PAR-Partial Coherence, 1D and 2D

The Partial Coherence (PAR) option computes the polychromatic aerial image of a specified object, under partially coherent illumination, including the effects of aberrations and diffraction.

When to Use the Partial Coherence (PAR) Option

The PAR option should be used when you need to know the details of the image structure in cases for which the illumination is partially coherent. Usually, such considerations are important only when the size of the coherence patch (area of the object over which the light is correlated in phase) is comparable to or larger than the smallest detail which the system is capable of resolving. Evaluation options such as PSF, MTF and LSF assume that there is no correlation between adjacent points in the object, which is typical of objects which are self-luminous or are Lambertian transmitters/reflectors. A typical application of PAR would be to determine the image produced by a projection system used in microlithography.

PAR computes the polychromatic intensity profiles of a single one-dimensional object (zero width line, single or multiple-bar target, or edge) or of a combination of rectangular two-dimensional objects, with or without background. The objects are illuminated with partially coherent light, and the computed intensity profiles include the effects of aberrations, diffraction, and, if specified in the one-dimensional case, a finite width scanning slit or linear image motion.

PAR has two modes of computation, a one-dimensional calculation and a two-dimensional calculation. The modes are mutually exclusive. The one-dimensional calculation is done if and only if no two-dimensional objects are specified. If any two-dimensional objects are specified, all commands relating to the one-dimensional calculation are ignored and the two-dimensional calculation is done.

Default Operation

For X and Y zero-width line objects at each field point and zoom position, and for the depth-of-focus values defined in the LDM (FFO, IFO, NFO), the aberrated, diffraction image profiles are constructed (weighted and integrated over all wavelengths) under the assumption of fully coherent illumination. These X and Y profiles are listed along with the geometrical shadow and image scan coordinates.

Command Mnemonics
(alphabetical)

ADD	AZI	BAC	BAR	BGI	BGP
BOS	CDT	CON	CRO	DEP	DIS
DKP	DOS	GRI	INN	INT	LAB
LEV	LEV INC	LEV NUM	LIS	LPM	MIC
NEG	NRD	OVE	PEA	PER	PHN
PGR	PLO	RAN COL	RAN SCA	RCN	RNA
RNX	RNY	ROT	SCN	SHA	SLI
SRC	TGR	TIT	WBF	XMA	XMI
XPR	Y	YC	YPR		

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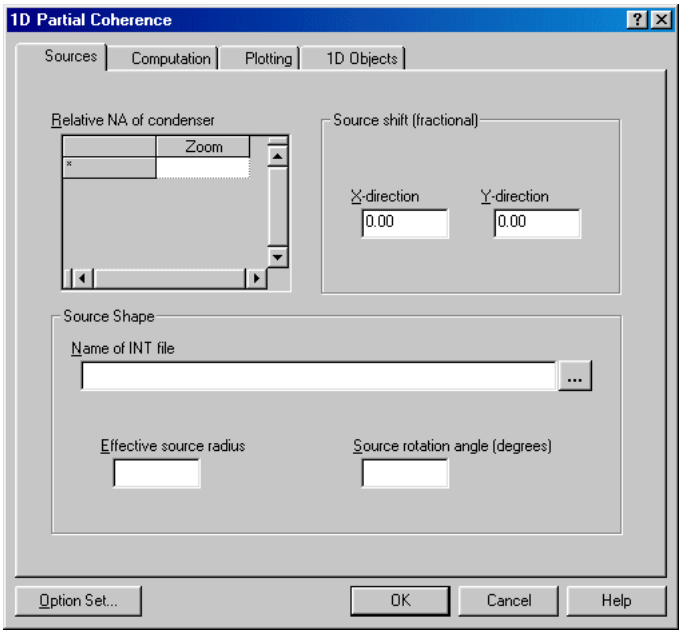
Defining Source Coherence Settings for 1D Partial Coherence

To define source coherence/position settings for 1D Partial Coherence, choose the **Analysis** > **Diffraction** > **1D Partial Coherence** menu. The **1D Partial Coherence** dialog box displays, with the **Sources** tab automatically displayed. Define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
RNA fraction_of_fill....f, z		
Relative NA of condenser	Specifies relative NA (numerical aperture) of condenser, as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. Use up to 5 RNA commands to overlay curves on the same plot. **Range**: 0.0 (fully coherent) to 2.0 (incoherent); 1.0 represents the condition where the condenser just fills the pupil. If 2.0 or greater is used in the one-dimensional calculation, a faster, incoherent calculation is done, and output is labeled "INCOHERENT ILLUMINATION." Time of calculation: proportional to the square of RNA value; at RNA 0.25, equivalent to PSF option; at RNA 1.99, about 60X as much; at RNA 2.0, equal to RNA 0.25. **Note:** Currently, the field qualifier is only supported on the command line.	0.0. Full coherence.
RNX x_shift_of_fill....f, z		
Source shift (fractional): X-direction	Specifies decenter condenser fill pattern in X direction by this fraction of the pupil. **Note:** Currently, the field qualifier is only supported on the command line.	0.0

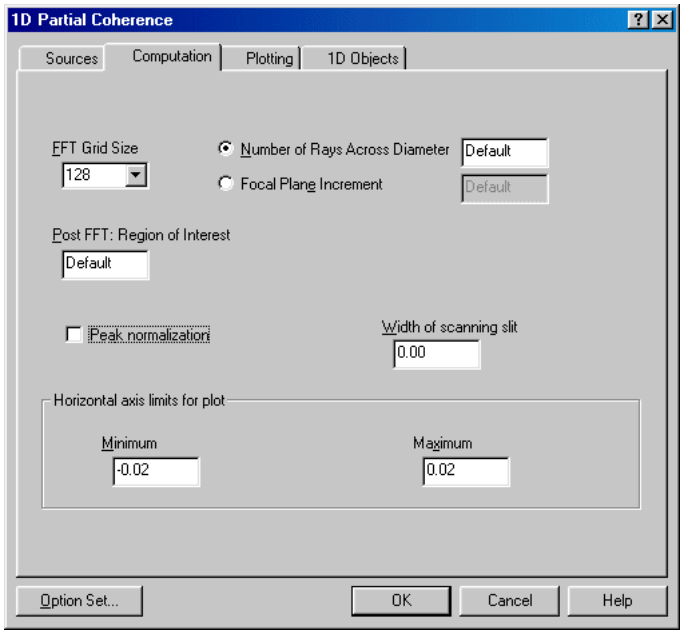
Command Syntax		
Screen Control	**Explanation**	**Default**
RNY y_shift_of_fill....f, z		
Source shift (fractional): Y-direction	Specifies decenter condenser fill pattern in Y direction by this fraction of the pupil. **Note:** Currently, the field qualifier is only supported on the command line.	0.0
SRC [Zi] [Fk] [ST1 | ST2 | ST3] filename [eff_src_radius [rot_angle_degr]]		
Source shape	Define source distribution via .INT file. Any .INT file type can be used, but if the values will be negative (e.g., for SRC ST1) the INT file type must support negative values (i.e., BIR, SUR, WFR). Background intensity value (BGI) is ignored. Default for effective radius is 1.0, and default for rotation angle is 0.0. The effective radius is in relative numerical aperture units. The source coordinate system matches the entrance pupil coordinate system. The polarization state of a source point is defined by specifying the values of the Stokes parameters (S0, S1, S2, and S3) with an .INT file. If the SRC command is used without a keyword, the S0 parameter (which is proportional to the source intensity) is defined. If the SRC command is used with the ST1, ST2, or ST3 keywords, the S1, S2, or S3 parameters are defined, respectively. Thus, complete specification of the source polarization state requires four SRC commands with four separate .INT files. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. **Note:** Currently, the field and zoom qualifiers are only supported on the command line.	Not done.
SRC [Zi] [Fk] ANN rna_min rna_max		
Command line only	Defines an annular source where the annulus is defined by a minimum relative NA (numerical aperture) of the condenser (rna_min) and a maximum relative NA of the condenser (rna_max). The relative NA (numerical aperture) of the condenser is defined as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. See "Annulus and multi-pole source shape examples" on page 19-332 for examples of the ANN source shape.	Not done.

Command Syntax		
Screen Control	**Explanation**	**Default**
SRC [Zi] [Fk] CIR #_poles rna_min rna_max [rot_angle_degr] or **SRC** [Zi] [Fk] SEC | BUN #_poles rna_min rna_max pole_subtense [rot_angle_degr]		
Command line only	Defines a multi-pole intensity distribution where the number of poles (#_poles) is 2 or more, and the poles are spaced uniformly in azimuth. The shape of each pole is determined from the CIR, SEC, and BUN keywords, where: • CIR is a circle • SEC is a sector • BUN is bun shaped The annulus in which the poles are placed is defined by the minimum and maximum relative NA, or RNA (rna_min and rna_max). The angular subtense of the pole at the center of the source is pole_subtense (applies only to SEC and BUN). The poles are arranged so that the first pole is always at the top (+y). The entire pattern may be rotated by rot_angle_degr; the default rotation is 0.0. For all of the above sources distributions, a central spot may be added by using the RNA command. The RNA value must be greater than zero and less than rna_min. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. See “Annulus and multi-pole source shape examples” on page 19-332 for examples of the CIR, SEC, and BUN pole shapes.	Not done.

Command Syntax		
Screen Control	**Explanation**	**Default**
SRC POL [RAD | LIN | MIX | CIR | CIL] [fraction_pol]		
Command line only	Defines the polarization that goes with the intensity pattern. If omitted, the source is unpolarized. The polarization is defined for the first pole in the unrotated intensity pattern and rotates with any rotation of the pattern. The fraction of polarization (fraction_pol) defaults to 1.0. If a number between 0 and 1 is entered, the remainder goes into the orthogonal state. A value of 0.5 is equivalent to an unpolarized source. A value of 0.0 is equivalent to orthogonal polarization. The types of polarization are: • RAD is radial. This is the default. • LIN is linear in X. • MIX is linear in X for the first pole, but changes for each pole. • CIR is right circular. • CIL is left circular. If RNA is included in the pattern, it receives the same polarization as the first pole. RAD is linear polarization along a radius of the pattern, and varies with position in the pattern. LIN applies the same polarization to each pole. MIX (sometimes called mixed or segmented polarization) applies a different linear polarization to each pole, depending on position; the angle of polarization stays aligned with a radius. For example, for a quadrapole with MIX and a fractional polarization of 1.0, poles 1 and 3 would have linear polarization in X, and poles 2 and 4 would have linear polarization in Y.	Not done.

Defining Computation Controls for 1D Partial Coherence

To define computation controls for 1D Partial Coherence, choose the **Analysis** > **Diffraction** > **1D Partial Coherence** menu. The **1D Partial Coherence** dialog box displays. Click the **Computation** tab, and define the controls on this tab as described in the table below.

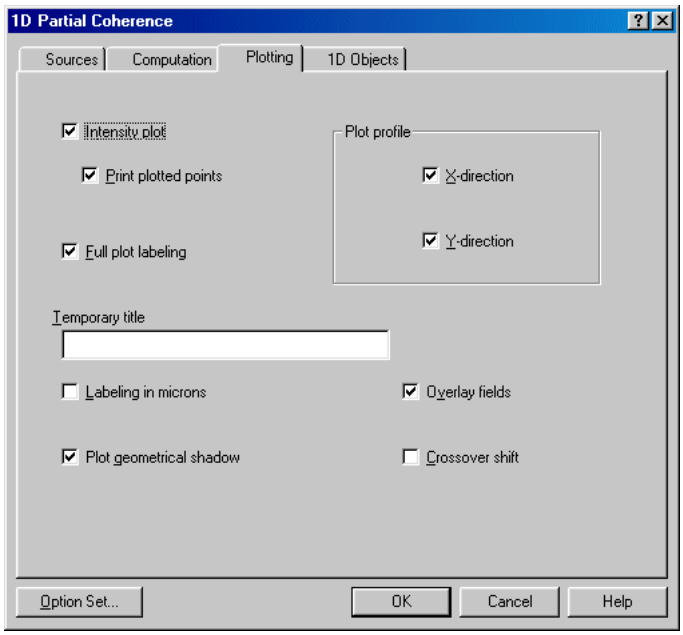


Command Syntax		
Screen Control	**Explanation**	**Default**
TGR num_fft_grd_pow_of_two		
FFT: Transform grid size	Transforms grid size. **Range**: 16 or more, must be a power of 2. Unless overridden by NRD or GRI, also determines the number of rays traced in proportion to TGR**2. Use to improve accuracy for systems with large or unusual obscurations, or to increase size of the image area analyzed relative to the Airy disc.	128
PGR num_integration_grid_width		
FFT: Integration grid size	Specifies integration grid size. **Range**: Any odd number less than TGR. Restricts the area used for display; excluded data is assumed to have 0 energy.	TGR - 1.
PEA Yes | No		
Peak normalization	Normalizes intensity profiles to a peak value of 1.0. Override: unless NEG is used, PEA will always be done for bars of zero width.	No, generally.
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. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both.	TGR/2 at short wavelength.

Command Syntax		
Screen Control	**Explanation**	**Default**
GRI image_grid_spacing....z		
Image grid spacing	Specifies grid spacing measured on the image surface - alternative to 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. Use either NRD or GRI, if desired, not both.	Shortest wavelength * fnumber/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.)
SLI scan_slit_width | No....z		
Width of scanning slit	Scans image with a slit of finite width. Use also to simulate linear image motion. No is equivalent to a zero width slit.	No.
XMI min_of_plot....z		
Horizontal axis limits for plot: Minimum	Use only with **Intensity plot** (PLO). Most negative abscissa of the plot, in dimensions of the image (lens units on the image surface). For edge traces, use 0.0.	- GRI * TGR/2
XMA max_of_plot....z		
Horizontal axis limits for plot: Maximum	Use only with **Intensity plot** (PLO). Most positive abscissa of the plot, in dimensions of the image (lens units on the image surface).	+ GRI * TGR/2

Defining Plot Settings for 1D Partial Coherence

To define computation controls for 1D Partial Coherence, choose the **Analysis** > **Diffraction** > **1D Partial Coherence** menu. The **Diagnostic Option PAR** dialog box displays. Click the **Plotting** tab, and define the controls on this tab as described in the table below.

