PSF-Point Spread Function

The Point Spread Function (PSF) option computes the characteristics of the image of point objects, including the effects of diffraction.

When to Use the Point Spread Function Option

Use the Point Spread Function (PSF) option for the following purposes:

- To generate and display the aberrated diffraction structure of the polychromatic image at all fields and at several adjacent focal surfaces, if desired. Displays include listings and/or plots (both oblique projection and contour); normalizations (**INT** command) include:
  - Peak intensity as 100%
  - Strehl - Perfect lens is 100%
  - dB normalization, with noise threshold elimination (**Output threshold** setting, or **THR** command).

  Grids can be selected, if desired, for transform grids, pupil filling of transform grid, or grid spacing on the image.
- Analysis of significantly out-of-focus images can be done (**Near field propagation** setting or **PRO** command).
- Anamorphosed scaling can be used to handle widely different X and Y image profile sizes (**Anamorphic scale factor** setting or **XSC** command).
- Phase in the image, rather than intensity, can be displayed (**List phase** setting or **PHA** command).
- Output can be converted to detector energy for a given circular or rectangular detector placed at each image plane grid point - convolution of image and detector (**Detector energy** settings or **DEX**, **DEY** commands).
- Encircled energy tables and plots can be generated (**Encircled energy** settings or **ENC** command).
- Output can be converted to the image of two point sources for given X, Y separations - convolution of image and sources (**Convolution with image of two point objects** settings or **PAI** command).
- Any of these combinations that generate grid tables also can be converted and output as .INT files (intensity type), for analysis by other programs.

Polarization and Gaussian or user-defined (.INT file) apodization are all included in the analyses.

Default Operation

For each field point and zoom position, and for the depth-of-focus values defined in the LDM (FFO, IFO, NFO), the point spread function is constructed by converting the pupil function into the diffraction image, weighted and integrated over all wavelengths. This image patch is represented as a listing of intensity values (normalized to 100) in a 128 x 128 grid with the chief ray or optical axis as the center point on the grid, which spans an area about 13 Airy disc diameters wide (for the shortest wavelength). PSF uses Gaussian and user-defined (.INT files) apodization, and polarization if present in the lens data.

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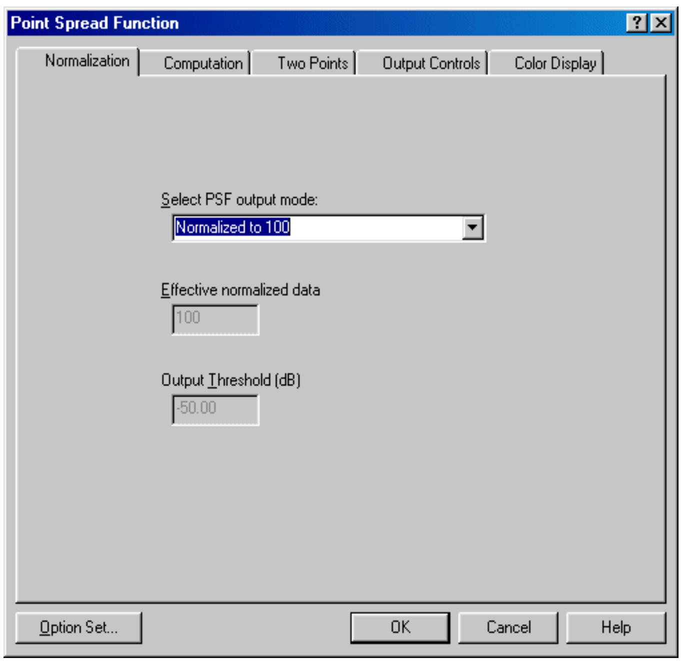
Command Mnemonics
(alphabetical)

ADD	BAC	COM	CON	DEX	DEY
DIS	ENC	GRI	INT	LEV	LIS
NRD	PAI	PER	PGR	PHA	PLO
PRO	RAN COL	RAN SCA	ROT	SIZ	TGR
THR	TIT	WBF	WIN	XDE	XMA
XSC	Y	YC			

Defining Analysis Type Settings

To define analysis type settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Point Spread Function** menu. The **Point Spread Function** dialog box displays, with the **Normalization** tab automatically selected. Define the controls on this tab as described in the table below.



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Command Syntax

Screen Control	Explanation	Default
INT [NOR | STR | DB | listed_peak_intensity | No....z]		
Select PSF output mode	Selects form of intensity normalization: **Normalized to 100 (NOR)** Normalized to peak = 100 **Strehl (STR)** Normalized to perfect lens peak = 100 **Decibels (DB)** dB falloff from the peak = 0 **Normalized to value (listed_peak_intensity)** Normalized to peak = value specified in **Effective normalized data** field. **No output (No)** Skip computation and display for this zoom position. If you select **Strehl** (STR), and obscuration is present, the peak value is relative to a perfect lens of the same obscuration; if Gaussian apodization is present, the peak is relative to a perfect lens with the same apodization. **Note:** INT can be used with PAI or DEX, DEY, but not both; output will be provided for both the diffraction image and the convolved image. INT can also be used with ENC.	INT NOR, unless ENC or PAI or DEX, DEY are included.
Effective normalized data	Modifies the intensity display default for any zoom position. First select **Normalized to value** in the **Select PSF output mode** field, and then specify a value in this field other than 100, which is the default value. Is a zoomable parameter; right-click over this field to access the **Zoom Editor**. **From the command line:** Equivalent to using the listed_peak_intensity qualifier in the INT command.	
THR output_noise_threshold_db....z		
Output threshold (DB)	Used only when you select **Decibels** in the **Select PSF output mode** field (INT DB). Suppresses noise below the value you enter in this field (output_noise_threshold_db); sets lower values to entered value for plots, deletes lower intensity values in listings. Helpful in smoothing plots.	-50

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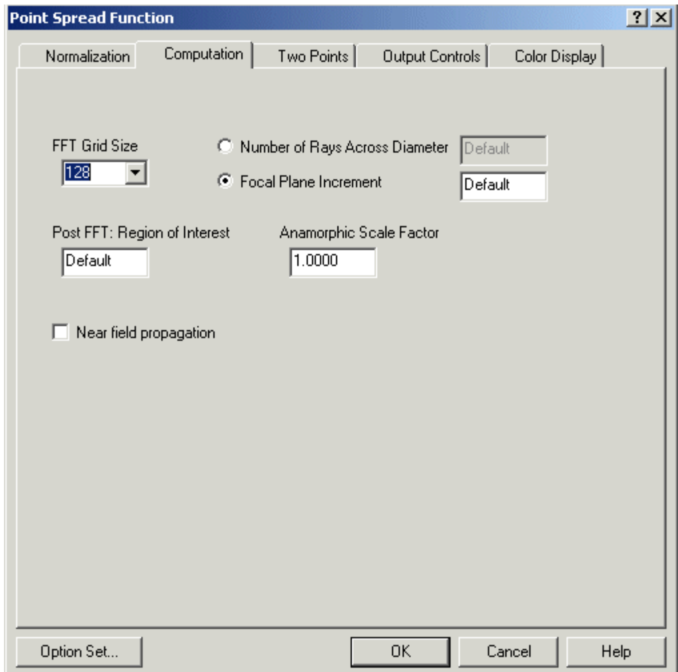
Defining Computation Controls

To define analysis type settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Point Spread Function** menu. The **Point Spread Function** dialog box displays. Click the **Computation** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
TGR num_fft_grid_pow_of_two		
FFT grid size	Specifies transform grid size (TGR). **Range**: 16 or more, must be a power of 2. Unless overridden by **Number of rays across diameter** (NRD) or **Focal plane grid increment** (GRI), also determines the number of rays traced in proportion to TGR**2. Use to improve accuracy for systems with large or unusual obscurations, or to increase the size of the image area analyzed relative to the Airy disc.	128
PGR num_integration_grid_width		
Post FFT: Region of Interest	Specifies integration grid size. **Range**: Any odd number less than **FFT grid size** (TGR). Restricts the area used for display and for centroiding, moments, encircled energy, etc.; excluded data is assumed to have 0 energy in all of these operations.	TGR-1.

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Command Syntax		
Screen Control	**Explanation**	**Default**
NRD num_rays_across_diameter....z		
Number of rays across diameter	Specifies number of rays traced across the pupil diameter for the shortest wavelength; other wavelengths are proportionately smaller to make image plane grids match. See also **Focal plane grid increment** (GRI) description. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Is a zoomable parameter; right-click over this field to access the **Zoom Editor**. You can use either **Number of rays across diameter** (NRD) or **Focal plane grid increment** (GRI), but not both.	TGR/2 at short wavelength.
GRI image_grid_spacing....z		
Focal plane increment	Specifies grid spacing measured on the image surface - is an alternative to **Number of rays across diameter** (NRD). Use to choose a more convenient number than the default. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Is a zoomable parameter; right-click over this field to access the **Zoom Editor**. You can use either **Number of rays across diameter** (NRD) or **Focal plane grid increment** (GRI), but not both.	Shortest wavelength * f-number/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.)
PRO Yes | No		
Near field propagation	Select to use near-field propagation, instead of far-field. Use when the image is out of focus and much larger than the Airy disc and occupies at least half of the output grid; the default **Focal plane grid increment** (GRI) value will be set to this value. The lens should be in focus. Use non-zero FFO to defocus.	No.
XSC scale_x_psf_by_factor....z		
Anamorphic scale factor	Scales X dimension of image by the specified factor. Used to handle highly anamorphic exit pupils. The largest (X or Y) numerical aperture of the exit pupil is used in establishing default values for **Focal plane grid increment** (GRI)/**Number of rays across diameter** (NRD); this may lead to insufficient sampling in either the X or Y dimension, depending on which was largest; check this with the Pupil Map (PMA) option. Use this field to scale up the X dimension of the image, which correspondingly reduces the number of pupil sampling points in the X direction, and vice versa. **Example**: An anamorphic scale factor of 2 scales the X dimension of the image by 2, and the focal plane grid increment or number of rays across diameter by 0.5. The reciprocal of the value will be written to the header of any files created with WIN.	1.0

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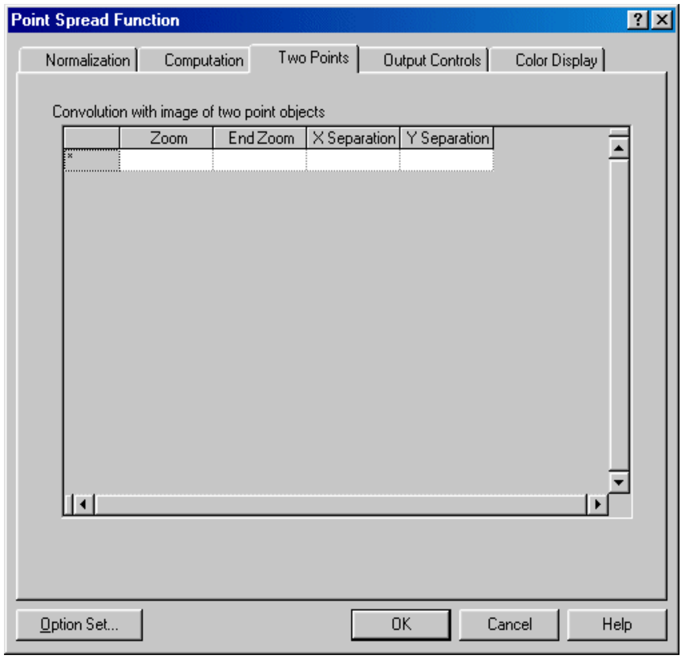
Defining Settings for Two Point Sources

To define settings for two point sources for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Point Spread Function** menu. The **Point Spread Function** dialog box displays. Click the **Two Points** tab, and define the controls on this tab as described in the table below.



