Optical design software like CODE V® provides many capabilities for analyzing the performance of optical systems. For optical performance, the capabilities are often separated into two major categories: geometrical and diffraction.

Accurate FFT-Based Diffraction Calculations

When using the FFT-based diffraction features, CODE V automatically handles several computational details:

- The ray grid used to determine the complex amplitude in the exit pupil is distributed evenly in direction cosine space. Each ray then represents equal projected solid angle and the intensity computation can be accurately done. For systems with pupil aberration between the entrance and exit pupils, this means that the ray grid in the entrance pupil will be distorted to achieve the needed equi-direction cosine distribution in the exit pupil.
- CODE V automatically includes obliquity factors so that the correct PSF is computed even if the image plane is tilted relative to the incoming wavefront.

There are three interdependent user inputs associated with the FFT-based analyses. The default values work well for many systems, but you should verify that the inputs will provide results with the desired accuracy based on their system attributes. The inputs are:

- Transform Grid Size (TGR)—TGR defines the number of sample points (rays) along one direction of a square grid, traced to the exit pupil. It also defines the number of sample points across the image area used for representing the PSF. The default is 128, resulting in 16,384 rays. The TGR value must be a power of 2.
- Number of Rays across Diameter (NRD)—NRD defines the number of sample points across the entrance pupil. For reasons that we will describe later, this is a smaller number than the transform grid size. The default is the TGR/2.
- The grid separation of sample points across the image area (GRI)—GRI is an alternate input to NRD, and defines the separation of sample points across the PSF. You can define NRD or GRI, but not both.

These inputs are related as shown in this equation: GRI = λ (f/#) (NRD / TGR). Figure 2 illustrates the interdependency of TGR, NRD and GRI. The default GRI results in approximately 5-samples across the Airy disk of a diffraction limited spot.

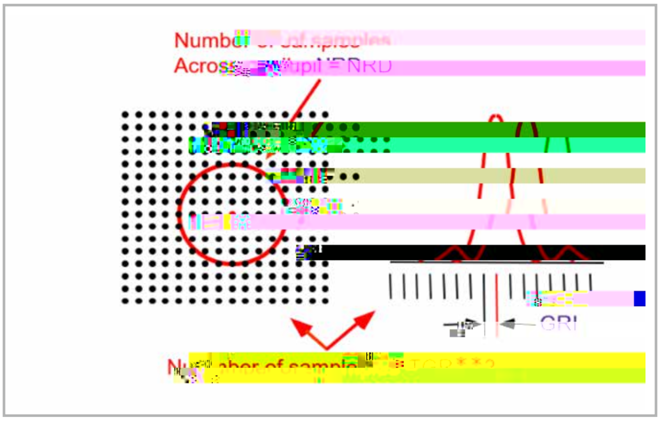


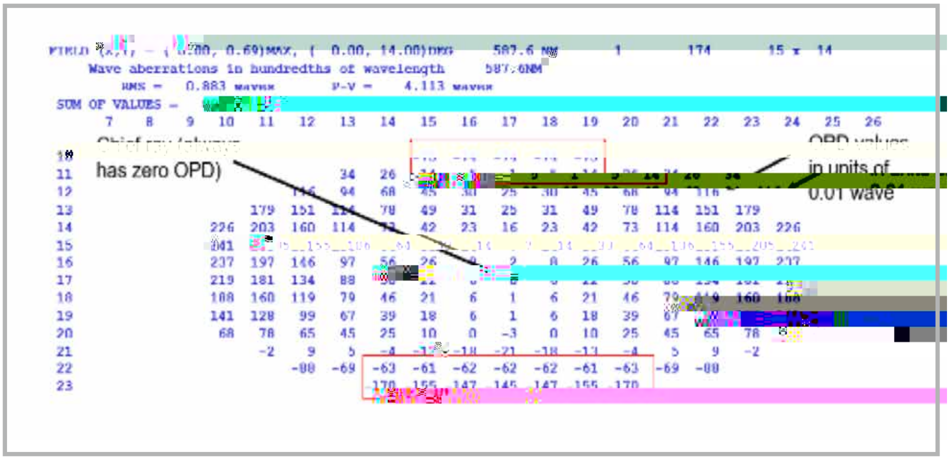
Figure 2: Interdependency of TGR, NRD and GRI for FFT-based analysis