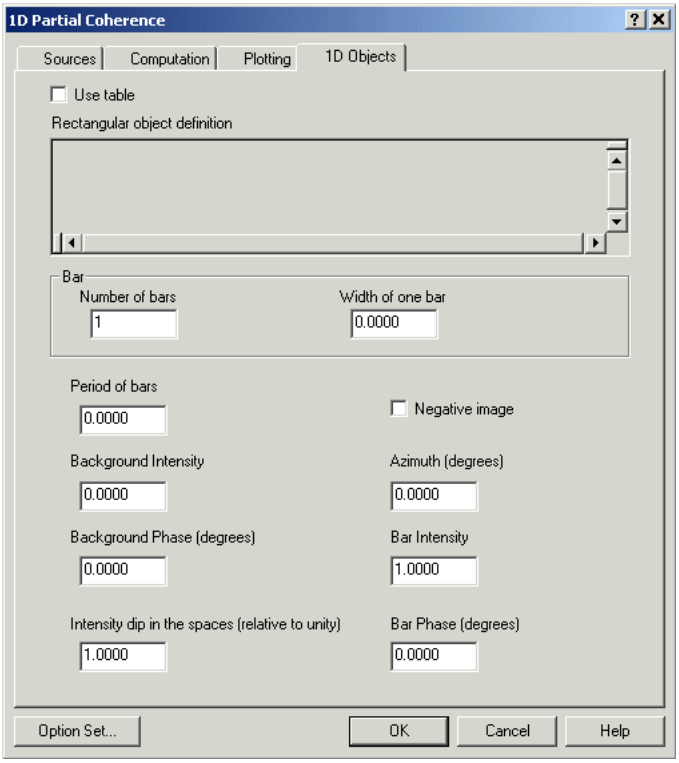


Command Syntax		
Screen Control	**Explanation**	**Default**
PLO [LIS] Yes | No....z		
Intensity plot **Print plotted points**	Plot X and Y intensity profile(s) and geometrical shadow (perfect image of the object); one X and Y pair of profiles is generated for each RNA command. For the axis of a rotationally symmetric system, only X is plotted. A single page plot containing all fields is generated for each zoom position, if only one RNA is used; for more than one RNA, fields are put on separate plots. LIS generates listing of plotted points.	Yes.
XPR Yes | No....z		
Plot profile: **X-direction**	Use only with **Intensity plot** (PLO). Plot X profile; No cancels X profile.	Yes, if neither XPR nor YPR are entered.
YPR Yes | No....z		
Plot profile: **Y-direction**	Use only with **Intensity plot** (PLO). Plot Y profile; No cancels Y profile.	Yes, if neither XPR nor YPR are entered. No, for on-axis in a rotationally symmetric system.
LAB Yes | No....z		
Full plot labeling	Use only with **Intensity plot** (PLO). Label plot in standard manner. Use of No eliminates plotting of border, title, line legend, wavelength weights and most axis numbers for that zoom position - quick plot. To suppress the automatic time and date stamp on plots, use the TAD No command. See “Plot Labeling” on page 1-87 for details.	Yes. Labeling is included.
TIT 'temporary_title'(20+20)....z		
Temporary title	Use only with **Intensity plot** (PLO). Up to 40 characters 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.	Uses the first 40 characters of the system title.
MIC Yes | No		
Labeling in microns	Use only with **Intensity plot** (PLO). Label plot in microns; all other inputs and outputs remain in lens units.	No.
SHA Yes | No....z		
Plot geometrical shadow	Use only with **Intensity plot** (PLO). Include geometrical shadow (perfect image of the object); No cancels plotting of the shadow.	Yes.
OVE Yes | No....z		
Overlay fields	Use only with **Intensity plot** (PLO). Overlay fields on one plot for each zoom position; No generates separate plots for each field.	Yes.

Command Syntax		
Screen Control	**Explanation**	**Default**
CRO Yes | No		
Crossover shift	Use only with **Intensity plot** (PLO). Shift all curves so that the 50% relative intensity points coincide at the right hand (+) edge of the geometrical shadow. Useful for comparing relative slopes, but positional relationships are lost.	No. Plot curves in actual position.

Defining Object Settings for 1D Partial Coherence

To define object settings for 1D Partial Coherence, choose the **Analysis** > **Diffraction** > **1D Partial Coherence** menu. The **1D Partial Coherence** dialog box displays. Click the **1D Objects** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
BAR num_of_bars width_ of_one_bar....f, z		
Bar: **Number of bars** **Width of one bar**	Specifies a bar object pattern. **Number of bars** (num_of_bars) can be 1,2,3,..., as long as the pattern can fit in the image plane grid width (TGR * GRI); FFT process implies adjacent grids with the same pattern, so infinite bar patterns are possible. **Width of one bar** (width_of_one_bar) is expressed in dimensions of its geometrical image. **Range**: 0.0 to GRI * TGR/2; use this upper limit or a value significantly larger than the image width, with 1 bar, to simulate an edge. **Note:** Currently, the field qualifier is only supported on the command line.	1 bar, 0.0 width. A zero-width line.
PER distance_between_bar_centers....f, z		
Period of bars	Use only with **Bar** settings (BAR), for more than 1 bar. Period of multi-bar pattern expressed as separation of bar centers in dimensions of its geometrical image. **Range**: 0 to infinity; recommended: > BAR width. **Note:** Currently, the field qualifier is only supported on the command line.	2 times BAR width. Equal bars and spaces.
BGI background_fract_int....f, z		
Background intensity	Adds background intensity; compresses bar pattern to range above background. **Range**: 0.0 (no background intensity) to 1.0 (no range left for pattern intensity variations); if high values are wanted, consider using NEG. **Note:** Currently, the field qualifier is only supported on the command line.	0.0
NEG Yes | No		
Negative image	Inverts (complements) the intensity pattern of the object; i.e., black becomes white and white becomes black.	No.
AZI object_azimuth_degr....z		
Azimuth (degrees)	Specifies object orientation. Rotates the object by the specified angle.	0.0

Command Syntax		
Screen Control	**Explanation**	**Default**
DEP min_fract_intensity....f, z		
Intensity dip in the spaces (relative to bars)	Use with multi-bar patterns. Defines the fractional dip to the minimum intensity in the space(s) relative to the bars at 1.0. **Range**: 0.0 to 1/(1-BGI); i.e, from no dip in intensity to a dip below background all the way to zero intensity. **Note:** Currently, the field qualifier is only supported on the command line.	1.0. Dip to background intensity (BGI) in the spaces.
INN intensity_transmittance....f, z		
Bar intensity	Adds intensity transmittance to the bars in a 1D object if NEG No (white), or subtracts the intensity transmittance value from 1.0 if NEG Yes (Black). Range: 0.0 to 1.0. If you want to apply different intensity values to individual bars in a 1D object, use the RCN command, or the **Rectangular object definition** spreadsheet in the 1D PAR dialog box. **Note:** Currently, the field qualifier is only supported on the command line.	0.0
PHN [ALT] bar_phase....f, z		
Bar phase (degrees)	Adds a phase (in degrees) to the bars in a 1D object. ALT (command line only) adds 180 degrees to the phase of every other bar. If you want to apply different phase values to individual bars in a 1D object, use the RCN command, or the **Rectangular object definition** spreadsheet in the 1D PAR dialog box. **Note:** Currently, the field qualifier is only supported on the command line.	0.0
BGP background_phase....f, z		
Background phase (degrees)	Adds a background phase (in degrees) to a 1D object. **Note:** Currently, the field qualifier is only supported on the command line.	0.0

Command Syntax		
Screen Control	**Explanation**	**Default**
RCN width [location [intensity [phase_in_degrees]]]		
Rectangular object definition: **Width** **X Location** **Intensity** **Phase**	Allows you to specify parameters for individual bars in a 1D object. In the GUI, select the **Use Table** checkbox to enable these data input fields. Defines a rectangular object of given x size (width) and x location, with specified intensity (transmittance or reflectance) and phase (in degrees). The widths must be entered, and correspond to the size of the corresponding image, i.e., are input as object size times system magnification. The range for intensity is 0.0 to 1.0; the default is 1.0. The default for phase is 0.0. Up to 64 nonoverlapping rectangular objects can be entered. **Note about Rectangular Object Definition Intensity** The rectangular object definition intensity is typically a value between 0.0 and 1.0; however, there are cases where it may be applicable to define a higher value. For example, when simulating a 1D mask for which a rigorous electric field simulation has been performed, the resulting intensity may be greater than 1.0. This effective mask transmittance function, with maximum intensities greater than 1.0, could be represented as a series of rectangles in RCN in order to simulate its imagery under a partially coherent optical projector.	None entered.

Defining Output Controls for 1D Partial Coherence

The following output control commands are available from the command line only.

Command Syntax		
Screen Control	**Explanation**	**Default**
LIS Yes | No....z		
Command line only	Use (with No) to turn off listed output when only plotting or output to the buffer is wanted.	Yes.
WBF Bk		
Command line only	Write the PAR output to the specified buffer (not B0). Buffer will contain header information and intensity output. WBF acts independently of LIS.	Not done.

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Defining Perturbed Wavefront Settings for 1D Partial Coherence

The following wavefront perturbation settings are available from the command line only.

Command Syntax		
Screen Control	**Explanation**	**Default**
ADD Fn [Wm] [B | Q]		
Command line only	Add a wave front 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 bi-lateral 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.

Linewidth Computation Controls for 1D Partial Coherence

The following commands comprise computations intended to meet the demand for yet smaller and smaller microlithographic features. The computations are based on the critical dimension (CD) of the image, given a one-dimensional, partially coherent image. Note that these commands can only be entered on the command line or used in a sequence file.

Some examples of the use of these computations include:

- learning how small errors in lens parameters affect the CD variation across the chip
- assessing compensation schemes given a specified tolerance
- understanding how a full polarization analysis affects process window computations.

One benefit of these capabilities is that lens manufacturers can assess their as-designed lens in terms of their customers' CD specs.

Although these commands were created with lithographic systems in mind, they will work with any system that produces imagery in PAR.

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In addition to the following commands, there are two PAR macros that support specialized microlithography functions: PAR_BOSSUNG and PAR_RESIST_PROFILE. For more details, see “Microlithography Macros” on page 25D-66.

Command Syntax		
	Explanation	**Default**
CDT [LEF | RIG | CEN | DIF | AVG | ALL] [intensity_threshold | N]		
Command line only	Computes the width of the image (Critical Dimension or CD) of one bar of a bar object at a given intensity threshold. CDT will also compute the distortion (overlay error), as well as the image log-slopes at threshold. Further, in a multiple bar pattern, CDT will find the CD’s, distortions, and log-slopes of each bar, as well as left-right differences and averages. If there is more than one bar: • LEF: computes the linewidth of the leftmost bar. • RIG: computes the linewidth of the rightmost bar. • CEN: for odd values of N, computes the linewidth of the central bar; for even values of N, computes the average of the two bars surrounding the center of the pattern. • DIF computes the difference in linewidth between the two outermost bars. • AVG computes the average linewidth of all the bars. • ALL computes the linewidths of all of the bars. (Bar orientation is specified with the AZI command.) intensity_threshold: Enter a threshold level or enter N to turn the feature off.	CEN Intensity threshold: 0.3
DOS [linewidth | N]		
Command line only	Exposure dose-to-size: Computes the exposure dose relative to the mask size. Determines the dose that produces a CD of a desired size (“dose-to-size”). The dose is the reciprocal of the intensity threshold when the image is normalized to unity with a clear mask. Such a result is averaged over the field using the field weights specified with the optical system, and is output as a function of focus. If there is more than one bar: The dose-to-size is taken at the central bar for odd N (where N is the number of bars), or the average of the two bars surrounding the center of the pattern for even N. If there is more than one field: The dose-to-size is the weighted average over all fields. Enter N to turn this feature off.	The geometrical linewidth.

Command Syntax		
	Explanation	**Default**
BOS [Bk] [LEF | RIG | CEN | DIF | AVG | ALL] [linewidth [min_percent max_percent num_percents]] | N or **BOS** [Bk] CDT [LEF | RIG | CEN | DIF | AVG | ALL] [CD_threshold [min_percent max_percent num_percents]] | N		
Command line only	Computes a focus exposure matrix for each field and places the results in an output buffer. See "Bossung Calculation" on page 19-337 for more details about the focus exposure matrix computation. BOS will compute the nominal dose (i.e., the dose-to-size) and best focus, and then use these to compute the CDs over the specified range of foci and doses. If there is more than one bar: • LEF: computes the linewidth of the leftmost bar. • RIG: computes the linewidth of the rightmost bar. • CEN: for odd values of N, computes the linewidth of the central bar; for even values of N, computes the average of the 2 bars surrounding the center of the pattern. • DIF computes the difference in linewidth between the two outermost bars. • AVG computes the average linewidth of all the bars. • ALL computes the linewidths of all of the bars. (Bar orientation is specified in with the AZI command.) Linewidth: Specify a linewidth to determine a nominal dose through a dose-to-size computation. If there is more than one field, this nominal dose is the average of the dose-to-size over all fields. Minimum and Maximum percent of nominal dose and number of doses: Specify the minimum and maximum percent of the nominal dose and the number of doses to be used in the focus-exposure matrix. (The focus range is specified within PAR as FFO, IFO, NFO.) [Bk] (optional): directs the output to buffer k. Enter N to turn this feature off. **BOS CDT Command Form** You can override the BOS command's dose-to-size calculation with the BOS CDT command form, in which you specify a CD threshold value (CD_threshold) that is used to calculate the dose-to-size. The CD threshold is a reciprocal of the desired dose-to-size value, and replaces the linewidth parameter in the BOS command syntax.	CEN If none of the four numbers are specified, then the linewidth is that specified in BAR, the percentages are 0, and the number is 1. If only a linewidth number is given, or only one or both percentages, then the default percentage values are 0, 0, 1. Buffer output: screen

Command Syntax		
	Explanation	**Default**
DKP [GAU | DBG | LOR] width_param_1 [width_param_2 [width_param_3]] | N		
Command line only	Performs a convolution of the image intensity with a specified diffusion kernel. Describes the resolution of the resist. DKP can also be used to describe XY stage vibrations in synchronous scanning, as long as the vibration analysis determines that the XY displacements can be modeled as either a Gaussian, Double Gaussian, or Lorentzian distribution. In addition to being the imaging medium, the resist, like photographic film, has some decidedly nonlinear effects that stem from the impact of the development process. This process introduces some parameters that can have a significant impact on the CD behavior through-focus and dose. A zeroth-order approximation to such development is, in fact, linear, and involves treating resist development effects as a blurring of the image. The kernel is usually a Gaussian (GAU) form, but users can also specify Lorentzian (LOR) or double-Gaussian (DBG) as well. GAU and LOR require one width parameter, while DBG requires three. A different number of parameters will trigger a warning, and defaults will be enabled. If DKP DBG and width_param_3 are not between 0 and 1, a warning will be issued and default parameters will be used. Enter N to turn this feature off.	GAU is the default kernel; 0 for all parameters

Command Syntax		
	Explanation	**Default**
LPM contrast absorption resist_thickness min_develop_rate [refractive_index develop_time] | N		
Command line only	Turns on the Lumped Parameter Model (LPM) for modeling the resist development process. The imaging system takes a square wave and makes a sine wave, and the resist chemistry takes that sine wave and tries to make a square wave again. The LPM models this by raising the values of the intensity in the resist to some large power γ. There is an assumption that the intensity in the resist drops with resist depth exponentially, as in Beer's Law, described by an absorption α. Because of this absorption, the value of the resist thickness must be specified. Because there is development activity even in the presence of complete darkness, the minimum develop rate, r_m must be specified. Parameters: Contrast: resist gamma; the power by which the exposure energy (rel dose*intensity) is raised in the develop rate function. Absorption: vertical absorption (alpha) of the resist in inverse lens units. Resist thickness: in lens units. Min_develop_rate: in lens units/second; the develop rate in the absence of light. The absence of the above parameters will lead to an error. Refractive_index (optional) Develop_time (optional) Enter N to turn this feature off. The end result of the LPM is that resist profiles become trapezoidal in shape, characterized by a bottom CD and a sidewall angle. The bottom CD is known to have a negative bias for dark lines and a positive bias for spaces. See "Detailed Description of the Lumped Parameter Model" on page 19-316.	Not done.
SCN Yes | No		
Command line only	For SCN Yes, the image is integrated over the field for each zoom position. You can specify multiple scan lines by zooming the system, where each zoom position corresponds to a scan line. For the weighting, specify the LDM weights as a function of field and zoom. CODE V allows up to 25 fields and 99 zooms so it is possible to simulate 99 scan lines where each line is modeled with 25 images.	No