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Command Syntax		
Screen Control	**Explanation**	**Default**
PAI [Zk | Zi..j] x_separation y_separation		
Convolution with image of two point objects	Replaces output with a display to show the image convolved with the image of two point objects with the equivalent geometrical image surface X and Y separations. Each point in the display grid becomes the relative energy of the combined image. **Range**: Less than 1/2 the full grid dimension. Output is generated for each field and focus position, in all zoom positions, unless restricted with Zk|Zi..j. Can't be used with **Detector Energy** settings (DEX, DEY); can be used with **PSF output mode** settings (INT). **Start Zoom (Zk|Zi)** Allows you to restrict the zoom position(s) included in the two-point source analysis output. Specifies the starting zoom position in a range of zoom positions included in the output. You can also use this field to specify a single zoom position included in output. **End Zoom (Zj)** Allows you to restrict the zoom positions included in the two-point source analysis output. Specifies the ending zoom position in a range of zoom positions included in the output. **X Separation** (x_separation) Specifies the geometrical image surface X separation used in the display grid. **Y Separation** (y_separation) Specifies the geometrical image surface Y separation used in the display grid.	No, assumes single point source only.

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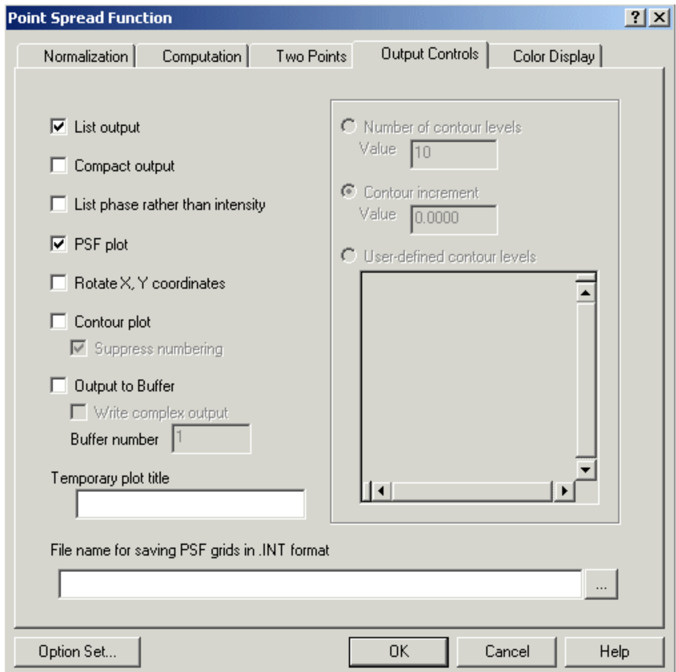
Defining Output Controls

To define output control settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Point Spread Function** menu. The **Point Spread Function** dialog box displays. Click the **Output Controls** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
LIS Yes | No....z		
List output	De-select (No) to turn off listed output when only plotting is wanted. Is a zoomable parameter; right-click this field to access the **Zoom Editor**.	Yes.
COM Yes | No....z		
Compact output	Normal listed grid displays include two blank lines between grid rows to make vertical and horizontal scales equal. Select this checkbox (COM Yes) to cancel the blank lines. Is a zoomable parameter; right-click this field to access the **Zoom Editor**.	No.
PHA Yes | No....z		
List phase rather than intensity	Changes output in grid to represent phase in the image, instead of intensity. Is a zoomable parameter; right-click this field to access the **Zoom Editor**.	No.

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<table>
<tr><th colspan="3">Command Syntax</th></tr>
<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">PLO Yes | No....z</td></tr>
<tr><td>PSF plot</td><td>Plots intensity (INT) and/or convolution using Convolution with image of two point objects (PAI) or Detector Energy in X and Y directions (DEX,DEY) as a single page oblique projection plot for each field point. Vertical scale of the peak: 4 inches corresponds to 100%. Is a zoomable parameter; right-click this field to access the Zoom Editor.</td><td>Yes.</td></tr>
<tr><td colspan="3">ROT Yes | No....z</td></tr>
<tr><td>Rotate X, Y coordinates</td><td>Use only with PSF plot setting (PLO). Rotates oblique projection plot 90° in X-Y plane, to reveal hidden features. Is a zoomable parameter; right-click this field to access the Zoom Editor.</td><td>No.</td></tr>
<tr><td colspan="3">CON [SUP] Yes | No....z</td></tr>
<tr><td>Contour plot</td><td>Plots intensity (INT) and/or convolution using Convolution with image of two point objects (PAI) or Detector Energy in X and Y directions (DEX,DEY) as a single-page contour plot, with numbered contours, for each field point. Is a zoomable parameter; right-click this field to access the Zoom Editor.</td><td>No.</td></tr>
<tr><td>Suppress numbering</td><td>Suppresses numbering for contour plot. Is a zoomable parameter; right-click this field to access the Zoom Editor.

From the command line: Equivalent to using the SUP qualifier with the CON command.</td><td></td></tr>
<tr><td colspan="3">TIT 'temporary_title'(20+20)....z</td></tr>
<tr><td>Temporary title</td><td>Specifies up to 40 characters that are plotted in two 20-character lines for the title of the designated zoom position; if no zoom position is designated, the title is applied to all. Is a zoomable parameter; right-click this field to access the Zoom Editor.</td><td>Uses the first 40 characters of the system title.</td></tr>
<tr><td colspan="3">LEV [contour_level_fraction....30]
or LEV INC contour_increment_fraction
or LEV NUM num_contour_levels</td></tr>
<tr><td>Number of contour levels</td><td>Use only with Contour plot setting (CON). Specifies the number of levels plotted between minimum and maximum values. The resulting increment is rounded to a reasonable value which may shift the count.

From the command line: Equivalent to using the LEV NUM command.</td><td>LEV NUM 10.</td></tr>
</table>

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Command Syntax		
Screen Control	**Explanation**	**Default**
Contour increment	Use only with **Contour plot** setting (CON). Specifies equal separation of contours between minimum and maximum levels. Values are in fractions of the intensity. **Range**: 0 to 1.0. **From the command line:** Equivalent to using the LEV INC command.	LEV NUM 10.
User-defined contour levels	Use only with **Contour plot** setting (CON). Specifies up to 30 values for plotted contours. Omitting values returns to default. Values are in fractions of the intensity. **Range**: 0 to 1.0. **From the command line:** Equivalent to using the LEV command.	LEV NUM 10.
WBF [CMP] Bk		
Output to Buffer/Write complex output/Buffer number	Writes the PSF output to the specified buffer (not B0). Buffer will contain header information and PSF output. Default is to write intensity output, normalized as the PSF output. If PHA Y is given, phase output is written. If CMP qualifier is used, complex output is written (real and imaginary components). CMP is only operative for monochromatic systems. WBF acts independently of LIS.	Not done.
WIN int_filename		
Filename for saving PSF grids in .INT format	Generate a file, with the specified name, containing the PSF in the grid form of standard .INT type files (see LDM). Click the ... button to browse directories and select an existing file. File records produced are: Five comment records including grid spacing, defocus value, units, field/zoom positions, wavelengths and wavelength weights Title GRD x_size y_size FIL WVL wavelength SSZ scale_size NDA -32767 The file values following are the PSF values over the grid scaled to use a maximum dynamic range of 32767. The SSZ value, scale_size, and the dynamic range depend on the form of normalization specified: Normalization — Range of Values — scale_size INT NOR — 0 to 32767 at peak — 32767 INT STR — 0 to ≤ 32767 at peak — 32767 INT DB — -32766 for THR threshold to 0 at peak — 32766 Separate files are generated with ascending version numbers for each successive field.	No files generated.