To compute an accurate PSF, the following four conditions must be met:

1. A large enough NRD so that the system aperture shapes are adequately sampled
    a. An adequately sampled pupil is particularly important for systems with oddly shaped apertures or obscurations
2. A large enough NRD so that the optical path difference (OPD) change between adjacent rays is less than 0.5 waves
    a. Keeping the OPD change < 0.5-waves prevents erroneous artifacts from being computed/displayed (aliasing)
    b. This condition suggests that an aberrated system likely needs a higher NRD versus a well-corrected system, for similar accuracy
3. A large enough patch at the image (Image Patch = TGR*GRI) so that there is zero energy at the edge of the grid
    a. An adequately sized image patch is also needed to prevent erroneous artifacts from being computed/displayed (aliasing)
    b. CODE V will warn you if the energy at the edge of the grid is above a threshold. When you receive this error, increase the TGR or increase the GRI value
4. A small enough GRI so that the details of the PSF are adequately sampled
    a. This is really a user choice based on the detail needed

Since a larger NRD means a larger GRI (for a constant TGR), the only way to maintain or increase sampling of the system apertures and also get a smaller GRI (for more detail in the PSF), is to increase the transform grid size.

To verify that the OPD between adjacent sample points is < 0.5 waves, you can use the CODE V Pupil Map (PMA) feature. PMA will print out and plot the wavefront OPD map for each field at each wavelength. The units are 0.01-waves, so the value difference between adjacent sample points should be < 50, as shown in Figure 3.