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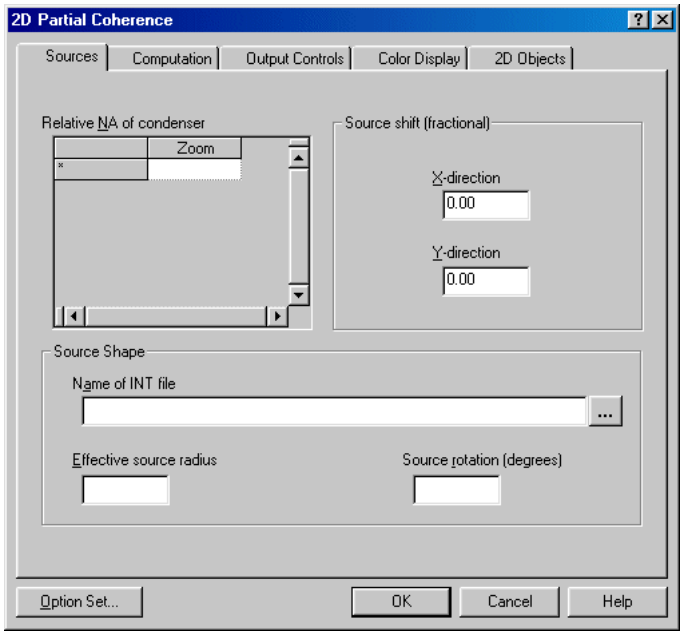
Defining Source Coherence Settings for 2D Partial Coherence

To define object settings for 2D Partial Coherence, choose the **Analysis** > **Diffraction** > **2D Partial Coherence** menu. The **2D Partial Coherence** dialog box displays, with the **Sources** tab automatically selected. Define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
RNA fraction_of_fill....f, z		
Relative NA of condenser	Specifies relative NA (numerical aperture) of condenser, as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. Use up to 5 RNA commands to overlay curves on the same plot. **Range**: 0.0 (fully coherent) to 2.0 (incoherent); 1.0 represents the condition where the condenser just fills the pupil. Time of calculation: proportional to the square of RNA value; at RNA 0.25, equivalent to PSF option; at RNA 1.99, about 60X as much; at RNA 2.0, equal to RNA 0.25. **Note:** Currently, the field qualifier is only available on the command line.	0.0. Full coherence.
RNX x_shift_of_fill....f, z		
Source shift (fractional): X-direction	Specifies decenter condenser fill pattern in X direction by this fraction of the pupil. **Note:** Currently, the field qualifier is only available on the command line.	0.0

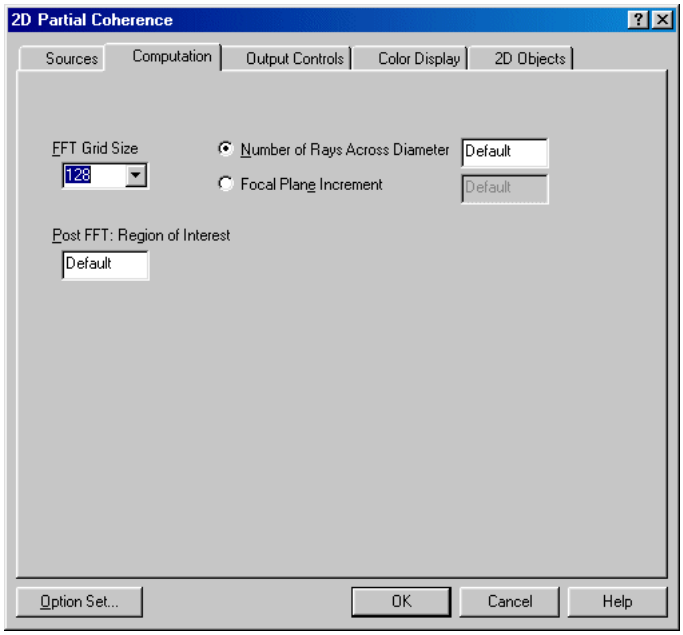
Command Syntax		
Screen Control	**Explanation**	**Default**
RNY y_shift_of_fill....f, z		
Source shift (fractional): Y-direction	Specifies decenter condenser fill pattern in Y direction by this fraction of the pupil. **Note:** Currently, the field qualifier is only available on the command line.	0.0
SRC [Zi] [Fk] [ST1 | ST2 | ST3] filename [eff_src_radius [rot_angle_degr]]		
Source shape	Define source distribution via .INT file. Any .INT file type can be used, but if the values will be negative (e.g., for SRC ST1) the INT file type must support negative values (i.e., BIR, SUR, WFR). File type is BIR (or any other file type that allows both positive and negative values). Background intensity value (BGI) is ignored. Default for effective radius (**Effective source radius**) is 1.0, and default for rotation angle (**Source rotation angle(degrees)**) is 0.0. The effective radius is in relative numerical aperture units. The source coordinate system matches the entrance pupil coordinate system. The polarization state of a source point is defined by specifying the values of the Stokes parameters (S0, S1, S2, and S3) with an .INT file. If the **SRC** command is used without a keyword, the S0 parameter (which is proportional to the source intensity) is defined. If the **SRC** command is used with the ST1, ST2, or ST3 keywords, the S1, S2, or S3 parameters are defined, respectively. Thus, complete specification of the source polarization state requires four **SRC** commands with four separate .INT files. **Note:** Currently, the field and zoom qualifiers are only available on the command line.	Not done.
SRC [Zi] [Fk] ANN rna_min rna_max		
Command line only	Defines an annular source where the annulus is defined by a minimum relative NA (numerical aperture) of the condenser (rna_min) and a maximum relative NA of the condenser (rna_max). The relative NA (numerical aperture) of the condenser is defined as a fraction of the full pupil, i.e., the fraction of the pupil that is filled by the light source. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. See “Annulus and multi-pole source shape examples” on page 19-332 for examples of the ANN source shape.	Not done.

Command Syntax		
Screen Control	**Explanation**	**Default**
SRC [Zi] [Fk] CIR #_poles rna_min rna_max [rot_angle_degr] or **SRC** [Zi] [Fk] SEC | BUN #_poles rna_min rna_max pole_subtense [rot_angle_degr]		
Command line only	Defines a multi-pole intensity distribution where the number of poles (#_poles) is 2 or more, and the poles are spaced uniformly in azimuth. The shape of each pole is determined from the CIR, SEC, and BUN keywords, where: • CIR is a circle • SEC is a sector • BUN is bun shaped The annulus in which the poles are placed is defined by the minimum and maximum relative NA, or RNA (rna_min and rna_max). The angular subtense of the pole at the center of the source is pole_subtense (applies only to SEC and BUN). The poles are arranged so that the first pole is always at the top (+y). The entire pattern may be rotated by rot_angle_degr; the default rotation is 0.0. For all of the above sources distributions, a central spot may be added by using the RNA command. The RNA value must be greater than zero and less than rna_min. If the zoom and/or field qualifier is omitted, the input applies to all zoom positions and/or field positions. See “Annulus and multi-pole source shape examples” on page 19-332 for examples of the CIR, SEC, and BUN pole shapes.	Not done.

Command Syntax		
Screen Control	**Explanation**	**Default**
SRC POL [RAD | LIN | MIX | CIR | CIL] [fraction_pol]		
Command line only	Defines the polarization that goes with the intensity pattern. If omitted, the source is unpolarized. The polarization is defined for the first pole in the unrotated intensity pattern and rotates with any rotation of the pattern. The fraction of polarization (fraction_pol) defaults to 1.0. If a number between 0 and 1 is entered, the remainder goes into the orthogonal state. A value of 0.5 is equivalent to an unpolarized source. A value of 0.0 is equivalent to orthogonal polarization. The types of polarization are: • RAD is radial. This is the default. • LIN is linear in X. • MIX is linear in X for the first pole, but changes for each pole. • CIR is right circular. • CIL is left circular. If RNA is included in the pattern, it receives the same polarization as the first pole. RAD is linear polarization along a radius of the pattern, and varies with position in the pattern. LIN applies the same polarization to each pole. MIX (sometimes called mixed or segmented polarization) applies a different linear polarization to each pole, depending on position; the angle of polarization stays aligned with a radius. For example, for a quadrapole with MIX and a fractional polarization of 1.0, poles 1 and 3 would have linear polarization in X, and poles 2 and 4 would have linear polarization in Y.	Not done.

Defining Computation Controls for 2D Partial Coherence

To define computation controls for 2D Partial Coherence, choose the **Analysis** > **Diffraction** > **2D Partial Coherence** menu. The **2D Partial Coherence** dialog box displays. Click the **Computation** tab, and define the controls on this tab as described in the following table.

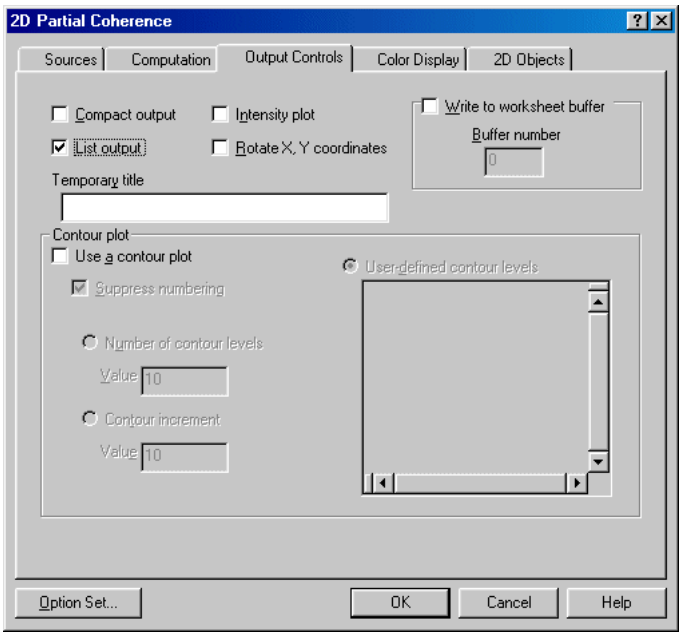


Command Syntax		
Screen Control	**Explanation**	**Default**
TGR num_fft_grd_pow_of_two		
FFT: **Transform grid size**	Transforms grid size. **Range**: 16 or more, must be a power of 2. Unless overridden by NRD or GRI, also determines the number of rays traced in proportion to TGR**2. Use to improve accuracy for systems with large or unusual obscurations, or to increase size of the image area analyzed relative to the Airy disc.	64
PGR num_integration_grid_width		
FFT: **Integration grid size**	Specifies integration grid size. **Range**: Any odd number less than TGR. Restricts the area used for display; excluded data is assumed to have 0 energy.	TGR - 1.
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. **Range**: Recommended - no more than 2 times up or down from the default; look out for artifacts of extreme choices. Use either NRD or GRI, if desired, not both.	TGR/2 at short wavelength.

Command Syntax		
Screen Control	**Explanation**	**Default**
GRI image_grid_spacing....z		
Image grid spacing	Specifies grid spacing measured on the image surface - alternative to 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. Use either NRD or GRI, if desired, not both.	Shortest wavelength * fnumber/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.)

Defining Output Controls for 2D Partial Coherence

To define output controls for 2D Partial Coherence, choose the **Analysis** > **Diffraction** > **2D Partial Coherence** menu. The **2D Partial Coherence** dialog box displays. Click the **Output Controls** tab, and define the controls on this tab as described in the table below.

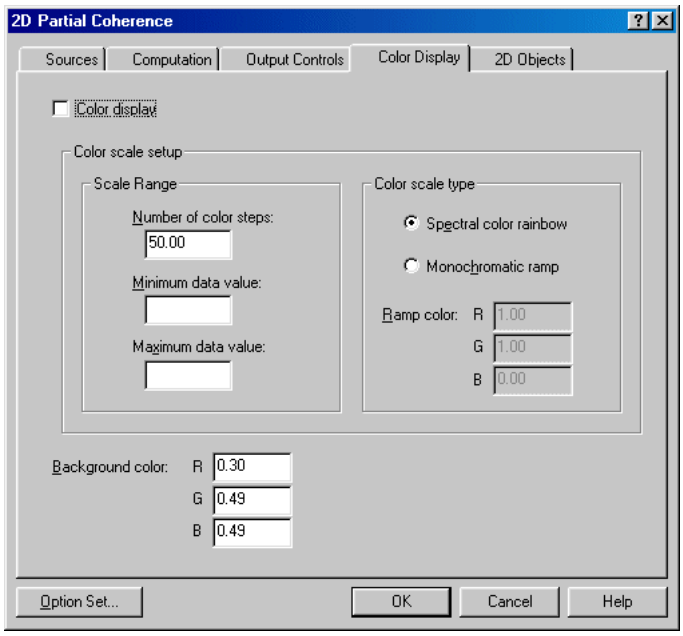


Command Syntax		
Screen Control	**Explanation**	**Default**
COM Yes | No....z		
Compact output	Normal listed output includes blank lines to make vertical and horizontal scales equal. COM Yes cancels the blank lines.	No.
LIS Yes | No....z		
List output	De-select (No) to turn off listed output when only plotting or output to the buffer is wanted.	Yes.

Command Syntax		
Screen Control	**Explanation**	**Default**
WBF Bk		
Write to worksheet buffer number	Writes the PAR output to the specified buffer (not B0). Buffer will contain header information and intensity output. WBF acts independently of LIS.	Not done.
PLO Yes | No....z		
Intensity plot	Plots intensity as a single page oblique projection plot.	Yes.
ROT Yes | No....z		
Rotate X,Y coordinates	Use only with PLO. Rotates oblique projection plot 90° in X-Y plane, to reveal hidden features.	No.
TIT 'temporary_title'(20+20)....z		
Temporary title	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 specified, the title is applied to all.	Uses the first 40 characters of the system title.
CON [SUP] Yes | No....z		
Use a contour plot **Suppress numbering**	Plots intensity as a single page contour plot with numbered contours. Select **Suppress numbering** (SUP) to eliminate the contour numbering.	No.
LEV [contour_level_fraction....30] or **LEV INC** contour_increment_fraction or **LEV NUM** num_contour_levels		
Number of contour levels	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.	LEV NUM 30.
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 30.
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 30.

