the beam radius on surface 2 is larger than on surface 1 because of diffraction. Now trace a real ray at pupil point (0, .5), which is at the $1/e^{**2}$ point.

SYNOPSIS AI>RAY P 0 0 .5 SURF

INDIVIDUAL RAYTRACE ANALYSIS

FRACT. OBJECT HEIGHT HBAR 0.000000 GBAR 0.000000
 FRACT. ENTRANCE PUPIL COORD. YEN 0.500000 XEN 0.000000
 COLOR NUMBER 1

SURF	X	RAY VECTORS			(X DIR TAN)	(Y DIR TAN)	(INC. ANG.)
		Y	Z	ZZ	HH	UNI	
OBJ	0.000000	0.000000	0.000000	0.000000	0.000549		
1	0.000000	0.136910	0.000000	0.000000	0.000549	0.031434	
2	0.000000	0.164338	-0.005301	0.000000	0.022307	3.663636	
3	0.000000	0.209062	-0.000397	0.000000	0.031846	1.060103	
4	0.000000	3.395560	0.057666	0.000000	0.009449	3.769940	
5	0.000000	3.413463	-0.047616	0.000000	-5.576629E-05	1.057009	
6	0.000000	3.410672	0.000000	0.000000	-5.576629E-05	0.003195	

REDUCED RAY ANGLES IN RADIANS AT IMAGE SURFACE

PSI (X) PHI (Y) Z
 0.000000 -5.576629E-05 0.000000

SYNOPSIS AI>

The path of this real ray closely approximates the **BEAM** trace. We now have a tool that lets you analyze and optimize such a system using real rays. As long as the beam is expanded early on in the system (so diffraction has little effect thereafter) this real-ray approximation is useful and simple to set up.

Complications

But there are sometimes complications. Suppose, for example that there is an element right at the waist. If thickness number 1 is zero, or if that surface is not a dummy, the program cannot make the adjustments described above. Instead, it then adjusts the geometry so that it can trace an OBA object (finite object distance) where

```
TH0 = 1.0E14
YPO = TH0 * DIV
YMP1 = WAIST * RBS
YP1 = 0.0
```

Thus, the object is then at infinity and the entrance pupil radius is a function of the input OBG waist. In this situation, the program can still run the BEAM analysis, but diffraction is not taken into account with real rays, as it was before. If the first element expands the beam, however, then diffraction plays little role anyway and this is still a useful approach.

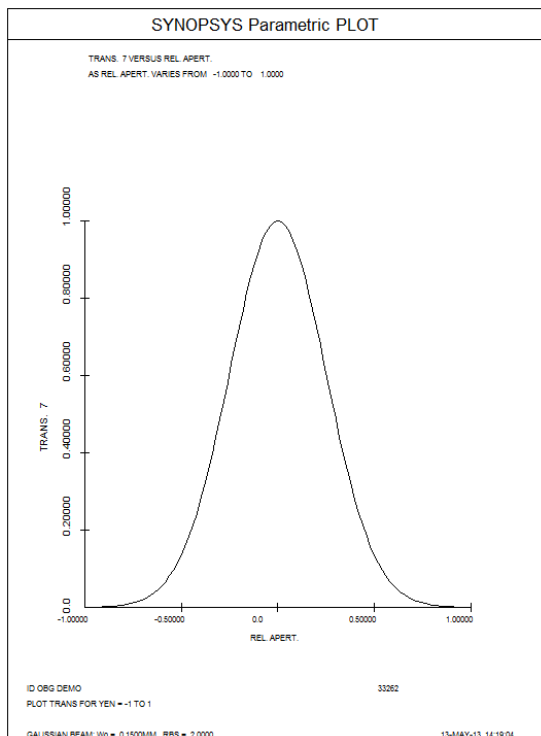
But what if there are one or more surfaces or elements in the beam where it is still very small? Suppose an expander is located, say one meter from the waist, and there are several fold mirrors along the way. The trick first described only operates between surfaces 1 and 2, remember, and diffraction between other surfaces would be neglected in that case but not in this one. Fortunately, there is another trick, and it's very simple.

What you do is assign a thickness of one meter to surface 1 (or whatever the distance is before the expander), put a dummy surface 2 at that distance, and then assign a thickness of *minus* a meter (or whatever is needed to get to the first element or mirror) to surface 2. Now the program can adjust the beam properties at the waist so that diffraction is taken into account at the dummy surface 2. If you trace a real ray, it will hit surface 2 at the same place as the Gaussian beam does, and you can refract from there according to the first rule.