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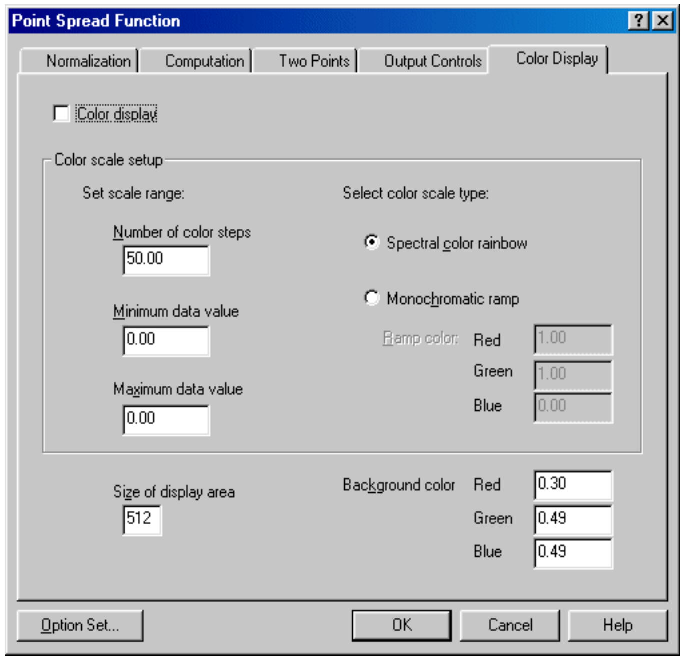
Defining Color Display Settings

To define color display settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Point Spread Function** menu. The **Point Spread Function** dialog box displays. Click the **Color Display** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
DIS Yes | No....z		
Color display	Displays intensity (INT) and/or convolution using using **Convolution with image of two point objects** (PAI) or **Detector Energy** in X and Y directions (DEX,DEY) as a color contour map for each field and zoom position. The displayed colors represent the different intensity levels in the image in two dimensions. This may only be displayed on devices that support color raster displays.	No.
RAN SCA num_steps [min_value max_value]		
Color scale setup: Set scale range: Number of color steps	Use only with **Color display** setting (DIS). Specifies the scaling of the data range as well as the number of color steps into which the range is divided. If the minimum and maximum values are omitted, the entire data range is shown.	50 (RAN SCA 50)
Color scale setup: Set scale range: Minimum data value	Use only with **Color display** setting (DIS). Specifies the starting value of the number of color steps into which the color contour map data range is divided.	0.00
Color scale setup: Set scale range: Maximum data value	Use only with **Color display** setting (DIS). Specifies the ending value of the number of color steps into which the color contour map data range is divided.	0.00

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Command Syntax		
Screen Control	**Explanation**	**Default**
RAN COL SPE | RGB [r_value g_value b_value]		
Color scale setup: Select color scale type: Spectral color rainbow	Use only with **Color display** setting (DIS). Specifies that a spectral color rainbow (blue to green to red) will be used to display the intensity data. **From the command line:** Equivalent to using RAN COL SPE.	Spectral color rainbow (RAN COL SPE)
Color scale setup: Select color scale type: Monochromatic ramp	Use only with **Color display** setting (DIS). Specifies that a monochromatic color ramp from black to the specified red, green and blue values will be used to display the intensity data. Use the **Red**, **Green**, and **Blue** fields to specify the color values; the default red, green and blue values are 1.0, 1.0 and 0.0, which creates a yellow ramp. **From the command line:** Equivalent to using RAN COL RGB.	Spectral color rainbow (RAN COL SPE)
SIZ max_pixels		
Size of display area	Use only with **Color display** setting (DIS). Specifies the maximum dimension, in pixels, of the rectangular area into which the data is drawn.	512
BAC r_value g_value b_value		
Background color: Red Green Blue	Use only with **Color display** setting (DIS). Specifies the background color for the region outside the data display area. Any text, titles and labels, are displayed over this color. The default color is dark slate gray.	0.30 0.49 0.49

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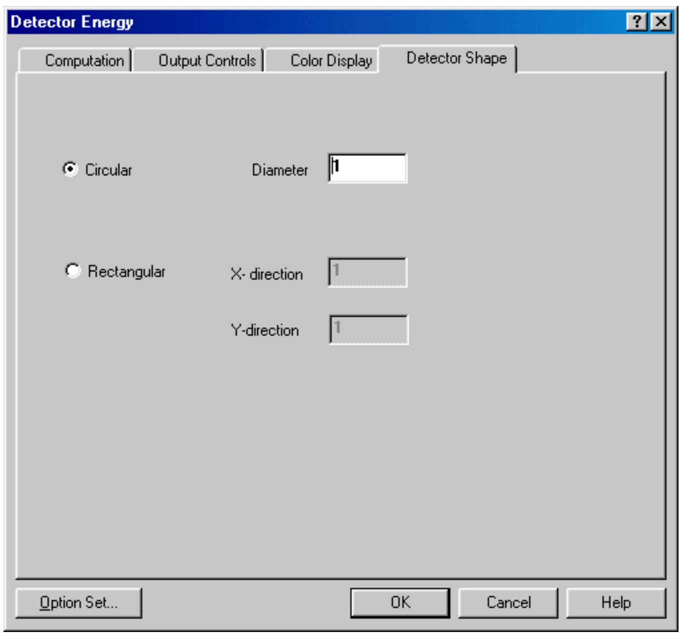
Defining Detector Energy Settings

To define detector energy settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Detector Energy** menu. The **Detector Energy** dialog box displays. Click the **Detector Shape** tab, and define the controls on this tab as described in the table below.

The **Computation**, **Output Controls**, and **Color Display** tabs are defined the same way as the identically named tabs in the **Point Spread Function** dialog box:

- For details about the Computation tab, see "Defining Computation Controls" on page 19-342.
- For details about the Output Controls tab, see "Defining Output Controls" on page 19-346.
- For details about the Color Display tab, see "Defining Color Display Settings" on page 19-349.



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Command Syntax		
Screen Control	**Explanation**	**Default**
DEX No | full_x_dim_of_detector.....z		
Circular/Diameter **or** **Rectangular/X-direction**	Replaces output with a display to show the image convolved with detector. Each point in the display grid becomes the relative energy on the detector when it is centered at the grid point; or it is equivalent to the image formed by the lens of a circular or rectangular object of corresponding geometrical size. Select the **Circular** radio button to specify a circular detector. Specify the full X dimension of the detector in the **Diameter** field. From the command line, is equivalent to using DEX only. Select the **Rectangular** radio button to specify a rectangular detector. Specify the X dimension of the rectangular detector in the **X-direction** field. You must also specify the Y dimension of the rectangular detector in the **Y-direction** field. From the command line, is equivalent to using DEX in combination with DEY. **Range**: Less than 1/2 the full grid X dimension. Can't be used with PAI; can be used with INT to include the INT output also.	No.
DEY No | full_y_dim_of_detector....z		
Rectangular/Y-direction	Select the **Rectangular** radio button to specify a rectangular detector. Specify the Y dimension of the rectangular detector in the **Y-direction** field. You must also specify the X dimension of the rectangular detector in the **X-direction** field. **From the command line:** Equivalent to using DEY in combination with DEX. **Range**: Less than 1/2 the full grid Y dimension.	No.

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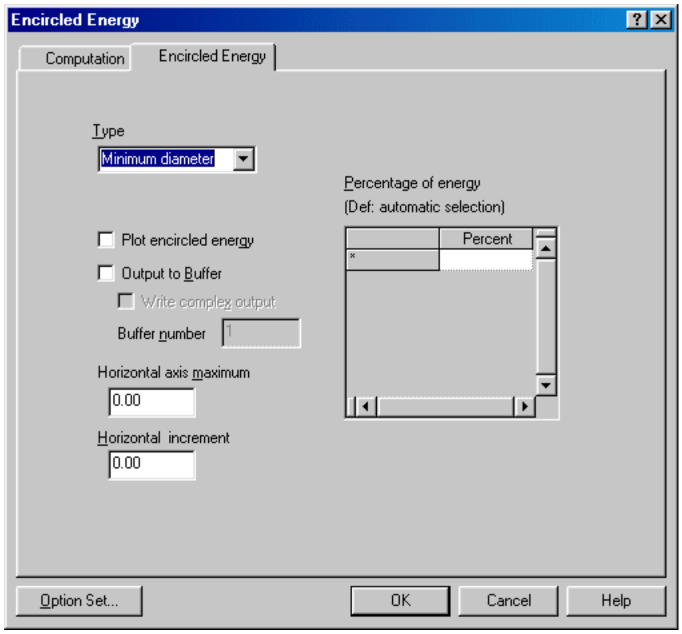
Defining Encircled Energy Settings

To define encircled energy settings for the Point Spread Function (PSF) option, choose the **Analysis** > **Diffraction** > **Encircled Energy** menu. The **Encircled Energy** dialog box displays. Click the **Encircled Energy** tab, and define the controls on this tab as described in the table below.

The **Computation** tab is defined the same way as the identically named tab in the **Point Spread Function** dialog box. For details about the Computation tab, see "Defining Computation Controls" on page 19-342.



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Command Syntax		
Screen Control	**Explanation**	**Default**
ENC [CHI | CEN] [PLO] Yes | No....z		
Encircled energy/Type	Replaces output with a table of encircled energy (circle diameters that just enclose fixed percentages of energy). One table is generated for each field, focus, and zoom position. Can be used with INT to include the INT output also. Select one of the following encircled energy types: **Minimum diameter (ENC)** Minimizes circles by scanning their centers along the Y axis running from the chief ray in the image; no scanning is done in the X direction. **Centered at centroid (ENC CEN)** Eliminates scanning. Places each circle center at the centroid. Center of circle displacements are with respect to the chief ray for the field. **Centered at chief ray (ENC CHI)** Eliminates scanning. Places each circle center at the chief ray.	No.
Plot encircled energy	Generates a plot of encircled energy. (Equivalent to PLO qualifier on the command line.)	
WBF [CMP] Bk		
Output to Buffer/Write complex output/Buffer number	Writes the PSF output to the specified buffer (not B0). Buffer will contain header information and PSF output. Default is to write intensity output, normalized as the PSF output. If PHA Y is given, phase output is written. If CMP qualifier is used, complex output is written (real and imaginary components). CMP is only operative for monochromatic systems. WBF acts independently of LIS.	Not done.
XMA horiz_axis_max....z		
Horizontal axis maximum	Use only with the **Plot Encircled Energy** setting (ENC ... PLO) for plot axis layout. Specifies the maximum image radius value to be plotted along the horizontal (X) axis of the plot (7 inches, 178 mm long). Is a zoomable parameter; right click this field to access the **Zoom Editor**.	Radius needed to encircle 95% of the energy.

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Command Syntax		
Screen Control	**Explanation**	**Default**
XDE incr_between_horiz_axis_ticks....z		
Horizontal axis increment	Use only with the **Plot Encircled Energy** setting (ENC ... PLO) for plot axis layout. Specifies the increment in image radius between ticks plotted along the horizontal (X) axis of the plot. If the value specified in the **Horizontal axis maximum** field (XMA) is not an even multiple of the **Horizontal axis increment** (XDE), the excess lies at the right hand end of the X axis. Is a zoomable parameter; right click this field to access the **Zoom Editor**.	Horizontal axis maximum/10 XMA/10
PER encircled_%....z		
Percentage of energy	Use only with **Encircled Energy** (ENC). Cancels the default set and selects the desired percentages for which circle diameters are to be calculated. You can specify up to 10 values (PER commands). **Range**: <100 - the diffraction spot goes to infinity. **Example**: PER 15;PER 65 will give tables for 15% and 65% only. Is a zoomable parameter; right click each field in the spreadsheet to access the **Zoom Editor**.	10,20,..90

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Defining Wavefront Perturbation Settings

Use the following commands to add a wavefront perturbation to the entrance pupil at a selected field and wavelength. Note that you can only define this analysis using the command line.