Defining Color Display Controls for 2D Partial Coherence

To define color display controls for 2D Partial Coherence, choose the **Analysis** > **Diffraction** > **2D Partial Coherence** menu. The **2D Partial Coherence** 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 [SRC] [Zi] [Fk] Yes | No		
Color display	Displays intensity (INT) 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. You can designate the field and zoom position to be included in the contour map. If this information is omitted, a color contour map is generated for each field and zoom position. **Note:** Currently, the field qualifier is only available on the command line. The SRC keyword specifies that the source intensity will be displayed in the color contour map. If the source is polarized, a vector plot showing the polarization will also be generated. **Note:** Currently, the SRC keyword is only available on the command line.	No.

Command Syntax		
Screen Control	**Explanation**	**Default**
RAN SCA num_steps [min_value max_value]		
Color scale setup: **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: **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: **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
RAN COL SPE | RGB [r_value g_value b_value]		
Color scale setup: **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: **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 **Ramp color**/**R**, **G**, and **B** 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)
BAC r_value g_value b_value		
Background color: **R** **G** **B**	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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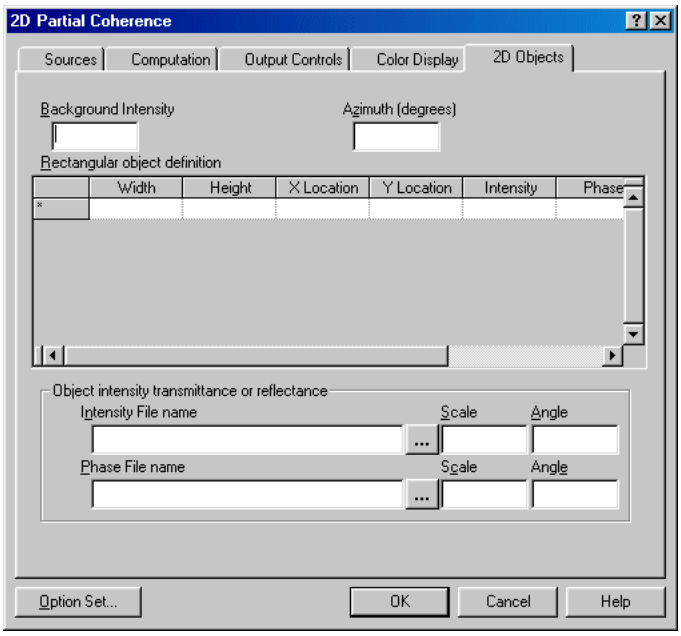
Defining Object Parameters for 2D Partial Coherence

To define object parameters for 2D Partial Coherence, choose the **Analysis** > **Diffraction** > **2D Partial Coherence** menu. The **2D Partial Coherence** dialog box displays. Click the **2D Objects** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
BGI background_fract_int....f, z		
Background intensity	Adds background intensity; compresses pattern to range above background. **Range**: 0.0 (no background) to 1.0 (no range left for pattern variations). Note: Currently, the field qualifier is only supported on the command line.	0.0
AZI object_azimuth_degr....z		
Azimuth (degrees)	Specifies object orientation. Rotates the object by the specified angle.	0.0

Command Syntax		
Screen Control	**Explanation**	**Default**
RCT x_width y_width [x_location y_location [intensity [phase_degr [rot_angle_degr]]]]		
Rectangular object definition	Specifies a rectangular object of given x and y size, at a given x and y location, with specified intensity (transmittance or reflectance), specified phase (in degrees), and specified rotation angle (in degrees). The widths must be entered, and correspond to the size of the corresponding image, i.e., are input as object size times system magnification. The range for intensity is 0.0 to 1.0; the default is 1.0. The default for phase is 0.0 and the default rotation angle is 0.0. Up to 64 nonoverlapping rectangular objects can be entered.	None entered.
INT filename radius [rot_angle_degr]		
Intensity file name	Specifies a .INT file for defining the object intensity distribution (transmittance or reflectance). The interferogram (.INT) file must be of the FIL type, with the units being relative intensity and the SSZ value being equivalent to unit intensity. Only one INT file command may be entered. If no INT command is given but PHA is given, the intensity is 1.0 at all points. **Note:** No check is made that intensity specified in the .INT file is 1.0 or less. The default for .INT file rotation angle is 0.0. Any rectangular objects entered with RCT will be ignored if INT is given.	No .INT file specified.
PHA filename radius [rot_angle_degr]		
Phase file name	Specifies a .INT file for defining the object phase distribution in degrees (transmittance or reflectance). The interferogram (.INT) file must be of the FIL type, with the units in degrees and the SSZ value being equivalent to one degree. Only one PHA file command may be entered. If no PHA command is given but INT is given, the phase is 0.0 at all points. The default for .INT file rotation angle is 0.0. Any rectangular objects entered with RCT are ignored if PHA is given.	No .INT file specified.

Defining Wavefront Perturbation Settings for 2D Partial Coherence

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 bi-lateral 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.

Discussion of Input and Computations

What to Include in the LDM Data

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

PAR does not use any pupil apodization, either Gaussian or user-defined, that is present in the lens (it does use .INT files attached to surfaces to modify the transmittance of individual surfaces). PAR uses polarization ray tracing, if it has been enabled (POL Y).

Usage

In certain classes of optical systems, an image is formed by light that is transmitted through a partially transparent object. Microscopes, enlargers, projectors, and projection printers in semi-conductor microlithography are examples of such systems. In these cases, the illumination is partially coherent and the usual concepts of point spread function and MTF cannot be used without some qualification.

PAR calculates the intensity profile of one-dimensional or two-dimensional objects. In the one-dimensional case, the object may be one, two, three, or more bars of finite width. The final image may be convolved with a scanning slit (**SLI**).

In the two-dimensional case, the object is composed of non-overlapping rectangles (**RCT**) or is specified by an interferogram file (**INT** and **PHA**). The calculation is based on a method of H. H. Hopkins (H. H. Hopkins, *Proceedings of the Royal Society*, London, A, 217, 408 [1953]). The calculation uses an effective source distribution in the exit pupil of the condenser which can be modified with an interferogram file. This effective source distribution is the image of the light source in the case of Kohler illumination. In the case of critical or an intermediate type of illumination, the user can model the imaging with partially coherent light by calculating the irradiance distribution in the exit pupil of the condenser and entering it using the **SRC** command. The ratio of the diameter of this disc to the pupil diameter affects the imagery and is adjustable (**RNA**). This ratio is, equivalently, the ratio of the numerical aperture of the condenser to the numerical aperture of the imaging system, both measured at the object being illuminated. A value of 0.0 corresponds to coherent illumination. As the ratio approaches infinity, the incoherent limit is reached. However, incoherent calculations are not done this way; there are faster methods. So, if a ratio of 2.0 or greater is requested in the one-dimensional case, an incoherent calculation will be done (in the two-dimensional case, the Hopkins method is still needed). When the ratio is 1.0, the pupil is just filled. In most cases, the ratio of 1.0 gives results which are very close to, but not exactly the same as, the incoherent case.

Typical Applications

A typical **RNA** value used in projection printing applications is 0.7 and in high quality systems has the effect of sharpening the edge of the line structure compared to an image found in incoherent light. A comparison of results with different ratios is given in Example 1 in the Description of Output section.

Default Assumptions

If no additional commands are entered, the following default assumptions are used:

- A one-dimensional calculation is done.
- Relative numerical aperture of the condenser is zero (full coherence).
- The object is a single bar with a line width of zero, and is evaluated at azimuths of 0° and 90°.
- Normalization of the line image profile by the area of an open frame (if line width is zero, normalization to unit height is done automatically) (see **PEA** command for further explanation).
- All field points and zoom positions (as defined in the LDM) are included.
- Wavelength weights are those of the system, determined in the LDM (WTW).

- The focal plane location is determined by the combination of the paraxial image distance and defocusing (as set in the LDM - FFO, IFO, NFO).
- The grid size is chosen to be:

$$\frac{(\lambda short)(f/no)}{2}$$

- No plotting is done unless requested (see "Plotting Controls" on page 19-314).
- The scanning slit width is zero (see **SLI** command).

Source Coherence Calculation Time Factors

The partial coherence calculation involves an integration over the source in addition to an integration over the pupil and is thus more complex and more time consuming than the calculation of the point spread function. Since the time required **INCREASES** approximately as the square of the size of the source, calculations with large **RNA** values may take a long time to compute. A value of 0.25 for the relative numerical aperture (**RNA**) takes about the same time as the calculation of the point spread function using the PSF option. Simulating the incoherent case with an actual partial coherence calculation becomes prohibitive for large **RNA** values. A value of 2.0 would take approximately 60 times as much computing time as the **RNA** 0.25 case.

Because the results in these cases are essentially the same as incoherent, a different calculation method is used in the one-dimensional calculation for **RNA** greater than or equal to 2. This calculation assumes incoherence and takes approximately the same computing time as the 0.25 **RNA** case.

Source Image Shift

The condenser fill pattern can be decentered relative to the pupil radius by a fraction of the pupil in the X (**RNX**) or Y (**RNY**) directions.

Source Distribution

The default assumes that the source is a uniform, circular disk. The **RNA** value defines the outer boundary of the disk. The disk can be shifted in the pupil (**RNX**, **RNY**). The source distribution can also be user-defined (**SRC**). In this case, **RNA**, **RNX**, and **RNY** are ignored, and the source distribution is specified in a .INT file, and the source size and orientation is specified with **SRC**. The source distribution is assumed to be the same at all points across the object.

Source Polarization

The **SRC** command allows specification of sources with polarization states that vary from point to point. The effects of the source polarization variation are included in the image intensity calculation.

The Stokes parameters at each source point are to satisfy the relationship, $S0^2 \geq S1^2 + S2^2 + S3^2$. If this relationship is not satisfied, the values of S1, S2, and S3 are uniformly scaled until $S0^2 = S1^2 + S2^2 + S3^2$. Any Stokes parameter that is not specified will be assigned a value of zero. If the S0 parameter is not specified, the values of S1, S2, and S3 will also be zero, even if specified. If at least one **SRC** command is issued with an ST1, ST2, or ST3 keyword, polarization ray tracing will be performed for a source with a varying polarization state.

The Stokes parameters at each source point are used to compute the set of Jones vector basis states. The pupil function for each field is calculated for the Jones vector basis states derived from the initial polarization state. The coherent and incoherent contributions of the projections of the desired polarization state at each source point onto the pupil function are used to compute the image intensity distribution.

Object Parameters

The object can be either a single one-dimensional object or a complex two-dimensional object composed of non-overlapping rectangles or specified by a .INT file, but not both. If no two-dimensional object is specified, the one-dimensional calculation is done. If any two-dimensional objects are specified, the two-dimensional calculation is done (and any one-dimensional object specified is ignored).

One-dimensional Object

The one-dimensional object is shown below in Figure 1. The object can be a single, double, or N-bar object (N=1,2,3,4 . . .). The number of bars and the width of each bar is specified with **BAR**; the default is a single bar of zero width. The number of bars which could be specified is theoretically infinite, so long as the pattern can fit within the image plane grid width (**TGR*GRI**) since the integration process implies adjacent grids with the same pattern. The bar width, which defaults to 0.0, has a range of 0.0 to **GRI * TGR**/2. The period between bars is specified with **PER**. Both the bar widths and bar periods are specified in terms of their geometrical image size.

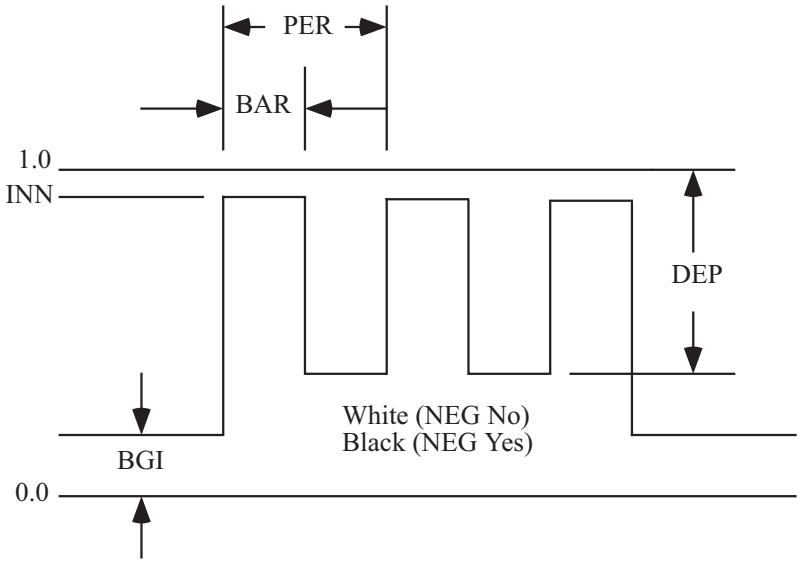


Figure 1. Schematic of the object parameters for a one-dimensional object

The image of an edge can be simulated by using a wide bar and looking at one-half of it. Specify only one bar with a width of **GRI * TGR**/2 to simulate an edge. Plotting controls will allow plotting only a portion of the data to show the edge better.

Background intensity can be added to the image (**BGI**). Since the bars always have an intensity of 1.0, **BGI** will effectively reduce the contrast of the bars against the background. The intensity dip between the bars can also be specified (**DEP**); the default is 1.0, meaning full dip to the background intensity **BGI**. The intensity pattern of the bars can be inverted (**NEG**); i.e., black becomes white and white becomes black; **NEG** No (default) means the bars are white.

The orientation of the whole object can also be specified (**AZI**); the default is 0° relative to the X axis (bars are perpendicular to the X axis).

PAR also supports a 1D phase-shifting mask specification. Use **INN** to add intensity transmittance to the bars in a 1D object if NEG No (white). For NEG Yes (black), INN subtracts the intensity transmittance value from 1.0. **PHN** adds a phase, in degrees, to the bars in a 1D object, and **BGP** adds a background phase, in degrees. If you want to apply different intensity and phase values to individual bars in a 1D object, use the **RCN** command. The RCN command also allows you to specify different width and X location values to individual bars. Note that the RCN command overrides any previously entered 1D object parameters. For example, BAR and PER commands are overridden by subsequent RCN command entries.

Two-dimensional Objects

Two-dimensional rectangular objects can be specified (**RCT**). The x and y full widths are specified, as well as the x and y location of the center of the rectangle. The intensity of each rectangular object can be specified (**Range**: 0.0 to 1.0, default 1.0) and its phase can be specified in degrees (default 0.0). Each rectangle can also be rotated (default angle is 0.0°). Up to 64 rectangular objects can be entered. Rectangular objects are not allowed to overlap; attempted entry of a rectangle which overlaps any other already entered rectangle will generate a warning and the entry will not be made.

The background intensity can be specified (**BGI**). This fills the background in between the rectangular sources.

In place of entry of multiple rectangular objects, a single user-defined object can be specified (**INT** and **PHA**). Two .INT files are used, one with **INT** to specify the intensity pattern, and one with **PHA** to specify the phase pattern. If either **INT** or **PHA** is given, all rectangular objects entered with **RCT** are ignored. If **INT** is not given, but **PHA** is given, the intensity is set to 1.0 at all points in the object. If **INT** is given but **PHA** is not given, the phase is set to 0.0 at all points on the object. For an object defined with **INT** or **PHA**, the value of **BGI** is ignored, as the background intensity is part of the intensity .INT file.