Beam profile

Let us look at that Gaussian profile. Type the following AI sentence:

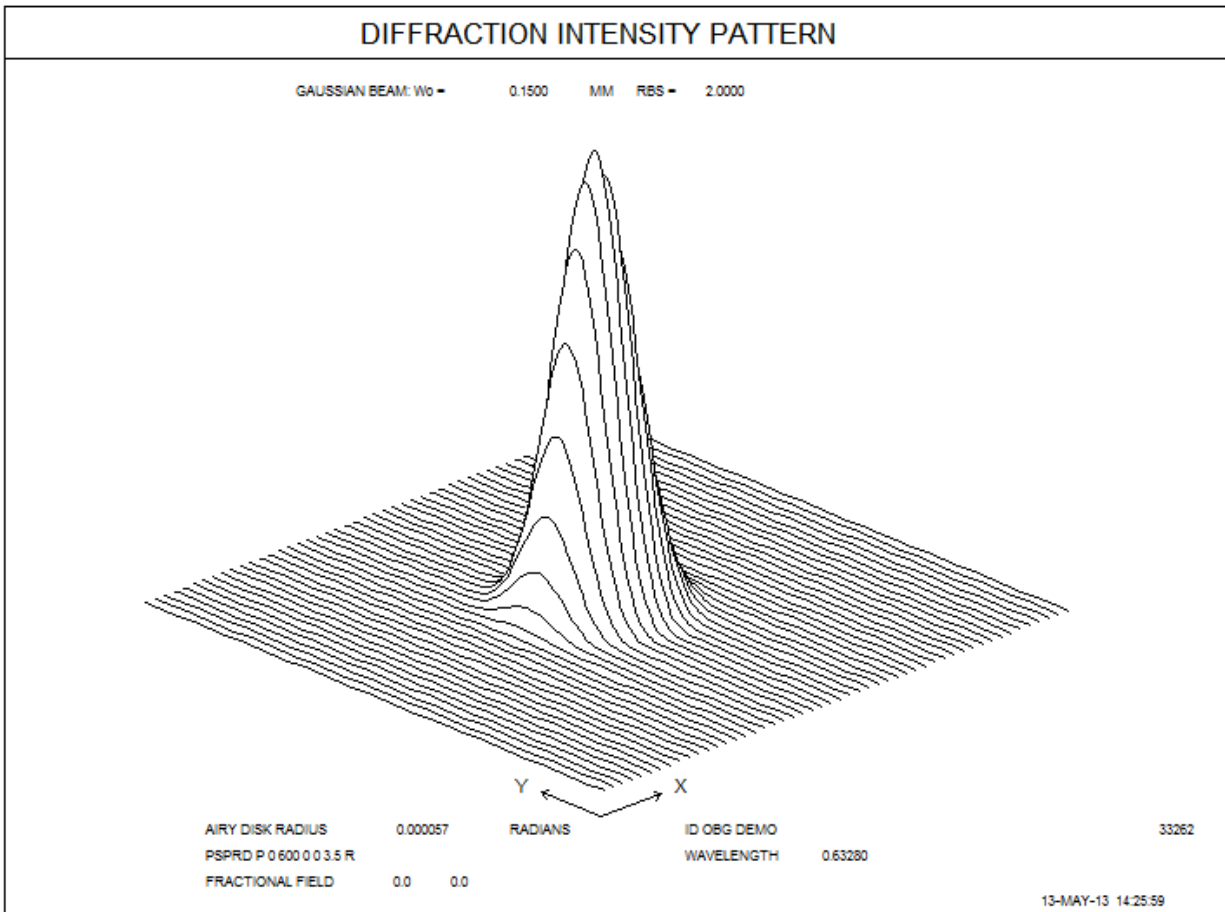
```
PLOT TRANS FOR YEN = -1 TO 1
```



This shows your beautiful Gaussian shape. There are other ways to see the shape too. In Lesson 11, we show how to make a MACro using the COMPOSITE aberration format to plot the profile, and Lesson 12 shows how to design a simple system to expand the beam and yield uniform intensity at the same time. There, we show how the diffraction-propagation program DPROP can analyze the improved energy distribution, giving yet another way to analyze this kind of beam.

Effect on image

To complete this lesson, we make a diffraction pattern of the output. Since the beam is Gaussian, the far-field image is also Gaussian in shape. Go to the **MDI** dialog, and ask for a PSPRD plot.



Indeed, we see there are no diffraction rings at all! That's a property of Gaussian beams. Diffraction takes place mainly around the edge of a beam, and if that edge is very fuzzy, having fallen off to a much lower value than at the center, then diffraction at the edge plays no role.

To read about other subtleties regarding Gaussian beams, including noncircular beams and the effects of beam quality, type **HELP OBG** in the Command Window.