Command Syntax		
Screen Control	**Explanation**	**Default**
ADD Fn [Wm] [B | Q]		
Command line only	Add a wavefront perturbation, to be given in Y, YC commands, to the entrance pupil at Fn field, Wm wavelength; Wm defaults to the reference wavelength. Determine pupil grid rows and columns to be used by running the PMA option with the same TGR and NRD or GRI. Symmetry can be designated to reduce the number of Y, YC commands as follows: B — bilateral symmetry in X; give only the left half of the pupil grid, including the center column and row (TGR/2 + 1). Q — quadrant symmetry; give only the upper left quadrant of the pupil grid, including the center column and row (TGR/2 + 1). neither — no symmetry; give all columns and rows.	No perturbation.
Y num_row perturbation_waves_x100....TGR **YC** perturbation_waves_x100....TGR		
Command line only	Use only with ADD. Start each row with Y command; row is designated by num_row. Express perturbations in waves x 100 (waves of error), starting with the leftmost pupil grid point through which a ray passes and continue to the pupil grid point required by the symmetry qualifier on the ADD command; use zero values to span any obscurations. Put as many perturbations on one record as desired; continue the row with the YC (Y Continue) command.	No perturbation.

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Discussion of Input and Computations

What to Include in the LDM Data

No additional LDM data is required. If you wish to do through-focus analyses, enter the LDM data for depth of focus (FFO, IFO, NFO).

Usage

The Point Spread Function (PSF) option computes the wave aberration of the system, and by Fast Fourier Transform (FFT), the diffraction image shape in the designated focal plane integrated over the wavelengths according to the weights assigned to the system in the LDM. This image patch is represented in the computer by intensity values in a grid across the image with the chief ray or optical axis as the center point of the grid.

Due to the nature of the FFT process, if the pupil function is represented by many points, such as the default grid interval provides, the diffraction image (say, the Airy disc) will be represented by few points. Thus, asking for a smaller output grid spacing (**Focal plane grid increment** setting or **GRI**) to enlarge the image size will provide more detail in the output but will use less data to represent the lens. This trade-off should be understood when choosing grid sizes. The default grid size should usually be the largest value used, while the smallest should be one-half of it. Values outside this range should be recognized as introducing increasingly large errors.

Due to the fact that points on a square grid are used to represent the pupil function which is approximately circular in symmetry, artifacts appear in the output when too small a grid interval is used (artifact: a structure not actually present in the system, but which appears to exist in plotted output, for example, due to an external agency such as mis-scaling). Thus, the default grid spacing, for a rotationally symmetric system, will produce a rather precise display of the Airy disc. A grid spacing of one-half this amount will enlarge the image but use one-fourth as much data to represent the lens. The square grid representation of the pupil function now does not look so circular; it has flats and steps of twice the size on it. This produces slight distortions (a few percent) in energy in a four-fold symmetric pattern which may give an aesthetically unpleasant appearance to what should be a rotationally symmetric image.

Default Assumptions

1. All field angles and zoom positions will be included.
2. Wavelengths and their weights will be those of the system, determined by entries in the LDM.
3. The focal plane is determined by the combination of the last thickness (THI Si-1) and defocusing (THI Si).
4. The grid size is chosen to be: $\dfrac{\lambda s \, * \, f/no}{2}$

   which results in the Airy disc diameter for the short wavelength (λs) being spread over 4.880 output grid elements. For curved image surfaces, the grid spacing is measured on the image surface. The f/no is determined from the largest numerical aperture over all the fields, using the reference rays to determine numerical aperture.
5. Intensity across the entrance pupil is assumed to be uniform unless pupil apodization is specified. (For fast, finite conjugate systems, the Lambertian source model results in non-uniformity across the pupil.)
6. Output is to be the relative intensity distribution in the image, on a scale of 100.
7. The size of the transform grid is 128 x 128.
8. The source is considered to be a zero diameter flat Lambertian disk, rather than a point. This is the correct model to use for image forming systems.

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Analysis Selection

The intensity display can be modified from the default by specifying a value other than 100 for any zoom position (**Select PSF output mode** and **Effective normalized data** settings or **INT**). The presence of the word STREHL (or S) after the **INT** command gives output of the intensity distribution in the image (for that zoom position) relative to a perfect lens image whose peak would be 100. If the lens has obscurations, the peak value is relative to a perfect lens which has the same obscurations. If, instead, apodization (Gaussian or user-defined .INT files) has been used (in the LDM), the peak is relative to a perfect lens with the same apodization. This is valid for both monochromatic and polychromatic images.

The use of the symbol DB (or D) for any position following the **INT** command gives output of the relative intensity distribution in the image, expressed as decibel fall off from the peak value. The values are:

$$\mathrm{dB} = 10 * \log_{10}\left(\frac{I}{I_{peak}}\right)$$

Used with **INT** DB only, the threshold command (**Output threshold (DB)** setting or **THR**) will set any intensity value which is lower than the value in the first field to equal the first field value. The entry must be a negative dB value (e.g., -50). This request is mainly for smoothing the lower limit on a DB plot, since noise tends to be magnified on a dB scale. The default value is -50.

Grid Considerations for Diffraction Calculations in CODE V

Certain diffraction calculations in CODE V use the Fast Fourier Transform (FFT) to determine the image distribution from the pupil function. These options include BPR, CEF, LSF, PAR, PSF, and TOR for the critical dimension (CD) calculation. When you are using any option that includes this FFT calculation, it's important to understand how the parameters included in the calculation interact.

The FFT needs a square grid of values where the number of points in one dimension of the grid (**FFT grid size** setting or **TGR**) is a power of 2. The default value of TGR is 128. The two other parameters that define the grid are the number of rays across the pupil diameter (**Number of rays across diameter** setting or **NRD**) and the spacing between samples in the image plane (**Focal plane grid increment** setting or **GRI**). The default value of GRI is λ(f/no)/2. The default value of NRD is TGR/2.

The formula relating the TGR, NRD, and GRI values is the following, where λ is the shortest wavelength in the wavelength range of the lens.

$$\mathbf{GRI} = \frac{\lambda s * f/no * \mathbf{NRD}}{\mathbf{TGR}}$$

These default values result in a GRI such that there are about 5 points across the first zero of the Airy disk. Thus, the sampled image area is about 13 times as wide as the diffraction pattern. You may change these parameters, but care must be taken to avoid unreasonable values. Since the NRD, GRI, and TGR parameters are related through the above equation, only two of the three should be changed.

The image grid interval (GRI) can be adjusted up or down by a factor of 2 (an adjustment smaller by more than a factor of 2 is allowed, but generates a warning). Decreasing the GRI results in higher sampling of the image at the cost of less sampling of the pupil. Increasing GRI by more than a factor of 2 from the default results in the transform grid being overfilled, clipping some of the rays that define the pupil.

Alternatively, the number of rays traced across the pupil diameter (NRD) for the shortest wavelength can be adjusted from the default of TGR/2. Increasing NRD increases the sampling of the pupil, but decreases the number of samples across the Airy disk in the image and vice versa. NRD should not be made the same or larger than TGR, or the transform grid will be overfilled, clipping some of the rays that define the pupil.

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Use either GRI or NRD, but not both, and beware of artifacts from extreme choices. It is often unwise to request a decrease in the grid interval of beyond a factor of two, because the pupil will be sampled by very few data points across the wavefront, especially in the long wavelengths. It may be necessary to increase TGR to arrive at meaningful values for NRD and GRI. However, note that increasing TGR will increase the analysis run time.

In general, an NRD value of at least 30 is recommended for a circular pupil. Unusual pupil shapes may require a larger value. In the image, the GRI value should be small enough to represent the detail needed. For linewidth calculations in PAR and TOR, at least 10 points across the line are recommended.

The integration grid, used to display the PSF and to do the auxiliary calculations such as centroiding, moments, encircled energy, etc., can also be modified (**FFT integration grid size** or **PGR**). The default size is TGR-1. If the PGR value entered is larger than the TGR value, it will be reduced to TGR-1. Any odd number less than TGR is allowed. A lower PGR value restricts the area used for analysis, such as when noise is to be suppressed. Note, however, that when PGR is less than TGR-1, excluded data is assumed to have 0 energy.

The following figures show the effects of various values of the grid parameters.

Figure 1 provides a high-level illustration of the effect of increasing TGR and NRD by a factor of 2.

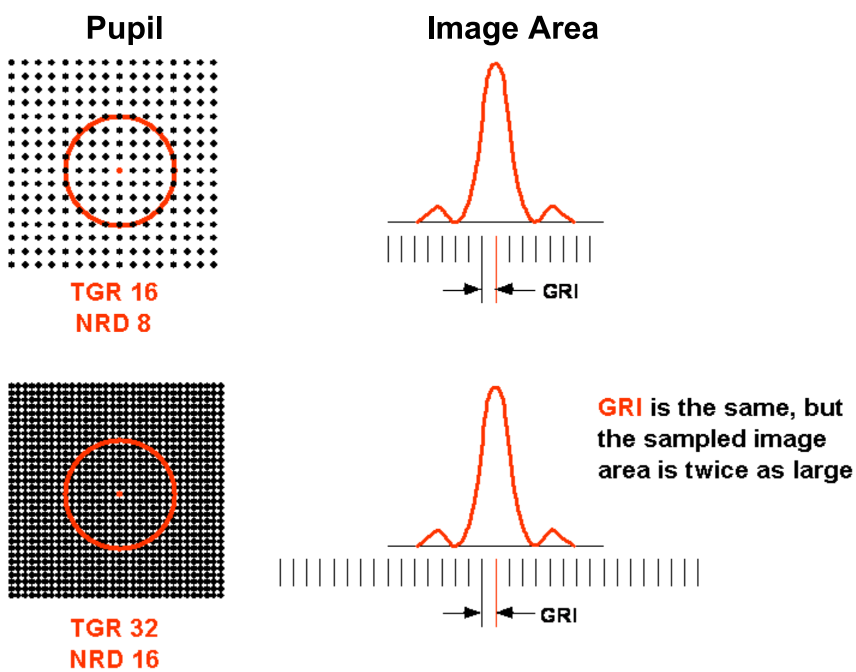

Figure 1. Effect of increasing TGR and NRD by a factor of 2

Figure 2 provides a high-level illustration of the effect of changing GRI.