Note: When using a grid .INT file for the **PHA** command in **PAR**, always use an **NNB** (nearest neighbor interpolation) specification on the second line of the .INT file.

The orientation of the entire object (all rectangle objects or the user-defined object) can be specified (**AZI**). The rotation is done around the object origin in the same sense as CDE (counter-clockwise as seen looking into -Z).

Grid Computation Controls

The default FFT grid size may not be convenient. It can be increased (**TGR**) by powers of 2 to improve accuracy for systems with large or unusual obscurations, or to increase size of the image area analyzed relative to the Airy disc. Unless overridden by **NRD** or **GRI**, **TGR** also determines the number of rays traced in proportion to **TGR****2. The integration grid size can also be restricted to an area for display (**PGR**), in which case any excluded data is assumed to have 0 energy.

The image grid interval (**GRI**) can be adjusted up or down by a factor of 2 (adjustment smaller by more than a factor of 2 is allowed, but generates a warning). Alternatively, the number of rays traced across the pupil diameter (**NRD**) for the shortest wavelength can be adjusted from the default of **TGR**/2, which will have a similar effect. 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 lens will be represented by very few data points in the wavefront, especially in the long wavelengths.

The formulas relating each of the values are the following:

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

$$\mathbf{PGR} < \mathbf{TGR}$$

The f/no is the f/number in the image space for the axial beam (or for 2X the largest half-beam at any field if larger than the axial beam).

In the 1D calculation, the output of a scanning slit can be simulated by specifying its width (**SLI**), which will be convolved with the final image. This may also be used to simulate linear image motion. The default is zero (no scanning slit).

For more details about grid computation controls, see the following discussion in the Point Spread Function (PSF) option documentation: "Grid Considerations for Diffraction Calculations in CODE V" on page 19-358.

Peak Normalization

The normalization of the output intensities depends on the conjugate ratio of the lens and on the effective numerical aperture of the object (NAO). The purpose of the normalization is as follows:

- For typical systems, such as with finite conjugate systems with moderate magnifications and numerical apertures, the image irradiance should give some indication of the amount of light that the mask diffracts outside of the entrance pupil of the lens.
- The normalization should indicate how much of the illumination is thrown away even in the absence of diffraction of the mask.
- If the RNA is greater than 1.0, then by definition, some of the illumination is thrown away because it cannot be accepted by the projection lens. The image irradiance should reflect this.
- In the case of long conjugates, where most of the illumination is not collected by the entrance pupil, the normalization needs to use a different metric for meaningful comparisons.

The normalization used in PAR for finite conjugate systems is as follows.

If the NAO > 0.05, the source is assumed to have a radiance of $1/[\pi*(RNA*NA)^2]$. Thus, as you vary the RNA, the total source energy is constant. It also means that for RNA < 1, an unobscured "open-frame" object will have an image with an irradiance of 1.0.

If the NAO > 0.05 and the RNA ≥ 2.0 (i.e., incoherent illumination), then the source is assumed to have a radiance of M^2/π, where M is the system magnification, NAO/NA. Note that this is just an extension of the normalization used for partially coherent illumination. If the illumination is incoherent, RNA*NAO = 1.0, or RNA = 1/NAO.

If the system is operating at long conjugates or whenever the NAO 0.05, the normalization is such that an "open frame" object will give unit irradiance in the image, provided that the illumination is bright field, i.e., some or all of the illumination is accepted by the entrance pupil of the system in the absence of any object.

This can be changed in the 1D calculation with **PEA**. If **PEA** is given, then the peak irradiance in the image is set to 1.0. **Note:** unless **NEG** is used, **PEA** is always done for the 1D calculation with bars of zero width.

Plotting Controls

1D Plotted Output

To generate plots, only the plot request is needed (**PLO**). There are other optional plotting commands, which if used, must accompany the **PLO** command, to tailor the result to specific needs. These include setting lower (**XMI**) and upper (**XMA**) limits for the plot's horizontal axis. To plot edge traces, for example, use **XMI** with a value of 0.0. Either the X (**XPR** N) or Y (**YPR** N) intensity profile can be suppressed, as can labeling (**LAB** N) when a quick plot is desired. Other labeling options include specifying a temporary title (**TIT**) and having the plot output dimensions labeled in microns (**MIC**) rather than in the default lens units.

The geometrical "shadow" (perfect image of the object) is ordinarily plotted, unless suppressed (**SHA N**). **Plots for each field angle are overlaid for each zoom position** *unless* more than one **RNA** is input. In that case, separate plots for each field angle are produced automatically to improve readability. The overlay assumptions can be altered (**OVE**). If you have multiple fields and multiple **RNA** values, **OVE** Yes (default) will give you a separate plot for each **RNA**, with multiple fields on each plot. If you specify **OVE** No, you

will get a separate plot for each field, with multiple **RNA**s on each plot. If you have only one field but multiple **RNA**s, and you want them all on the same plot, use **OVE** No.

Each curve in its actual position relative to the geometrical shadow. All curves in each plot can be shifted such that 50% relative intensity occurs at the right side of the geometrical shadow (**CRO**). This may be useful in comparing slopes for different **RNA** values or field positions, but care should be used in doing so since relative position information is lost in this process.

2-D Plotted Output

Three types of graphical output are available for the 2-D calculation:

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

More than one type of plot may be made in a single PAR run. For all three types of graphical output, a temporary title can be specified (**TIT**). Otherwise, the system title is used.

A 3-D oblique projection plot can be requested (**PLO**). PAR automatically scales the height, and a scale bar is drawn; the scale cannot be set by the user. Occasionally, detailed structure of the intensity is hidden by the peaks of the oblique projection plot. The X and Y coordinates can be rotated 90° (**ROT**) to overcome this effect.

A contour "map" of the image intensity can be requested (**CON**). The contour lines are numbered unless suppressed (**CON** SUP). Ten levels between the minimum and maximum intensity levels with reasonable rounding of the increment are the default (**LEV** NUM 10). The user may specify up to 30 contours (LEV n...30), the contour increment (**LEV** INC n), or override the number of contour levels (**LEV** NUM n). Levels are integral multiples of the contour increment. The number of levels plotted may change by one due to rounding.

A color contour map of the image intensity can be requested (**DIS**). For the color contour map, different colors represent different intensities. The number of colors used and the range of intensities displayed can be controlled with the **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 background color for the region outside the 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.

The colors for the fields will be set by CLS FLD. The first two line styles set by STL will be used for the R and T curves, respectively. If both line styles for R and T curves are solid lines, the line style for the R curve will default to line style #3. (See "Defining Configuration - Graphics" on page 24-16.)

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 leftmost 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 (**YC**). **Note:** In many cases it may be easier to define a perturbed wavefront as an interferogram (.INT file) in either Zernike polynomial or grid form. This data is placed on a dummy surface at an appropriate location in the system (see "Defining Interferometric Deformations and Intensity Apodization" on page 10-9).

Line Ratio

The line ratio is the ratio of the intensity at the center of the pattern compared to the intensity at the center of the pattern that would be produced by a system of equivalent aperture and apodization but with no wavefront aberration. It is useful in situations where the pattern that is set up in PAR consists of very narrow lines (barely resolved) and the pattern has a line centered at the center of the grid. Because there may be dips in the intensity for a bar target of finite width, it is possible for this ratio to exceed 1.0.

Detailed Description of the Lumped Parameter Model

The main principle behind any algorithm used in the simulation of resist develop processes is an equivalent Fermat's Principle:

The path that a particle of developer follows in an exposed resist between two points is that which takes the least time to traverse.

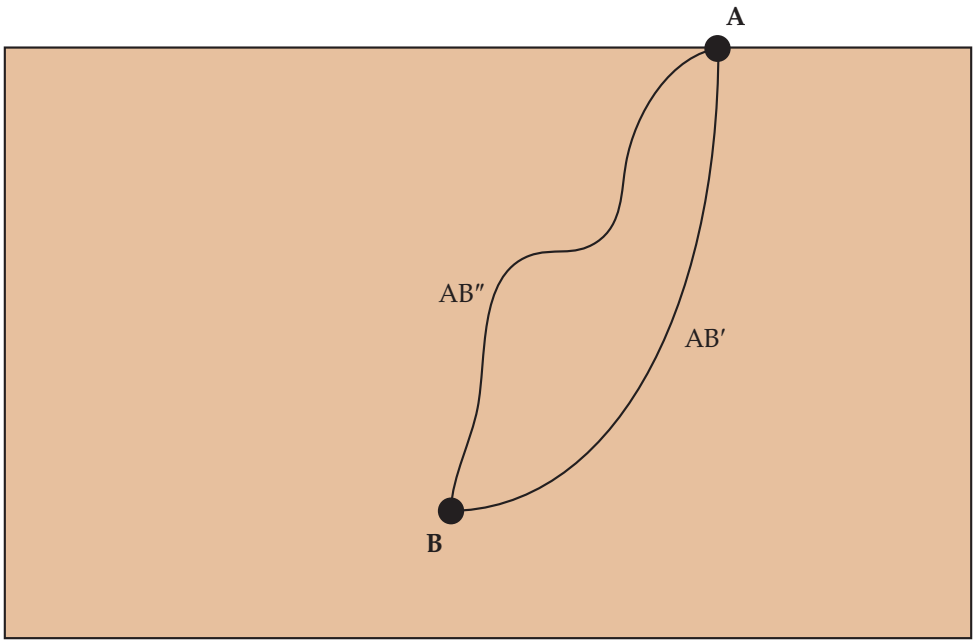


Figure 2. Possible paths a developer particle may take in traveling from point A to point B inside the resist.

Expressed mathematically, the time it takes for the developer particle to traverse from A to B is

$$t_{\mathrm{AB}} = \int_{\mathrm{AB}} \frac{ds}{r\left[x(s), z(s)\right]} \qquad (1)$$

Here, r is the develop rate function. (It is assumed that this rate function is time-independent. This is largely true for modern, chemically-amplified resists. More conventional resists experience bleaching, which is time-dependent.) The problem of minimizing time over fixed endpoints is familiar to those determining light ray paths in inhomogeneous media; in fact, one may associate r with the quantity $1/n$, with n being the index profile of a inhomogeneous medium. Therefore, the differential equations that describe the path of the develop "rays" are deduced from those for light rays in inhomogeneous media.

Lumped Parameter Model

Determining the rate function r in a full resist model involves the solution of a set of computationally intensive reaction-diffusion equations. Such a framework requires approximately 70 phenomenological parameters and vast computational resources, and is not feasible for this software. Rather, we use a simpler model for the

develop rate that is directly linked with the intensity profile *I* and uses only 5 parameters. This model is known as the Lumped Parameter Model (LPM) and takes the following mathematical form:

$$r = r_0\left(\frac{E}{E_0}I\right)^{\gamma} + r_m \qquad (2)$$

where the relative dose is E/E_0, r_m is a develop rate bias, and r_0 is a constant determined from the develop time t_d, resist thickness D.

Another aspect of the model is the method in which the resist stack on the wafer is treated. Normally, the wafer is coated with any number of film layers (resist, anti-reflection coatings, polysilicon, metal, etc.), on top of the silicon, and this combination can cause numerous standing waves in the rate profile within the resist. Then a Post-Exposure Bake step will smooth out the rate profile, resulting in a clean resist profile. Of course, all of these steps are too detailed for the users of this software. A better approach is to assume a single, infinitely-thick resist layer as the imaging medium; this has been used at IBM effectively in OPC work, and avoids the standing-wave issue and other process-specific quantities that are not desirable in the software.

The purpose of the resist thickness, then, is to determine a stopping point for the develop paths within the resist. Absorption in the resist is handled through a simple application of Beer's Law, which states that the intensity decays with resist depth as follows:

$$I(z) = I(0)\exp(-\alpha z) \qquad (3)$$

where α is the resist absorption. Although the absorptive behavior of the resist is much more complicated at the high NA values our customers are using, this form for the absorption is a standard in LPM calibration models, and represents what our customers are using.

The list of parameters needed for the LPM are as follows:

γ	contrast
α	absorption
t_d	develop time
D	resist thickness
r_m	develop bias

When all of this is put together, the develop rays can be traced given the parameter values listed above, and minimizing the value of the integral equation (1). As an example, consider the following system:

$I(x)$	1.12 $\mathrm{Sin}^2[2\pi x/0.4]$
g	3.0
a	0.9 μm^{-1}
t_d	60 sec
D	0.3 µm
r_m	0.02 nm/sec

The following resist profile is then generated:

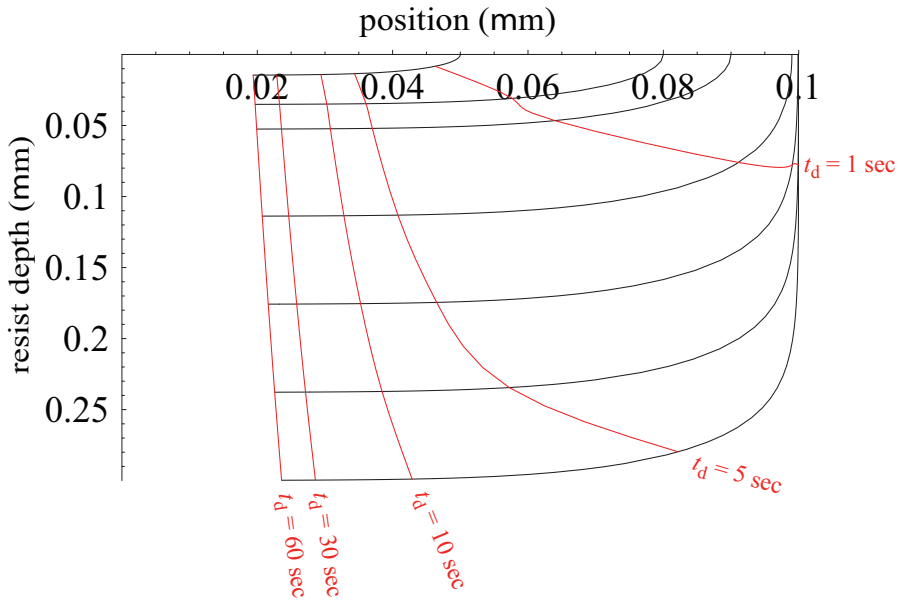


Figure 3. Illustrating the develop ray "paths" (black) and "wavefronts" (red) using a LPM.

As shown in Figure 3, the rays begin at the surface of the resist, where the developer is applied. The resist thickness is 0.3 µm, and the rays represent the unique path that ends at a given depth inside the resist in a given develop time. The image is due to a line with 100 nm ½-pitch, and the dark part is centered at the origin. Note that the wavefronts are not normal to the rays at earlier times because a cubic spline was used to draw the resist edges. Also note how quickly the development slows as time moves on; beyond 60 sec, there is no significant movement in the resist edge. Most important, note that the final resist edge is not vertical and has some slope, which is simple to compute with the LPM.