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FIELD (X,Y) = ( [illegible]0.00, 0.69)MAX, ( 0.00, 14.00)DEG     587.6 NM       1        174        15 x 14
     Wave aberrations in hundredths of wavelength      587.6NM
          RMS =    0.883 waves         P-V =    4.113 waves
 SUM OF VALUES = [illegible]
        7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26
 10  [illegible]
 11                                  34   26  [illegible]
 12                             146   94   68   45   30   25   30   45   68   94  116
 13                        179  151  114   78   49   31   25   31   49   78  114  151  179
 14                   226  203  160  114   73   42   23   16   23   42   73  114  160  203  226
 15                   241  [illegible]                                   64  106  155  205  241
 16                   237  197  146   97   56   26    9    2    0   26   56   97  146  197  237
 17                   219  181  134   88  [illegible]
 18                   188  160  119   79   46   21    6    1    6   21   46   79  119  160  188
 19                   141  128   99   67   39   18    6    1    6   18   39   67  [illegible]
 20                    68   78   65   45   25   10    0   -3    0   10   25   45   65   78
 21                         -2    9    5   -4  -13  -18  -21  -18  -13   -4    5    9   -2
 22                              -88  -69  -63  -61  -62  -62  -62  -61  -63  -69  -88
 23                                       -170 -155 -147 -145 -147 -155 -170
```

Figure 3: Wavefront OPD map at the Exit Pupil

In the data shown in red boxes in Figure 3, there are differences as large as 107 (> 1-wave) between points. To correct this, you would increase the NRD. However, if the TGR is kept constant, the grid spacing at the image will get larger. Alternatively, you can increase both the TGR and the NRD by the same factor, which will keep the image grid the same (but cover a larger area at the image). Figure 4 shows an example.

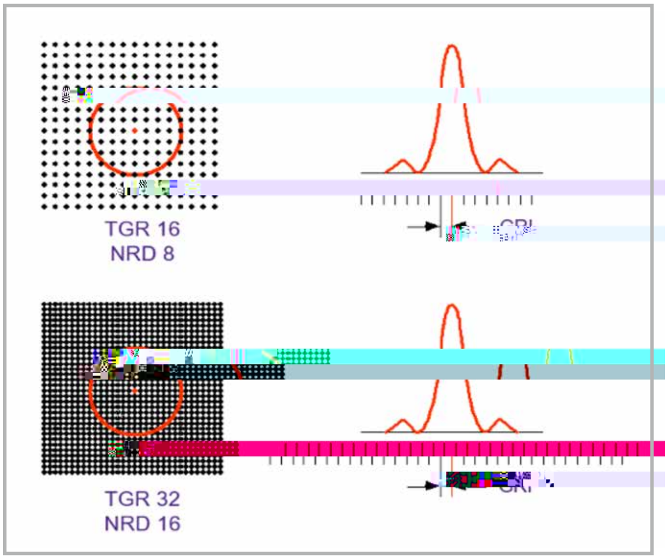


Figure 4: Increasing both TGR and NRD by the same factor covers a larger area at the image and maintains the image grid

It is important to think about these considerations, and their interdependence, when choosing inputs for your system.

Accurate Generalized Beam Propagation Analysis

CODE V Beam Synthesis Propagation (BSP) operates very differently than FFT-based diffraction computations. BSP is a beamlet-based propagator and models diffraction effects throughout the entire system. The input optical field (shown in red in Figure 5) is represented as a coherent summation of smaller beamlets (one of which is shown in blue). The individual beamlets are propagated through the system and all the beamlets are coherently summed to determine the optical field (and resulting intensity, amplitude, irradiance, phase, etc.) at any point in the system.