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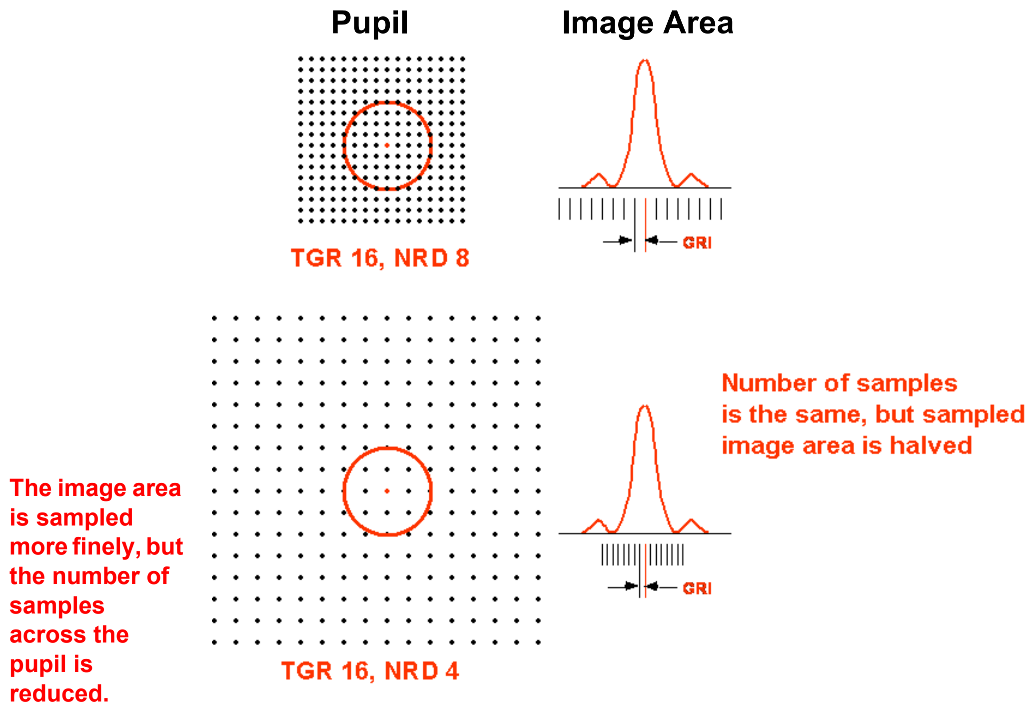

Figure 2. Dividing the GRI by a factor of 2

Figure 3 (a-f) shows the pupil and image (PSF) for a perfect lens for three different values of NRD: 64, 128, and 32 using the default TGR of 128. The pupil intensity grid shown is 128x128. In all the PSF figures (Figure 3b, Figure 3d, and Figure 3f), the grid shown is 64x64. Note that the detail in the Airy disk decreases as the sampling of the pupil increases.

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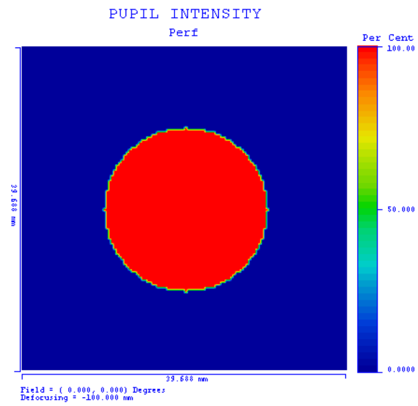

Figure 3a. TGR 128, NRD 64

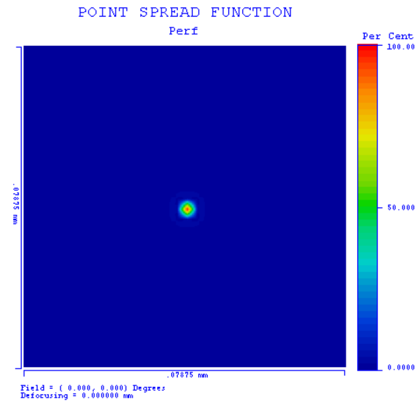

Figure 3b. Resulting value: GRI .00125

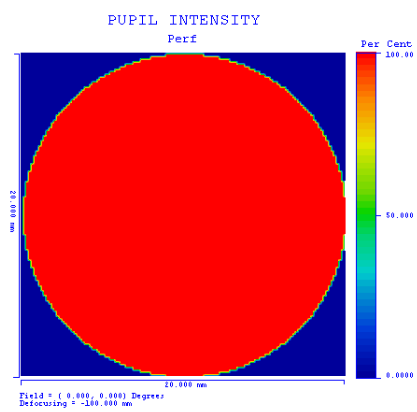

Figure 3c. TGR 128, NRD 128

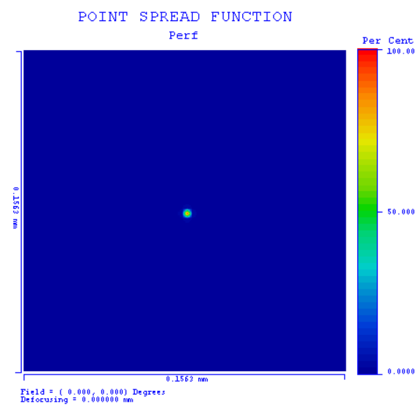

Figure 3d. Resulting value: GRI .00249

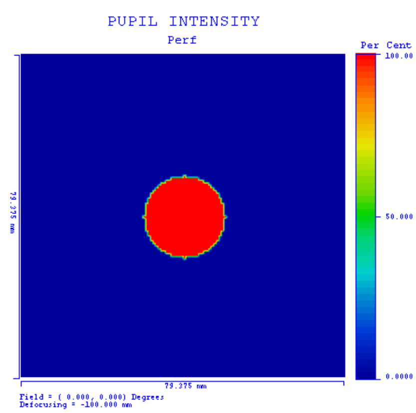

Figure 3e. TGR 128, NRD 32

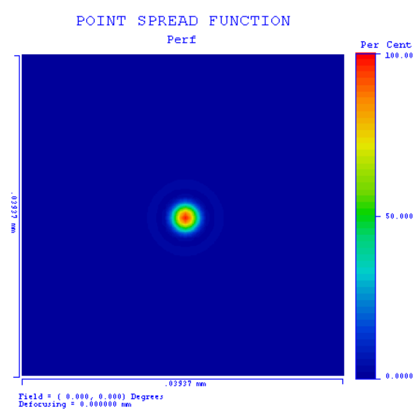

Figure 3f. Resulting value: GRI .00063

Figure 3. Pupil and image for a perfect lens for three different values of NRD

In Figure 3, if it was determined that NRD 64 is appropriate to adequately sample the pupil, but there is not enough detail in the Airy disk, the next step would be to increase TGR to 256. These results are shown in Figure 4 (a-f). The shown pupil intensity grid is 256x256. In all the PSF figures (Figure 4b, Figure 4d, and Figure 4f), the grid shown is 64x64. Figure 4e and Figure 4f show the pupil and PSF for TGR 256 and NRD

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64. The Airy disk in Figure 4f has twice the detail (i.e., twice the sampling) as the image in Figure 3b, while the pupil in Figure 4e has the same sampling as the pupil in Figure 3a.

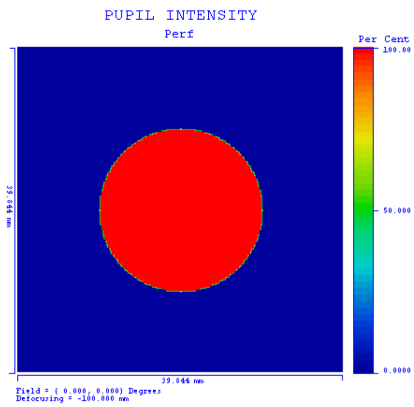

Figure 4a. TGR 256, NRD 128

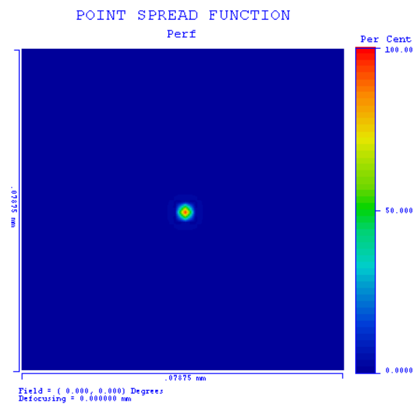

Figure 4b. Resulting value: GRI .00125

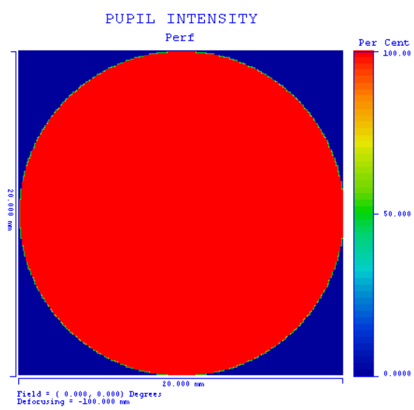

Figure 4c. TGR 256, NRD 256

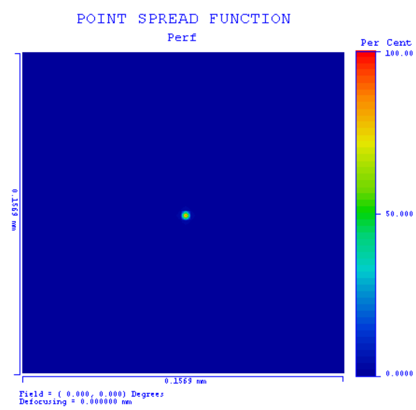

Figure 4d. Resulting value: GRI .00249

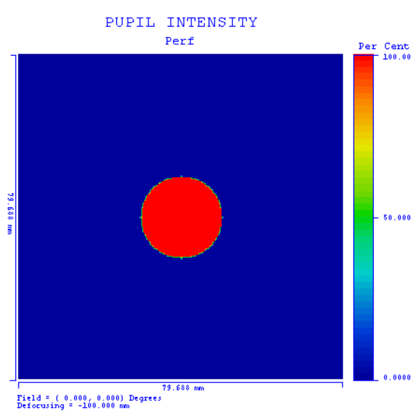

Figure 4e. TGR 256, NRD 64

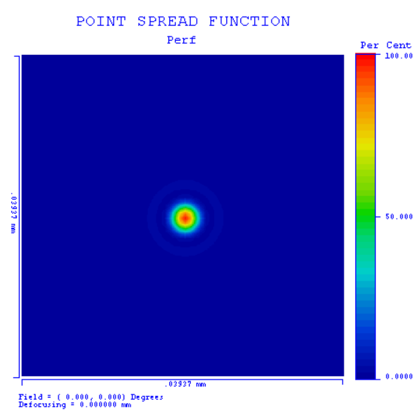

Figure 4f. Resulting value: GRI .00063

Figure 4. Pupil and image for a perfect lens with TGR increased to 256

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Focus Considerations

Multiple (or modified) focus positions may be specified to display the through-focus (or shifted) characteristics of the image. These are requested in the LDM prior to invoking PSF (see NFO, FFO, and IFO in “Specifying Through-Focus Data” on page 3-42).