The resist edge is typically measured at the bottom of the resist.

For practical reasons, the actual develop path used in CODE V is the segmented path described in Brunner & Ferguson.[1]

Edge Slope

As mentioned in the caption in Fig. 2, the slope of the resist edge $\Delta D / \Delta x_{\text{edge}}$ is relatively simple to compute within the LPM framework in the previous section. One determines edge slope by tracing two develop rays at different resist depth near the bottom of the resist.

Defocus Effects

Although equation (4) represents the main equation to solve that would produce an edge in the LPM, there has been an addition to the LPM within the past few years that has improved its accuracy (i.e., ability to calibrate to experimental data). This addition attempts to take the effects of defocusing through the resist into account. To effect this, the following functional form has been proposed[2]:

$$I(x,z) = \left[I_0(x) + I_1(x) z + I_2(x) z^2 \right] \exp(-\alpha z) \quad (4)$$

1. T. Brunner, R. Ferguson, "Approximate models for resist processing effects," in *SPIE v.* 2726, *Optical Lithography IX*, G.E. Fuller, ed., 198-207 (1996).
2. J. Byers, M. Smith, C. Mack, "3D Lumped Parameter Model for Lithographic Simulations", in *SPIE* vol. 4691, *Optical Lithography XV*, A. Yen, ed., 125-137 (2002).

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Description of Output

The PAR option produces a table of relative intensity values for objects oriented in two orthogonal directions. See plotted output examples in Figure 4, Figure 5, and Figure 6.

Examples

This is the lens data used in Example 1, Example 2, Example 3, Example 6, and Example 7.

```
LENS
TIT "0.5 NA Perfect Lens"
DIM mm
NA 0.5
WL 500
S 0 0
MOD
MFL 100 ; MED 100 ; MFD 1.0
S 0 0
PIM
GO
```

Example 1. Partial coherence example comparing 25% and 75% relative numerical aperture for a single bar object

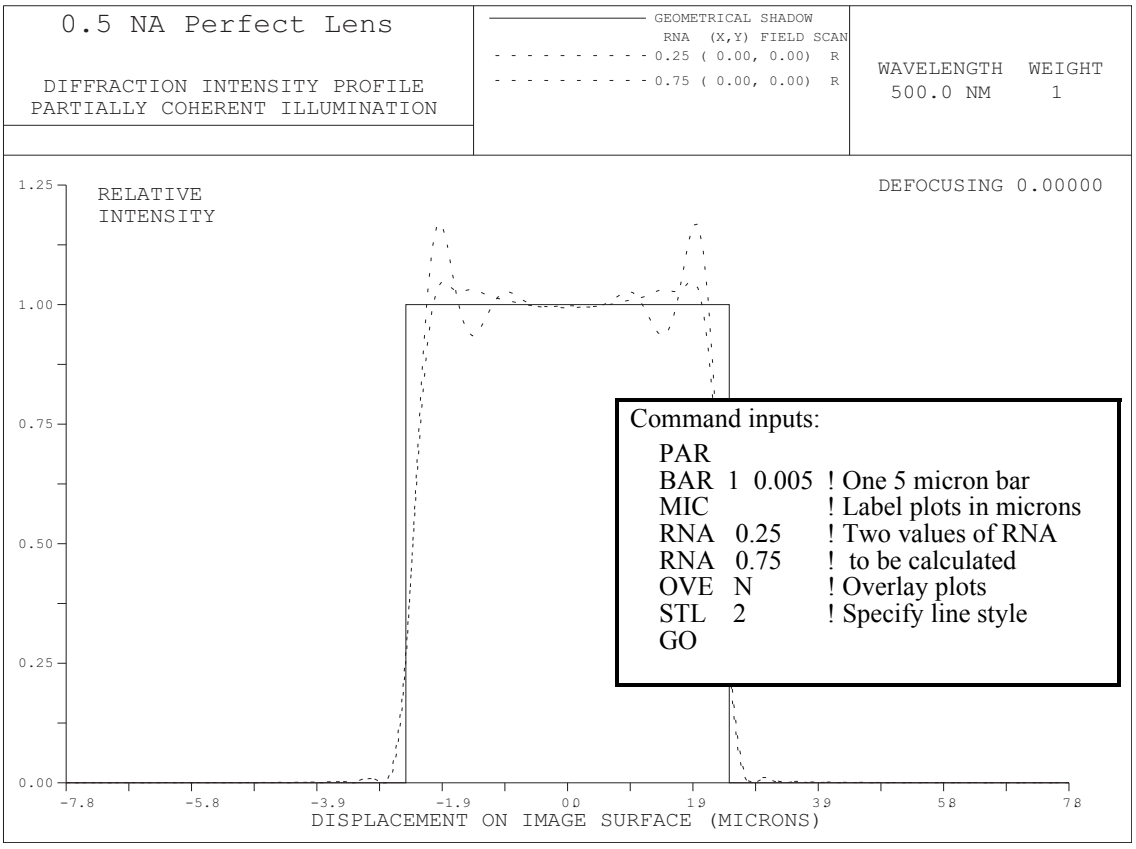

Figure 4. 1D PAR example for a single bar object

Example 2. Simulation of an edge in partial coherence by plotting from center of a wide bar with 10% relative numerical aperture.

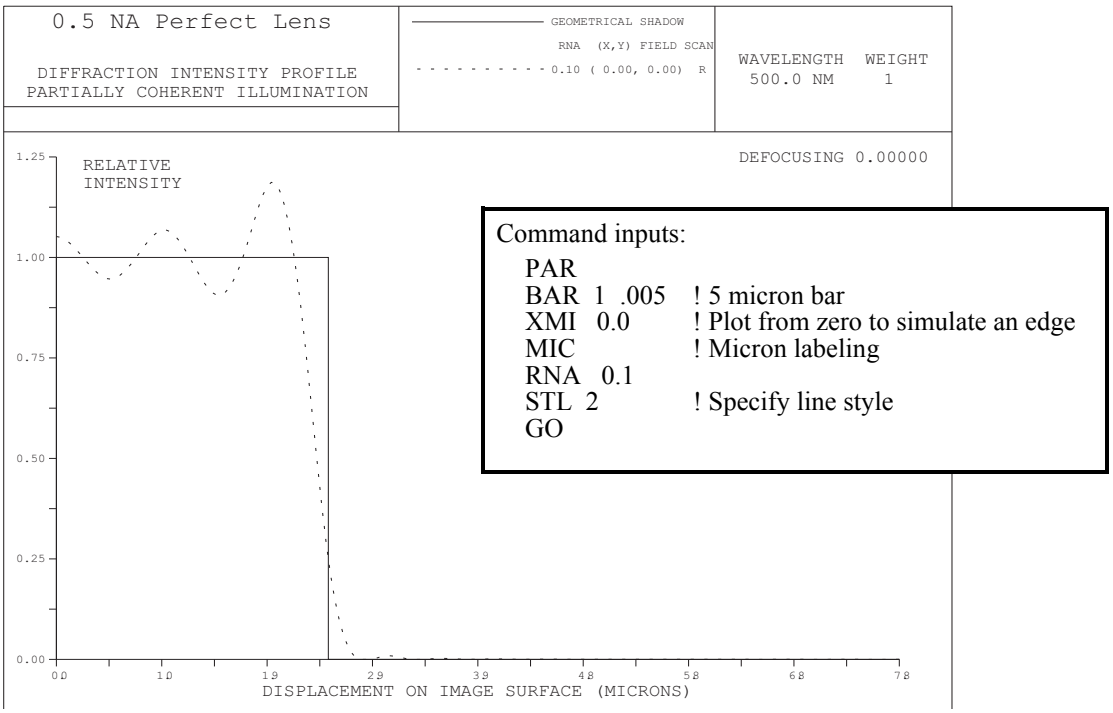

Figure 5. 1D PAR example for an edge

Example 3. Multi-bar object under incoherent illumination.

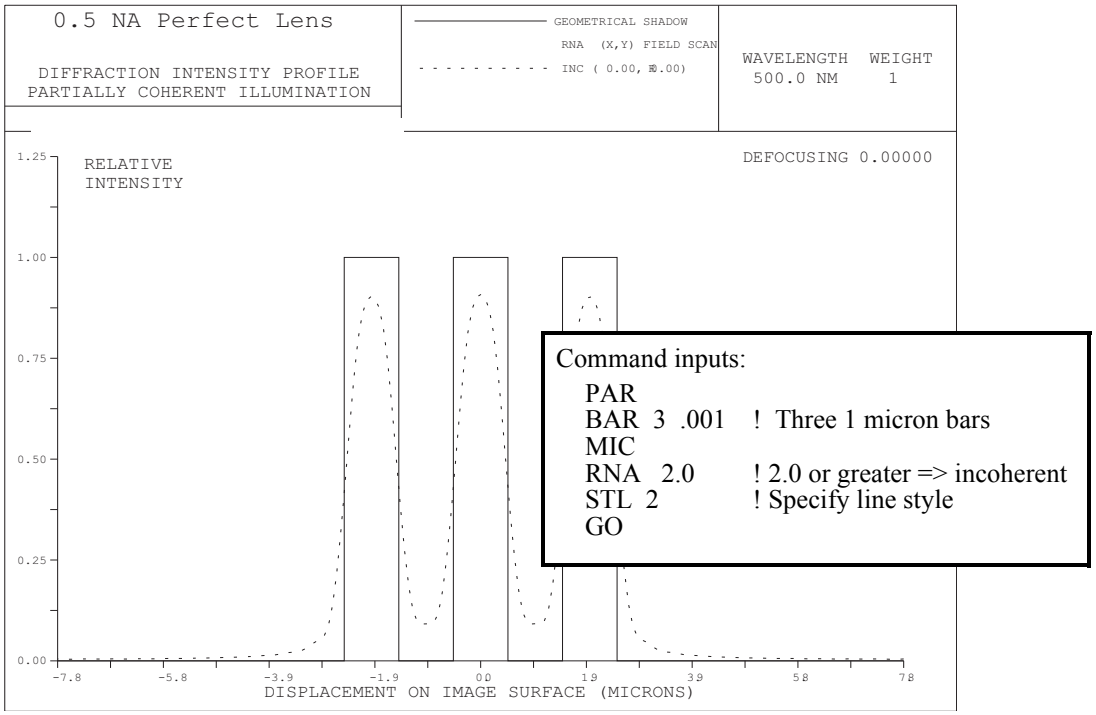

Figure 6. 1D PAR example for multi-bar object

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Example 4. Rectangular object definition

The following example illustrates how the rectangular object definition (RCN command) can be used to specify alternating phase-shift masks for a dioptric 1.1 numerical aperture 193 nm immersion lithography lens (U.S. Patent 6,891,596). The PAR output (see the following figure) shows imaging of dense 50 nm spaces.

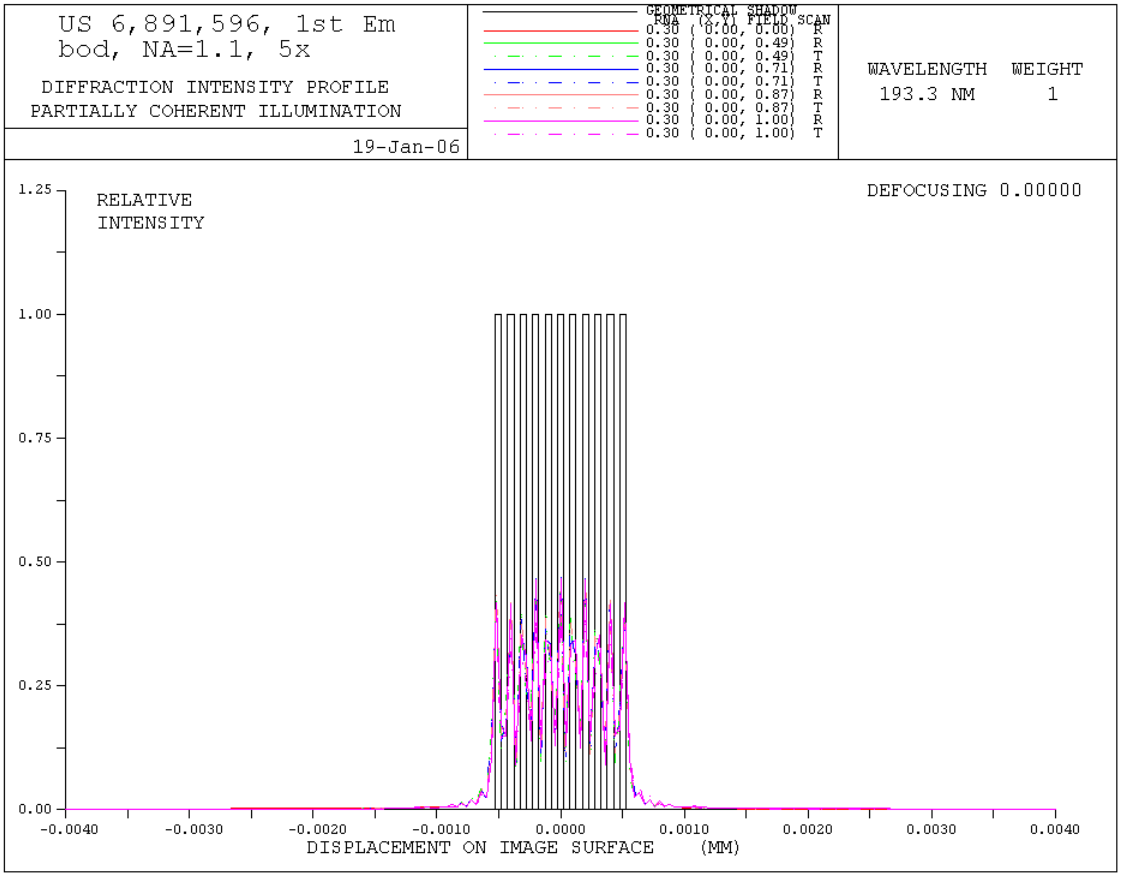

Figure 7. 1D PAR example for rectangular object definition (RCN)

The PAR commands to generate this plot are:

```
PAR
TGR 512
CON N
BAR 5 0.0001
PER 0.0002
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0005 + 0.0002*(^s - 1)) 1.0 0.0
RCN 0.00005 (-0.0004 + 0.0002*(^s - 1)) 1.0 180.0
RCN 0.00005 (-0.0004 + 0.0002*(^s - 1)) 1.0 180.0
RCN 0.00005 (-0.0004 + 0.0002*(^s - 1)) 1.0 180.0
RCN 0.00005 (-0.0004 + 0.0002*(^s - 1)) 1.0 180.0
RCN 0.00005 (-0.0004 + 0.0002*(^s - 1)) 1.0 180.0
BGI 0.0
BGP 0.0
NEG N
GRI .000015625
RNA .3
PLO
GO
```

Note: The RCN command overrides any previously entered 1D object parameters. In the example above, the BAR and PER commands are overridden by the RCN command entries that follow.

This example system is available on request from ORA Customer Service.