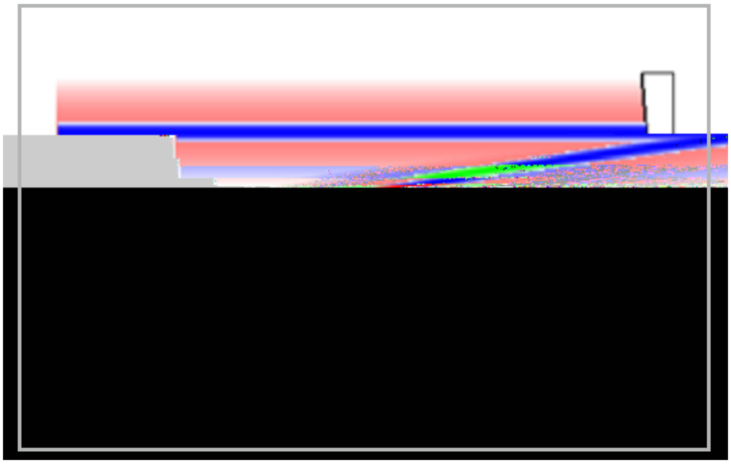
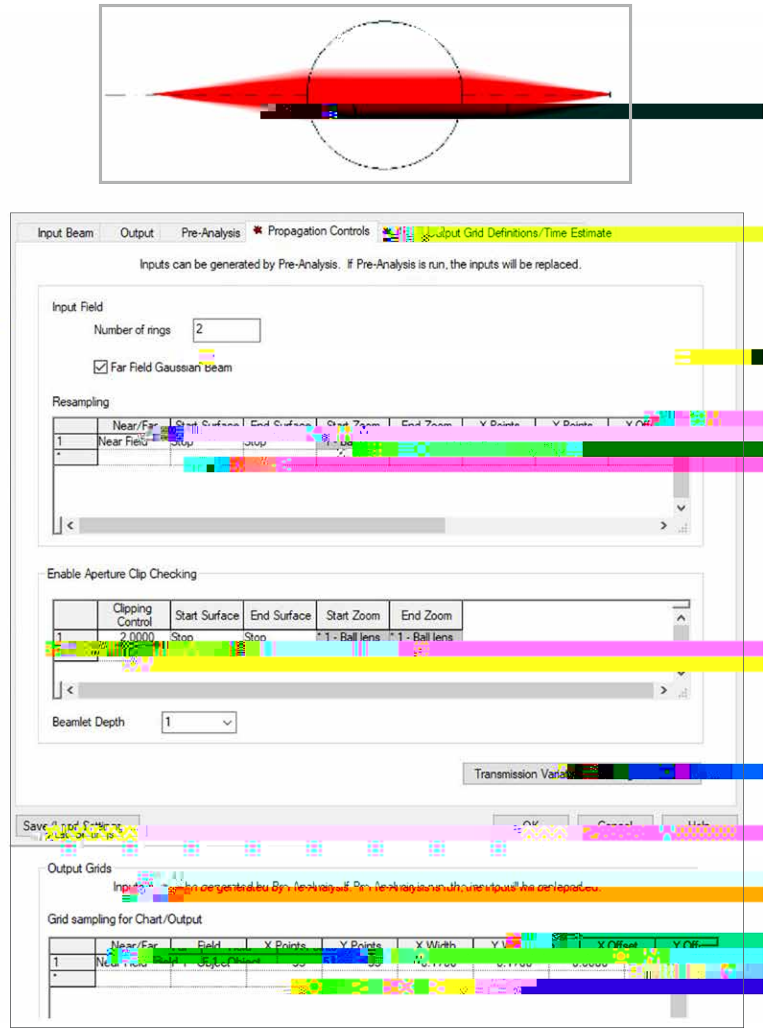


Figure 5: CODE V BSP represents the optical field by a coherent summation of individual beamlets

With a beamlet-based propagator, each beamlet carries a known amount of energy, so the pupil mapping used for the FFT-based analysis is not necessary. While there are many possible inputs and controls, BSP has a feature called Pre-Analysis that will determine optimal inputs based on your system, as well as the output you request. Pre-Analysis makes BSP very easy to use. The feature will recommend the initial sampling (i.e., number of beamlets) and whether resampling is required in the system (i.e., re-representing the optical field within the system with a new set of beamlets); this can, for example, avoid aberrated beamlets that decrease the accuracy of the calculation. Pre-Analysis will also indicate areas in the system where diffraction from aperture edges needs to be accounted for (clip checking). All of these parameters are included in BSP's propagation controls.

Pre-Analysis will also recommend output grid definitions. As mentioned previously, the set of beamlets are coherently summed at the location of interest to determine output. This coherent summation can be done on a coarse grid -- showing rough detail



Inputs can be generated by Pre-Analysis. If Pre-Analysis is run, the inputs will be replaced.

Input Field

Number of rings: 2

☑ Far Field Gaussian Beam

Resampling

	Near/Far	Start Surface	End Surface	Start Zoom	End Zoom	X Points	Y Points	Y Off
1	Near Field	Stop	Stop	1 - Ba				

Enable Aperture Clip Checking

	Clipping Control	Start Surface	End Surface	Start Zoom	End Zoom
1	2.0000	Stop	Stop	1 - Ball lens	1 - Ball lens

Beamlet Depth: 1

Output Grids

Inputs can be generated by Pre-Analysis. If Pre-Analysis is run, the inputs will be replaced.

Grid sampling for Chart/Output

	Near/Far	Field	X Points	Y Points	X Width	Y W	X Offset	Y Off
1	Near Field	1 - Object	53	53	0.1700	0.1700	0.0000	

Figure 6: BSP Pre-analysis generated Propagation Controls & Output Grids for the CODE V Ball Coupler sample lens

The Pre-Analysis suggested doing the coherent summation of beamlets on a grid of 53x53 points over a 0.17x0.17 mm square, to generate the output. This suggestion is based on a defining a coarse grid to show the large-scale detail in the resulting intensity at the image surface. If you zoom in, the result in Figure 7 does not show the expected rotational symmetry that should occur based on the geometry of the system.

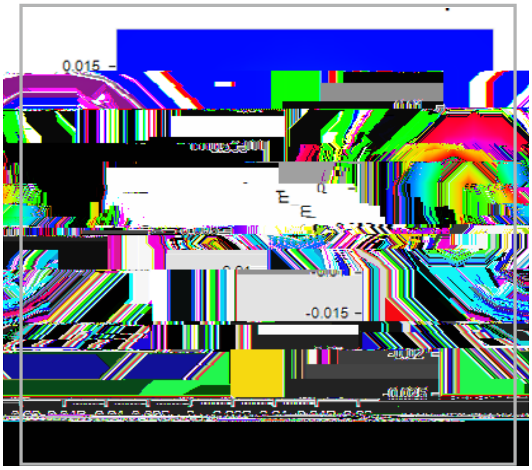


Figure 7: Intensity at image surface for ball sample lens with 53x53 output grid