When the image of the system is out of focus, is much larger than the Airy disc, and occupies at least half of the output grid, use near-field propagation (**Near field propagation** setting or **PRO**) instead of the normal far-field diffraction calculation. If no grid interval (**Focal plane grid increment** setting or **GRI**) is specified in conjunction with **PRO**, it will be selected so that the geometrical spot will fill about half the output array. The lens should be in focus. Use non-zero FFO to defocus. (See “Technical Notes” on page 19-372 for background on near field propagation.)

In general, the **GRI** value only applies to the first focal position. In normal use it is close enough so that other focal positions are accurate; if the systems are slow (high f/no), the user may have to run each focal position as a separate calculation to ensure that the scale chosen is used. If **PRO** (propagate) is used, the focal shift can be great (from pupil to near the image or beyond the image); for this, the printed value of the grid interval is re-calculated to show its true size for focal positions after the first.

Gaussian Apodization

To transform the uniformly illuminated pupil into one with a Gaussian intensity profile, use PUI, PUX, and PUY in the LDM (see “Defining Pupil Apodization” on page 10-3).

Anamorphic Scale Factor

The largest (X or Y) numerical aperture of the exit pupil is used in establishing default values for the **Focal plane grid increment** and the **Number of rays across diameter** settings (**GRI**/**NRD)**. With highly anamorphic exit pupils, this may lead to insufficient sampling in either the X or Y dimension, depending on which is larger. Check this with the Pupil Map (PMA) option. The X dimension of the image can be scaled up (**Anamorphic scale factor** setting or **XSC**), which reduces the number of pupil sampling points in the X direction, and vice versa. Example: **XSC** 2 scales the X dimension of the image by 2, and the **GRI** or **NRD** by 0.5. The reciprocal of the **XSC** value is written to any interferogram file with the **Filename for saving PSF grids in .INT format** field on the **Output Controls** tab (**WIN**).

Generating Grid Files for Other Programs

Images sometimes need to be analyzed by other programs outside of CODE V. To facilitate this, use the **Filename for saving PSF grids in .INT format** field (**WIN** command) to cause any of the series of Point Spread Function (**PSF**) grid-format analyses (**INT**, **PRO**, **PHA**, **DEX/DEY**, **PAI**) to be output to files in the.INT format described in the LDM; only encircled energy (**ENC**) of the major analysis forms in this option is not available this way.

The size of the grid that is written to the file is determined by the **FFT integration grid size** (**PGR**) value. The file will be in the standard CODE V interferogram file format, with the SUR/WFR/FIL indicator given as FIL, indicating intensity. A separate file will be written for each field, zoom, and defocus position.

The leading comments and title record contain the information described with the command syntax so that the conditions of generation are retained with the file. Note that the range of values in the file (32767) is sufficient to retain all of the accuracy that can be contained in the calculation; the value following SSZ in the file can be used to normalize the data (typically by dividing by it).

The output (intensity, or phase with PHA) can also be written to a buffer (**WBF**). The data in the buffer can then be utilized by a macro, or exported (BUF EXP) for further analysis outside of CODE V. The **WBF** command writes the PSF output to the specified buffer (not B0). The buffer will contain header information (e.g., grid size and grid increment) and PSF output. The default behavior is to write intensity output, normalized as the PSF output. If PHA Y is given, phase output is written. If the CMP qualifier is used, complex output data is written (real and imaginary components). The CMP qualifier is only operative for monochromatic systems. The **WBF** command acts independently of the **LIS** command.

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Listing Controls

The normal listed grid displays include two blank lines between grid rows to make the vertical and horizontal scales equal. The entire listed output can be suppressed (de-select the **List output** checkbox or use **LIS** N), or a more compact listing with blank lines suppressed can be selected (**Compact output** checkbox or **COM**). The output in the grid listing can be changed to represent phase in the image (**List phase** checkbox or **PHA**) instead of intensity if desired (see Born and Wolf, *Principles of Optics*, pp. 445-448 for discussion of phase behavior as a function of focus).

Plotting Controls

Three types of graphical output are available:

- A "three-dimensional" oblique projection plot (**PLO**)
- A contour "map" of the intensity levels (**CON**)
- A color display of the intensity contours (**DIS**).

3-D Projection Plots

There is automatic scaling for the oblique projection plots of intensity. The INTENSITY, INTENSITY DB, and INTENSITY STREHL plots are drawn so that 100% has a vertical deviation of 4 inches. For INTENSITY STREHL, the vertical height is less than 4 inches for a non-perfect lens; the vertical height, therefore, is a measure of absolute intensity. The Strehl ratio may be determined by taking the vertical height and dividing by 4.

Occasionally, the detailed structure of the image is hidden by the peaks of the oblique projection plot. The X and Y coordinates can be rotated 90° (**Rotate X, Y coordinates** checkbox or **ROT**) to overcome this effect.

Contours

As an alternative to the projection plot, contour "mapping" of the intensity levels in the image in two dimensions can be requested (**Contour plot** setting or **CON**). The contour lines will be numbered unless suppressed (**Suppress numbering** setting or **CON** SUP). Three levels between minimum and maximum with reasonable rounding of the increment are the default. (For a normalized PSF plot, the levels will be 0.9, 0.8, 0.7 ...., 0.1). The user may specify up to 30 contour levels (**Number of contour levels** field or **LEV** n..30), the contour increment (**Contour increment** field or **LEV INC** n) and override the number of contour levels (**LEV NUM** n). Levels will be integral multiples of the contour increment. The number of levels plotted may change by one due to rounding.

A temporary title can be specified for either type of plot (**TIT**). Otherwise, the system title is used.

Color Display

Another alternative to either the projection plot or the line contour mapping is a color contour map of the intensity level of the image (**Color display** setting or **DIS**). In this type of display, different colors represent different intensity levels. The number of colors and the range of levels can be controlled with the **Color scale setup** settings or **RAN SCA** command. A larger number of colors will give a continuous color gradation, whereas a smaller number will show contour edges better, giving a more quantitative effect. The intensities may be colored either by a spectral color rainbow, blue to green to red (**RAN COL** SPE), or by a monochromatic color ramp, black to a specified color (**RAN COL** RGB). The maximum size of the rectangular display area is 512 pixels; this can be changed (**SIZ**). The background color value for the region outside the data display area can be specified (**BAC**). This type of display is only available on devices that support color raster displays. Output for this type of display is controlled by the RGR command.

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Near Field Propagation

Use **Near field propagation** or **PRO** to get the PSF of an out-of-focus image which is much larger than the Airy disc. The lens should be in focus. FFO, IFO, NFO are used to introduce the defocus. This mode uses near field propagation (see “Technical Notes” on page 19-372).

Analysis for Circular and Rectangular Detectors

The energy falling within a detector will be listed in a display grid showing intensity values which replaces the normal listed display. Specify only the detector diameter in the X (skew) dimension for a *circular* detector (**Circular/Diameter** settings or **DEX** n). If the detector is *rectangular*, enter both the X and Y (meridional) full dimensions (**X-dir** and **Y-dir** fields or **DEX** n and **DEY** n). A convolution of the detector with the point spread function is done and an array is listed giving the relative values of the energy on the detector. The percent energy on the detector is given for the detector centered at the chief ray and for peak energy. This request is also equivalent to the image formed by the lens of a circular or rectangular object of corresponding geometrical size. The maximum detector dimension should be less than 1/2 the full grid X (or Y) dimension.

Analysis for Two Point Sources

The image of a pair of point sources may be requested (**PAI**). The listed output will display the image convolved with the image of two point objects with the equivalent geometrical image surface of the X and Y separations. Each point in the display grid becomes the relative energy of the combined image. Output is generated for each field and focus position, in all zoom positions, unless restricted with Zk|Zi..j. **Range:** less than 1/2 of the full grid dimension. Cannot be used with **Detector Energy** settings (DEX, DEY); can be used with **PSF output mode** settings (INT).

Encircled Energy of a Point Source

An alternate grid display available is one which displays circle diameters that enclose fixed percentages of light energy (**Encircled energy** settings or **ENC**). The circles are minimized by scanning their centers along the Y axis running from the chief ray in the image. No scanning is done in the X direction. **ENC** can be used with **INT**. Scanning can be eliminated, with each circle center placed at the chief ray (**CHI**) or at the centroid (**CEN**). One listed table is generated for each field, focus, and zoom position. Note that when you use **ENC CEN**, center of circle displacements are with respect to the chief ray for the field. Up to 10 user-defined percentages for which the circle diameters are to be calculated may be specified (**PER**) in a range of <100.

If the transform grid (TGR) or the grid increment (GRI) is too small, and the edge of the grid is encountered before the diameter for a specified energy level is found, CODE V will display the following message:

```
Diameter out of bound (minimum not found)
```

Note that this message is still displayed even when you have not requested to find the minimum diameter (i.e., CHI or CEN is selected). If you see this message, you should increase the TGR and/or GRI.

The **PSF plot** setting or **PLO** command causes a plot of encircled energy (percent energy as a function of spot diameter) to be generated. The default X axis maximum of this plot is the (95% encircled energy diameter for the particular system being evaluated. Sometimes, to facilitate comparisons of different designs, it is useful to plot the results for all of the designs at the same scale; this is done with the **Horizontal axis maximum** setting or **XMA** command, in which the maximum spot diameter (X coordinate maximum) is entered. The **Horizontal axis increment** setting or **XDE** command can be used to change the increment used in the labeling of the X axis in the plot.

Perturbed Wavefront Analysis

A wave front perturbation can be added to the entrance pupil (**ADD**) at a selected field and wavelength. Determine the pupil grid rows and columns to be used by running the PMA option with the same **TGR** and **NRD** or **GRI**. Perturbations are expressed as 100 * (waves of error), in rows and quantities specified (**Y**), starting with the left most pupil grid point through which a ray passes and continuing to the pupil grid point required by the symmetry qualifier on the **ADD** command (B, Q). Use zero values to span any obscurations. Put as many perturbations on one record as desired by continuing the Y row with the Y CONTINUE command (**YC**). Note that in many cases, perturbed wavefronts can be modeled more easily with the interferogram feature of CODE V (see "Defining Interferometric Deformations and Intensity Apodization" on page 10-9), but **ADD** allows discontinuities, different phase changes for each wavelength, and causes no ray direction changes.