Example 5. Intensity transmittance

The following example illustrates how intensity transmittance (INN command) can be specified for an attenuated 1D phase-shift mask. The lens system is the same dioptric 1.1 numerical aperture 193 nm immersion lithography lens shown in Example 4

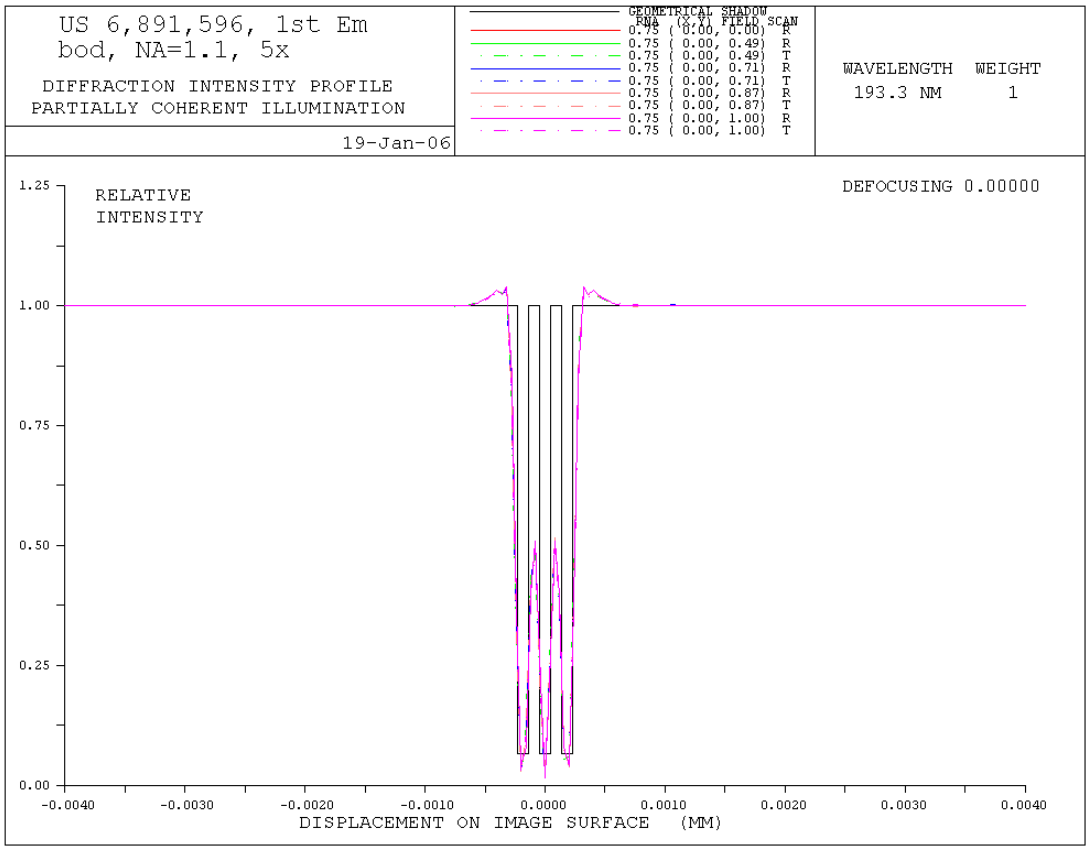

Figure 8. 1D PAR example for intensity transmittance (INN)

The PAR commands used to generate this output are:

```
PAR
TGR 512
CON N
BAR 3 0.00009
INN 0.065
PHN 180.0
PER 0.00018
BGI 1.0
BGP 0.0
NEG N
GRI .000015625
RNA .75
PLO
GO
```

This example system is available on request from ORA Customer Service.

Example 6. 2D PAR example of elbows in an integrated circuit design

This example is of several elbows such as might be found in an integrated circuit design. The goal would be to have the elbows as well differentiated as possible. The pattern is as follows.

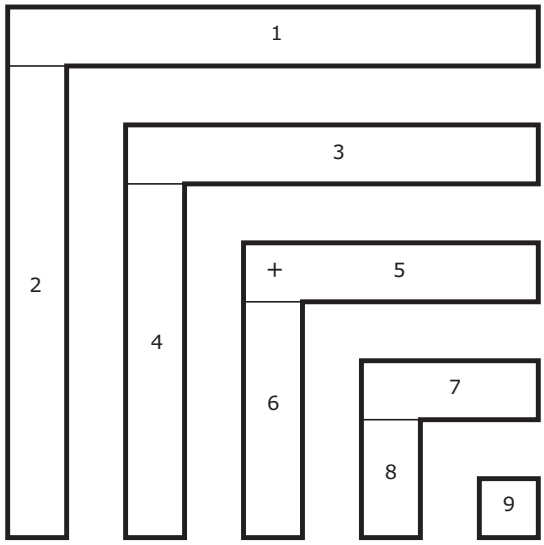

Figure 9. Elbow pattern for 2D PAR example

The pattern is shown by the outer dark lines. The center of the pattern is indicated by the +. Each line width is one micron (0.001 mm), and the spacing is also one micron. To model these elbows in PAR, each elbow is broken into rectangles, as indicated by the thinner lines and the rectangle numbers. The PAR inputs for this are as follows.

```
Command inputs:
   PAR
   RNA  1
   RCT  0.009  0.001   0.0000   0.0040          ! rectangle 1
   RCT  0.001  0.008  -0.0040  -0.0005          ! rectangle 2
   RCT  0.007  0.001   0.0010   0.0020          ! rectangle 3
   RCT  0.001  0.006  -0.0020  -0.0015          ! rectangle 4
   RCT  0.005  0.001   0.0020   0.0000          ! rectangle 5
   RCT  0.001  0.004   0.0000  -0.0025          ! rectangle 6
   RCT  0.003  0.001   0.0030  -0.0020          ! rectangle 7
   RCT  0.001  0.002   0.0020  -0.0035          ! rectangle 8
   RCT  0.001  0.001   0.0040  -0.0040          ! rectangle 9
   DIS  Y
   TIT  "2D PAR ELBOW PATTERN"
   GO
```

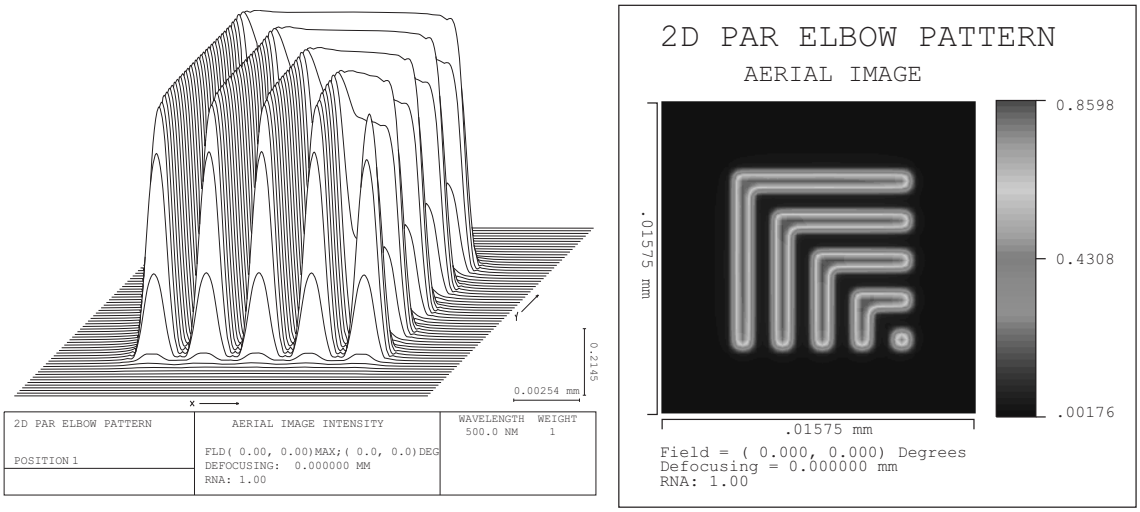

Figure 10. 2D PAR example of multiple elbows

We can also see how the image will degrade if the lens has spherical aberration. We will specify the lens to have 1 wave of spherical aberration at the edge of the pupil; this will give an RMS wavefront error of 0.082 waves, just above the 0.07 waves limit for what is often called the "functional equivalent" of diffraction-limited performance. As can be seen, this results in an unacceptable image, which would not be able to produce good lines in the IC photoresist.

Command inputs:

```
MCO S1 C11 1.0    ! Specify the module to have one wave of spherical aberration
PAR
RNA  1
RCT  0.009  0.001   0.0000   0.0040
RCT  0.001  0.008  -0.0040  -0.0005
RCT  0.007  0.001   0.0010   0.0020
RCT  0.001  0.006  -0.0020  -0.0015
RCT  0.005  0.001   0.0020   0.0000
RCT  0.001  0.004   0.0000  -0.0025
RCT  0.003  0.001   0.0030  -0.0020
RCT  0.001  0.002   0.0020  -0.0035
RCT  0.001  0.001   0.0040  -0.0040
DIS  Y
TIT  "2D PAR ELBOW PATTERN"
GO
```

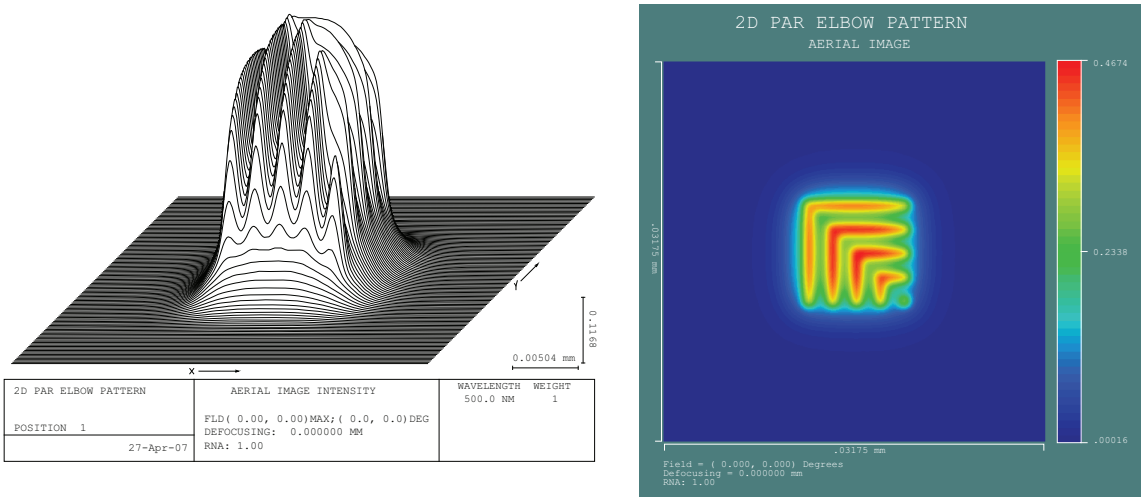

Figure 11. 2D PAR example of multiple elbows in the presence of spherical aberration

Example 7. 2D PAR example with rotated rectangle

This example is similar to Example 6, except some of the rectangles have been replaced by rotated rectangles. The pattern is as follows:

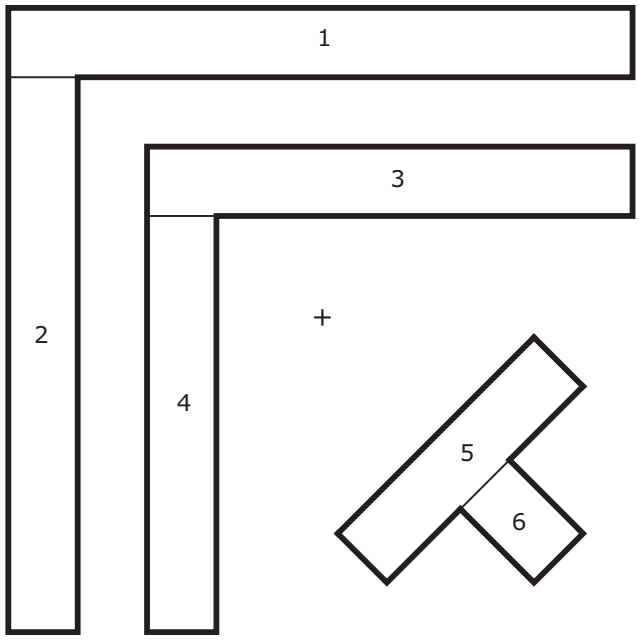

Figure 12. Rotated rectangle pattern for 2D PAR example

Again, the overall pattern of the 6 rectangles is shown by the dark outer lines and the center of the pattern is indicated by the +. The PAR inputs for this are as follows:

Command inputs:

```
   PAR
   RNA  1
!          X         Y         X          Y                              ROT
!        WID       WID       LOC        LOC        INT   PHA      ANGLE
RCT     0.009     0.001    0.0000     0.0040                                  ! Rectangle 1
RCT     0.001     0.008   -0.0040    -0.0005                                  ! Rectangle 2
RCT     0.007     0.001    0.0010     0.0020                                  ! Rectangle 3
RCT     0.001     0.006   -0.0020    -0.0015                                  ! Rectangle 4
RCT     0.004     0.001    0.0020    -0.0020      1.00    0.00     45.00      ! Rectangle 5
RCT     0.0015    0.001    0.002884  -0.002884    1.00    0.00    -45.00      ! Rectangle 6
   DIS  Y
   TIT "ROTATED BARS"
   GO
```

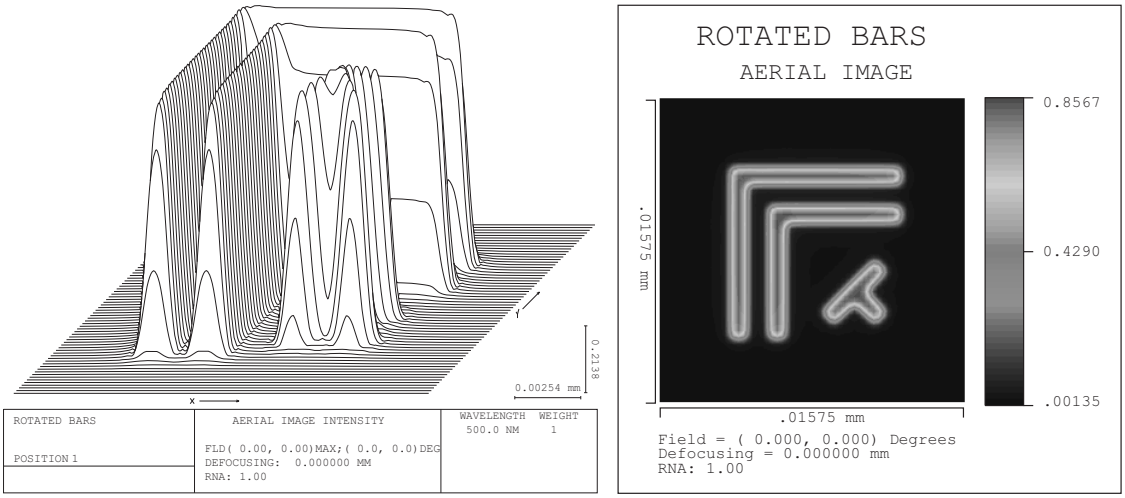

Figure 13. 2D PAR example with rotated rectangles

Example 8. Constant threshold CD

Here is an example of a perfect, single focus, 0.5 NA, λ = 500 nm system. Our goal is to find the CDs of the image of a four-bar test pattern at an image threshold of 0.3. Note that the "all" after the CDT command will find the CDs corresponding to all four of the bars for each field point. Also note that a Gaussian diffusion kernel of width 50 nm (DKP GAU 0.00002) has been employed.

```
LEN
TIT "Perfect lens, finite object, NA = .5, WL = 500, on-axis"
SO 0 10
S 0 -5
CIR 5.775
S 0 0
S 0 -5
STO
WL 500
NAO .5
CA APE
GO
POL N
FFO 0.000
IFO 0.000
NFO 1

PAR
TGR 512
CON N
BAR 4 0.0004
PER 0.0010
NEG N
GRI .000015625
RNA .75
CDT ALL 0.3
BOS N
DKP GAU 0.00005
PLO
GO
```