Combination Runs

A single set of calculations (without re-tracing rays) can lead to several different forms of output:

- Multiple focal planes (NFO, FFO, IFO entered in the LDM)
- **INT**, **ENC**, **DEX**, **DEY** or **INT**, **ENC**, **PAI** can be used together to get all three types of output in one run; only **DEX**, **DEY** can not be used with **PAI**.
- **PLO**, **CON** and **LIS** control which combination of plots and listings are to be included.

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Description of Output

Within the PSF option, the **PLO** or **CON** commands produce graphical output - either a "3D" oblique projection (**PLO**) or a contour plot (**CON**). The remainder of the commands generate either a two dimensional grid representing the focal plane with the grid interval as specified (**INT**, **PHA**), or tables of values (**DEX**, **DEY**, **ENC**, **PAI**). In two dimensional printed grids, there is a scale ("scale: one increment = xxx mm", etc.) for interpreting the grid. This grid value is the distance on the image surface between any two adjacent points (horizontal or vertical). The chief ray is always at the "center" grid point, i.e., for an N x N grid, the chief ray is at the point (N/2+1, N/2+1) for example, (33,33) in the default 128 x 128 FFT grid. See Table 1.

Because Y coordinates are plotted up and X to the right (relative to format), the images appear as seen in the direction of the negative Z axis.

Examples

Example 1. Point spread function (oblique projection) of the Double Gauss lens, stopped down to f/4, in the 14× off-axis field. (Text output not shown.)

```
Command inputs:
  RES   CV_LENS:DBGAUSS
  SCALE   EFY   50.0       !  Set effective focal length to 50.00 mm
  FNO   4.0                !  Stop lens down to f/4

  PSF
  COM                      !  Compact output; blank lines cancelled
  NRD   40                 !  Number of rays across pupil diameter
  GO
```

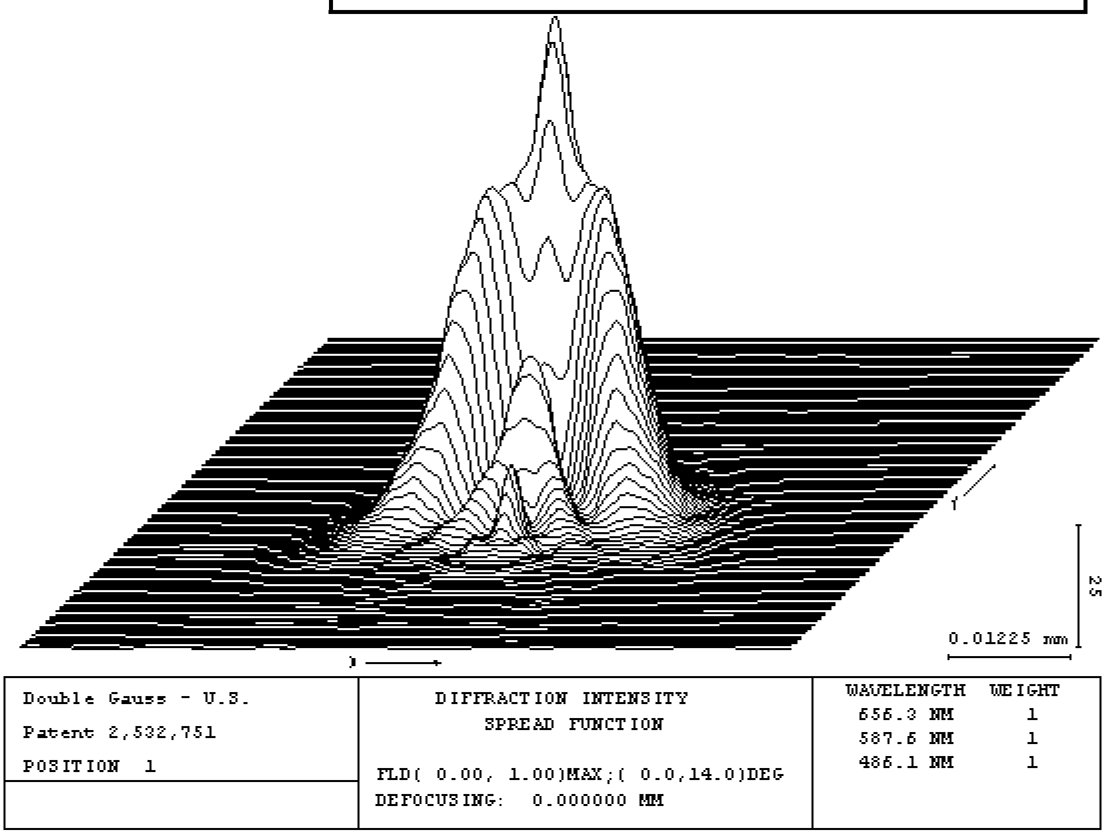

Figure 5. Perspective plot output from PSF

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Example 2. Point spread function (contour) of the same Double Gauss configuration shown in Figure 5.

```
Command inputs:
   PSF
   CON    SUP             ! Draw contours, suppress line numbers
   PLO  N
   COM
   LEV    .05  .15  .25  .35  .45  .65  .75      Specified contour levels
   NRD    40
   GO
```

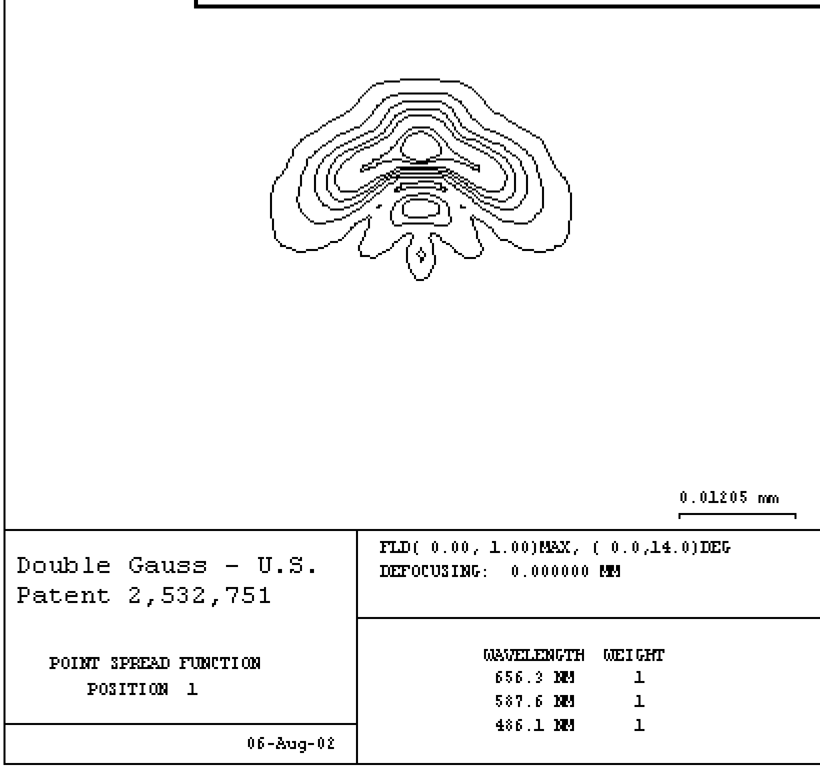

Figure 6. Contour plot output from PSF

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Example 3. Point spread function listed output for Cooke triplet.

Only first field output shown:

```
Command inputs:
   RES   CV_LENS:COOKE1

   PSF
   COM!  Compact listing
   INT   STR       !  Normalize peak by  Strehl  Ratio
   GO
```

Table 1. Partial listed output for Cooke triplet

```
  POSITION 1        WAVE OPTICS POINT SPREAD FUNCTION                             06-Aug-02

          Cooke Triplet f/4.5
                                                               WAVELENGTH   WEIGHT  NO. OF RAYS   PUPIL GRID
    FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG         656.3 NM       1       1757       47 x  47
    DEFOCUS =    0.000000 MM.                                   546.1 NM       2       2561       57 x  57
    SCALE: ONE INCREMENT= 0.00109365 MM.                        486.1 NM       1       3233       65 x  65
   STREHL intensity values are on a scale where peak intensity of a perfect lens = 100
 SUM OF VALUES =     649.
 Strehl Ratio = 0.6275
```

	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
59									1	1	1	1	1								
60							1	1	1				1	1	1						
61						1	1		1	2	3	2	1		1	1					
62						1		2	4	5	5	5	4	2		1					
63					1	1	1	4	5	6	8	6	5	4	1	1	1				
64					1		2	5	6	21	37	21	6	5	2		1				
65					1		3	5	8	37	63	37	8	5	3		1				
66					1		2	5	6	21	37	21	6	5	2		1				
67					1	1	1	4	5	6	8	6	5	4	1	1	1				
68						1		2	4	5	5	5	4	2		1					
69						1	1		1	2	3	2	1		1	1					
70							1	1	1				1	1	1						
71								1	1	1	1	1									

```
                                    X                 Y
   PSF centroid coordinates
   relative to chief ray       -0.0000000E-00    -0.0000000E-00   mm.


   Moment about
   the centroid:    Second      0.3813999E-04     0.3813999E-04
                    Third       0.2611329E-14    -0.1792435E-13
                    Fourth      0.6563196E-07     0.6563196E-07
```

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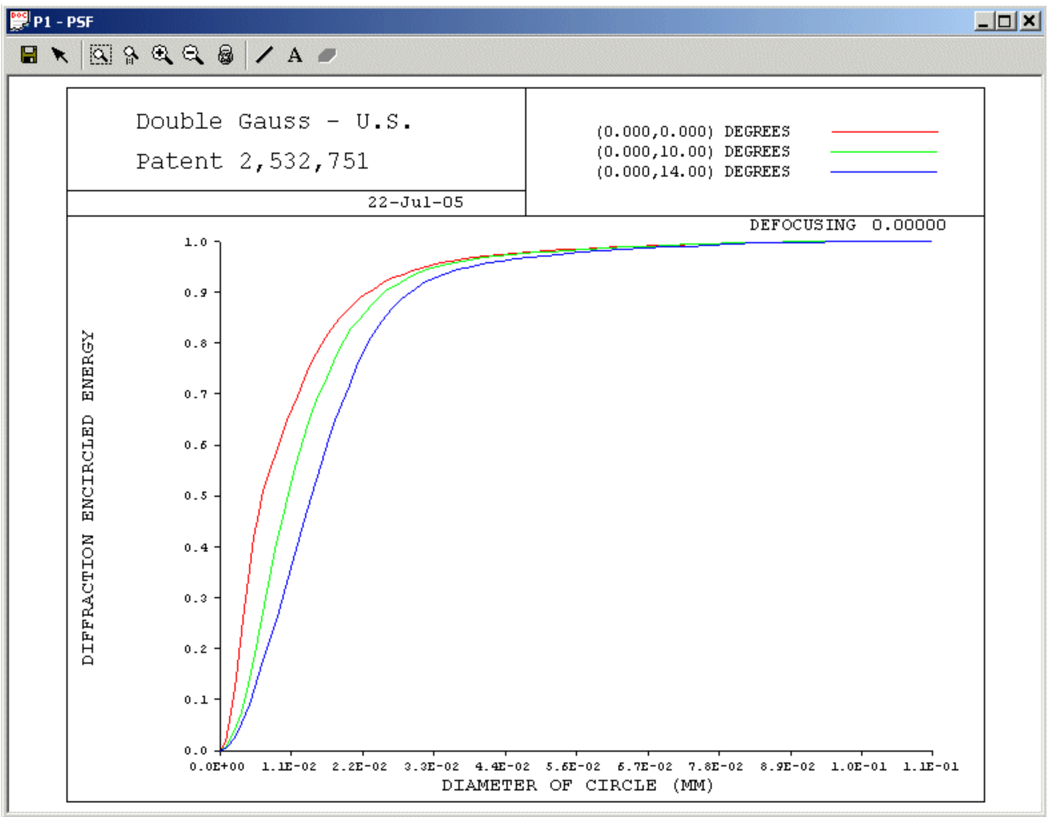
Example 4. Encircled energy output for Double Gauss configuration, including plotted and listed output.

```
Command inputs:
  RES   CV_LENS:DBGAUSS
  SCALE   EFY   50.0      !  Set effective focal length to 50.00 mm
  FNO   4.0               !  Stop lens down to f/4

  PSF
  COM                     !  Compact output; blank lines cancelled
  NRD   40                !  Number of rays across pupil diameter
  ENC PLO Y               !  Replace output with encircled energy
                                and generate plot
  GO
```




```
          APERTURE STOP
          SEMI-DIAMETER =       3.925113
            (Based on the maximum reference ray height at the stop.)

X and Y focal lengths for each field angle

   X        0.499853E+02        0.507445E+02        0.514869E+02
   Y        0.499853E+02        0.523120E+02        0.546611E+02


X and Y F-numbers for each field angle

   X            3.998824            4.059563            4.118956
   Y            3.998824            5.579945            7.288144
Reference sphere radius for each field angle

            0.573758E+02        0.588839E+02        0.604370E+02
```

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```
Optimum increment in image plane is  0.0009719 units.
Actual  increment in image plane is  0.0006074 units.
Transform grid size is  128 x  128
     POSITION  1        WAVE OPTICS RADIAL ENERGY DISTRIBUTION                      22-Jul-05

       Double Gauss - U.S. Patent 2,532,751
                                                                WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
 FIELD (X,Y) = ( 0.00, 0.00)MAX, (  0.00,   0.00)DEG     656.3 NM       1        681        29 x   29
 DEFOCUS =    0.000000 MM.                                587.6 NM       1        861        33 x   33
                                                          486.1 NM       1       1265        41 x   41
Diameter is minimized with respect to y-coordinate



              DIAMETER     CENTER
   PCT        OF CIRCLE   OF CIRCLE

    10         0.001952    0.000000
    20         0.002998    0.000000
    30         0.003914    0.000000
    40         0.005019    0.000000
    50         0.006597    0.000000
    60         0.009141    0.000000
    70         0.012098    0.000000
    80         0.015953    0.000000
    90         0.023136    0.000000
     POSITION  1        WAVE OPTICS RADIAL ENERGY DISTRIBUTION                      22-Jul-05

       Double Gauss - U.S. Patent 2,532,751
                                                                WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
 FIELD (X,Y) = ( 0.00, 0.71)MAX, (  0.00, 10.00)DEG     656.3 NM       1        527        29 x   23
 DEFOCUS =    0.000000 MM.                                587.6 NM       1        659        33 x   25
                                                          486.1 NM       1        967        39 x   31
Diameter is minimized with respect to y-coordinate



              DIAMETER     CENTER
   PCT        OF CIRCLE   OF CIRCLE

    10         0.003215   -0.001478
    20         0.005135   -0.001513
    30         0.006846   -0.001785
    40         0.008598   -0.002260
    50         0.010555   -0.002661
    60         0.012727   -0.002987
    70         0.015484   -0.003487
    80         0.019125   -0.004279
    90         0.025641   -0.005131
     POSITION  1        WAVE OPTICS RADIAL ENERGY DISTRIBUTION                      22-Jul-05

       Double Gauss - U.S. Patent 2,532,751
                                                                WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
 FIELD (X,Y) = ( 0.00, 1.00)MAX, (  0.00, 14.00)DEG     656.3 NM       1        349        29 x   17
 DEFOCUS =    0.000000 MM.                                587.6 NM       1        433        33 x   19
                                                          486.1 NM       1        631        39 x   21
Diameter is minimized with respect to y-coordinate



              DIAMETER     CENTER
   PCT        OF CIRCLE   OF CIRCLE

    10         0.004494   -0.001207
    20         0.007016   -0.001167
    30         0.009720   -0.001641
    40         0.011966   -0.002699
    50         0.014152   -0.003227
    60         0.016614   -0.003710
    70         0.019407   -0.004409
    80         0.023025   -0.005202
    90         0.029637   -0.006398
```

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Technical Notes

Isoplanatism and OSC

Any calculation that deals with extended objects depends upon isoplanatism—constancy of the point image patch as the field changes over the width of the object, e.g. over enough cycles of the MTF target to integrate properly. Isoplanatism is connected with Offense Against Sine Condition (OSC) and is destroyed by significant OSC residuals. OSC can also lead to invalid distribution of rays over the exit pupil, if not properly compensated.

In all CODE V options that deal with diffraction or accurate intensity calculations (ALI, CEF, LSF, MTF, PAR, PMA, PSF, TOR, and WAV), special programming has been incorporated to represent the local intensity and magnification changes that occur with OSC, so that any wavefront and point image is correctly apodized and calculated, even in the presence of large OSC; for example, an f/0.3 parabola would have massive OSC. This special process is valid in all forms of calculation (convolution, FFT, etc.) and has little effect on compute time.

Even though the calculation is accurate, the lack of isoplanatism will still cast doubt on the usefulness of any option results dealing with extended objects, when the image is changing so rapidly across the target. In these options (CEF, LSF, MTF, PAR, PMA, PSF), a test is made to see if OSC is sufficient to affect results. If so, a warning is issued to alert you that the system is not isoplanatic at the field in question.

F-Numbers, Focal Lengths and Reduction Ratios

In some of the CODE V options that deal with diffraction calculations (CEF, LSF, MTF, PAR, PMA, and PSF), the listed output includes focal lengths (or reduction ratios if the object distance is finite) and f-numbers based on the references rays at each field. A value for both the X and Y directions is given. These numbers vary with field and are useful for relating image dimensions to object dimensions and for simple relative illumination calculations. Also included are the reference sphere radii for each field. Diffraction is assumed to take place at the reference sphere.

The f-numbers (fno) are based on a calculation of the image intensity. Thus, if the pupils are approximately elliptical, an estimate of the relative illumination can be obtained from the product of the X and Y numerical apertures. (The numerical aperture is given by NA = 1/(2*fno).) This calculation assumes a Lambertian object and a uniformly illuminated exit pupil and ignores transmission losses in the lens. It includes the effect of a non-flat image surface. Note that, for a perfect thin lens with stop in contact and the object at infinity, the X numerical aperture is proportional to the cosine of the field angle while the Y numerical aperture is proportional to the 3rd power of the cosine, thus giving the cosine 4th law.

The reduction ratio, which is listed for a system with a finite object distance, is the ratio of an incremental distance on the image to the corresponding distance on the object, measured in a coordinate system normal to the surface. In general, a square patch on the image can represent a parallelogram shaped patch on the object, with the X and Y reduction ratios used to calculate the sides. The angle of the parallelogram is not listed although it is included in the internal calculation.

The focal length, which is listed for a system with an infinite object distance, relates the image patch size to an angle in object space. It can be thought of as the product of the f-number and pupil diameter, similar to the paraxial definition. Consistent with the other calculations, it assumes a measurement normal to the object surface which is typically flat for an object at infinity. Thus, dividing the image patch size by the focal length gives the change in the sine of the field angle. To get the change in angle, divide this number by the cosine of the field angle.

The reference sphere radius is also listed for each field. It is used to calculate the wave aberrations and is also used in the calculation of the focal lengths and f-numbers although it normally has very little influence on these numbers. It can be used to identify potential problems when the radius is so short that the reference sphere is within the caustic of the image.

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Near Field Propagation

The point spread function calculation in PSF is based on a Fourier Transform of the pupil function, where the pupil function contains the information describing the aberrations and the pupil shape. The Fourier Transform of the pupil function gives the complex distribution in the image and the complex square of this distribution gives the point spread function. For a description of the diffraction integral in terms of the pupil function, see, for example, H. H. Hopkins and M. J. Yzuel, *Optica Acta,* 1970, Vol. 17, No. 3, 157-182, Equation 29.

Near field propagation can be considered to be a case of an image which is far from focus. For example, if you want to see the distribution in the vicinity of the exit pupil, you would defocus by the distance of the exit pupil from the image. The distribution in the exit pupil is normally uniform. As you move away from the exit pupil, diffraction effects start to show up. The usual method, mentioned above, breaks down in this case because of the finite number of samples.

An alternate approach is to start with the Fourier Transform of the pupil function but, in this case, define it as the plane wave expansion of the pupil function. These plane wave components are then propagated a given distance from the exit pupil merely by modifying the phase. An inverse Fourier Transform then gives the complex distribution in the plane of interest and the complex square of this gives the intensity distribution. For converging and diverging beams, a scaling procedure is used to keep the size of the beam constant with respect to the size of the grid. This Fourier Transform approach to near field propagation is used in the **PRO** feature of PSF and is described in E. A. Sziklas and A. E. Siegman, *Appl. Opt.,* Vol. 14, No. 8, August, 1975, p. 1874.

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