The output image (with convolution of the diffusion kernel) is as follows:

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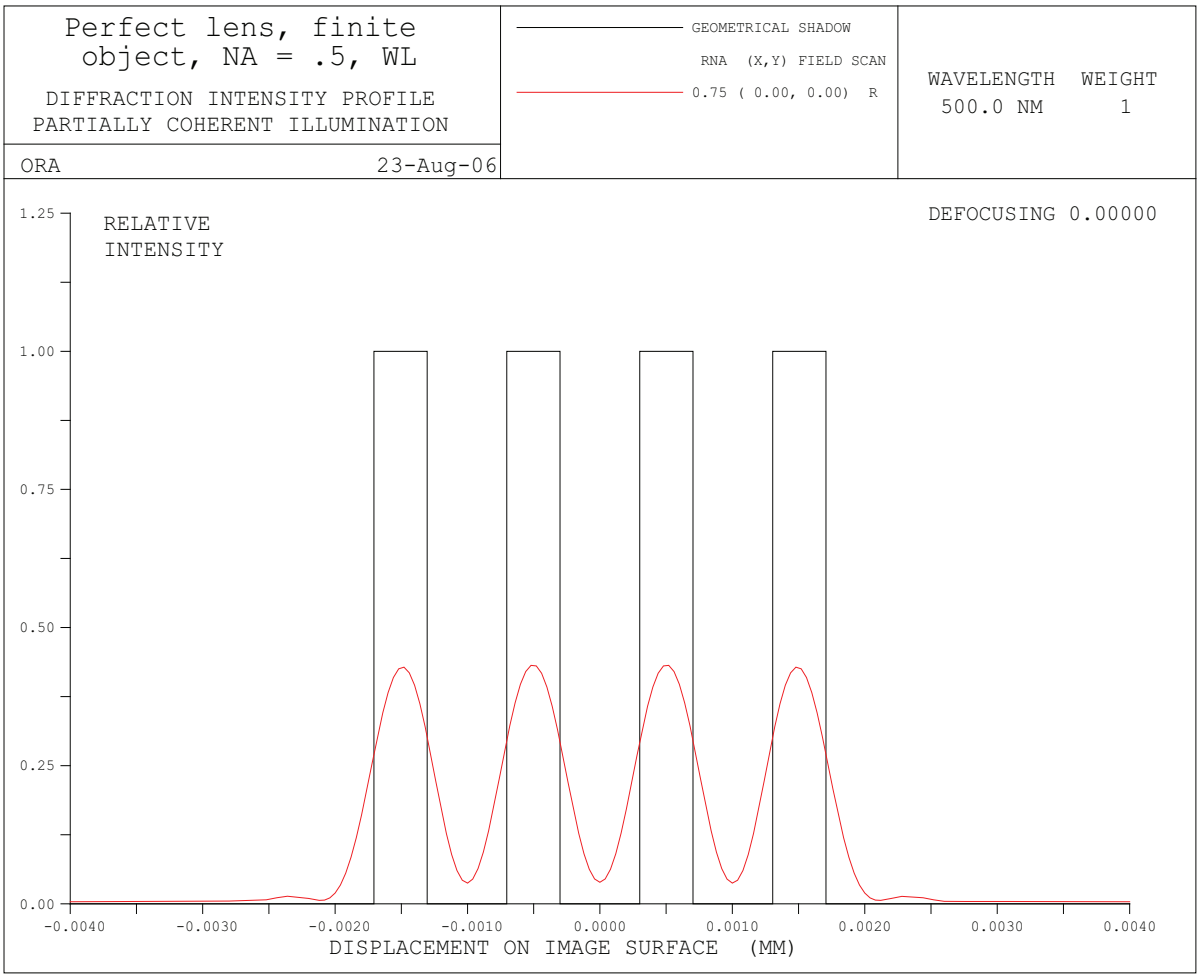

The diffusion kernel is Single Gaussian.

Width Parameters

Width 1	Width 2	Frac Width 1
0.050000	0.000000	0.000000

Linewidth Computation Results

Source				Bar	Linewidth (nm)		Line Center (nm)		Left/Right Log-slope (1/μm)	
#	Field	Focus	Dose	#	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.
1	1	0.00	3.33	1	377.57	377.57	13.36	13.36	3.84/ -3.99	3.84/ -3.99
1	1	0.00	3.33	2	391.37	391.37	-1.11	-1.11	3.93/ -3.90	3.93/ -3.90
1	1	0.00	3.33	3	391.37	391.37	1.11	1.11	3.90/ -3.93	3.90/ -3.93
1	1	0.00	3.33	4	377.57	377.57	-13.36	-13.36	3.99/ -3.84	3.99/ -3.84

Example 9. Lumped Parameter Model CD

We use the sequence in Example 8, but within the PAR block, we add the following command:

```
LPM 15.0 500.0 0.0002 0.00000002 60.0 1.0
```

The diffusion kernel is Single Gaussian

Width Parameters

Width 1	Width 2	Frac Width 1
0.050000	0.000000	0.000000

Linewidth Computation Results

Source				Bar	Linewidth (nm)		Line Center (nm)		Left/Right Log-slope (deg)	
#	Field	Focus	Dose	#	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.
1	1	0.00	3.33	1	410.71	410.71	13.14	13.14	91.59/ 88.44	91.59/ 88.44
1	1	0.00	3.33	2	426.10	426.10	-1.01	-1.01	91.50/ 88.50	91.50/ 88.50
1	1	0.00	3.33	3	426.10	426.10	1.01	1.01	91.51/ 88.51	91.51/ 88.51
1	1	0.00	3.33	4	410.71	410.71	-13.14	-13.14	91.56/ 88.41	91.56/ 88.41

Note that the slopes are now sidewall angles in degrees, instead of image log-slopes in 1/µm. Note also that the LPM does not affect the image intensity values.

Example 10. Lumped Parameter Model Dose-to-Size

We now modify the sequence used in Example 9 to find the dose that returns a linewidth of 400 nm through a focus range -1.0 to 1.0 µm, with five focus samples. The sequence is now:

```
LEN
TIT "Perfect lens, finite object, NA = .5, WL = 500, on-axis:
SO 0 10
S 0 -5
CIR5.775
S 0 0 BK7
S 0 -5
STO
WL 500
NAO .5
CA APE
GO
POL N

FFO -0.0010
IFO 0.0005
NFO 5
PAR
TGR 512
CON N
BAR 4 0.0004
PER 0.0010
NEG N
GRI .000015625
RNA .75
CDT N
BOS N
DKP GAU 0.00005
LPM 15.0 500.0 0.0002 0.00000002 60.0 1.0
DOS 0.0004
PLO
GO
```

The diffusion kernel is Single Gaussian.

Width Parameters

Width 1	Width 2	Frac Width 1
0.050000	0.000000	0.000000

Dose-to-Size Results

Focus	Dose-to-Size
-0.001000	3.309985
-0.000500	3.191246
0.000000	3.169812
0.000500	3.243098
0.001000	3.410131

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Example 11. Lumped Parameter Model Bossung Data

We modify the sequence in Example 10 to produce a set of linewidths from a process, which, at some nominal dose and focus, gives a linewidth of 400nm. The focus range is, again, -1.0 to 1.0, with five steps. The dose range will be -10% to 10% deviation from nominal dose, with a step of 5%. Note that the nominal dose is about 3.17 at 0.00 focus, which is the result from the previous section. The in-focus output is as follows: (Note: The bars from which the dose-to-size was computed are in bold type.)

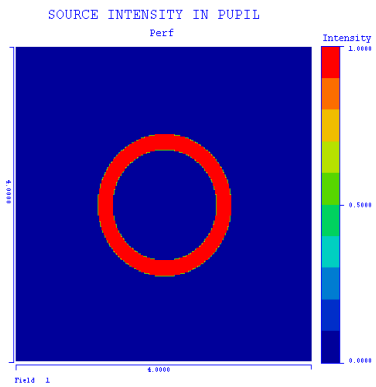
Linewidth Computation Results

	Source			Bar	Linewidth (nm)		Line Center (nm)		Left/Right Log-slope (deg)	
#	Field	Focus	Dose	#	Horiz.	Vert.	Horiz.	Vert.	Horiz.	Vert.
1	1	0.00	2.85	1	319.01	319.01	14.32	14.32	92.34/ 87.80	92.34/ 87.80
1	1	0.00	2.85	2	335.25	335.25	-1.23	-1.231	92.19/ 87.80	92.19/ 87.80
1	1	0.00	2.85	3	335.25	335.25	1.23	1.23	92.20/ 87.82	92.20/ 87.82
1	1	0.00	2.85	4	319.01	319.01	-14.32	-14.32	92.21/ 87.67	92.21/ 87.67
1	1	0.00	3.01	1	355.19	355.19	13.44	13.44	91.93/ 88.07	91.93/ 88.07
1	1	0.00	3.01	2	370.72	370.72	-1.08	-1.08	91.92/ 88.10	91.92/ 88.10
1	1	0.00	3.01	3	370.72	370.72	1.08	1.08	91.90/ 88.09	91.90/ 88.09
1	1	0.00	3.01	4	355.19	355.19	-13.44	-13.44	91.93/ 88/07	91.93/ 88/07
1	1	0.00	3.17	1	384.72	384.72	13.16	13.16	91.71/ 88.28	91.71/ 88.28
1	1	0.00	3.17	2	400.01	400.01	-1.02	-1.02	**91.69/ 88.32**	**91.69/ 88.32**
1	1	0.00	3.17	3	400.01	400.01	1.02	1.02	**91.68/ 88.31**	**91.68/ 88.31**
1	1	0.00	3.17	4	384.72	384.72	-13.16	-13.16	91.73/ 88.29	91.73/ 88.29
1	1	0.00	3.33	1	409.89	409.89	13.23	13.23	91.61/ 88.45	91.61/ 88.45
1	1	0.00	3.33	2	425.35	425.35	-1.03	-1.03	91.50/ 88.49	91.50/ 88.49
1	1	0.00	3.33	3	425.35	425.35	1.03	1.03	91.52/ 88.51	91.52/ 88.51
1	1	0.00	3.33	4	409.89	409.89	-13.23	-13.23	91.56/ 88.39	91.56/ 88.39
1	1	0.00	3.49	1	432.55	432.55	13.22	13.22	91.52/ 88.66	91.52/ 88.66
1	1	0.00	3.49	2	446.76	446.76	-1.24	-1.24	91.39/ 88.52	91.39/ 88.52
1	1	0.00	3.49	3	446.76	446.76	1.24	1.24	91.49/ 88.61	91.49/ 88.61
1	1	0.00	3.49	4	432.55	432.55	-13.22	-13.22	91.35/ 88.48	91.35/ 88.48

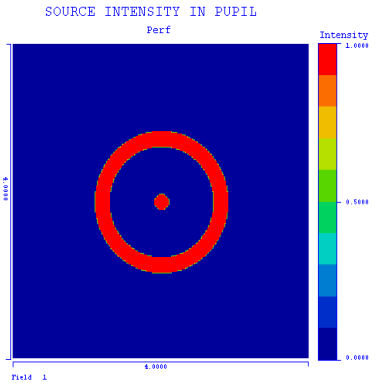
Example 12. Annulus and multi-pole source shape examples

Special forms of the SRC command allow you to define annular and multi-pole source shapes. The following figures show how these various forms can be defined, and include the SRC inputs used to define them.

Intensity Distributions of Annular Sources

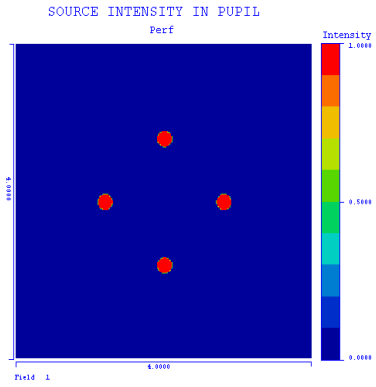


SRC ANN .7 .9

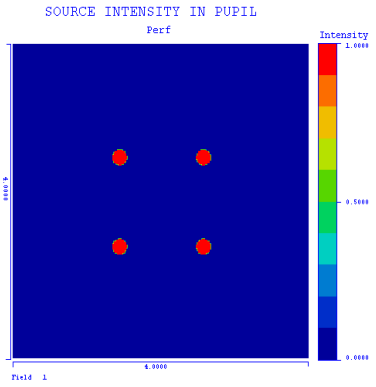


SRC ANN .7 .9
RNA .1

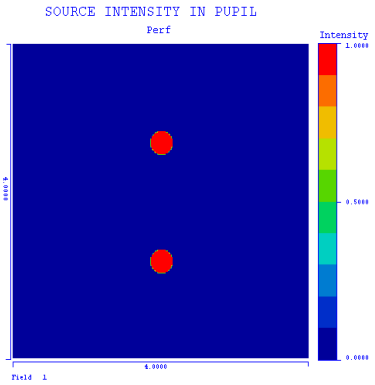
Intensity Distributions of Sources with Circular Poles



SRC CIR 4 .7 .9

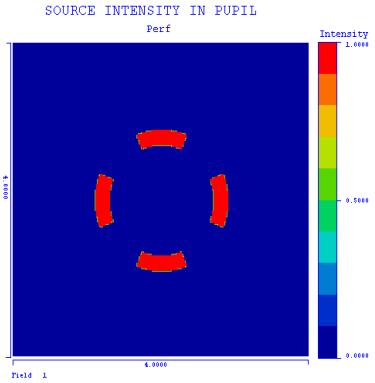


SRC CIR 4 .7 .9 45



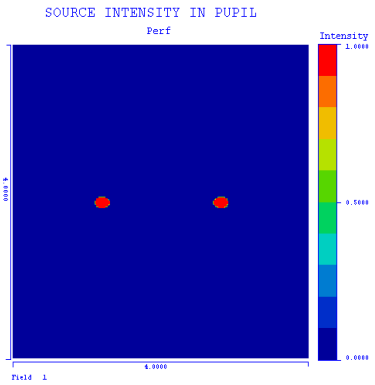
SRC CIR 2 .6 .9

Intensity Distribution of Source with Sector Poles

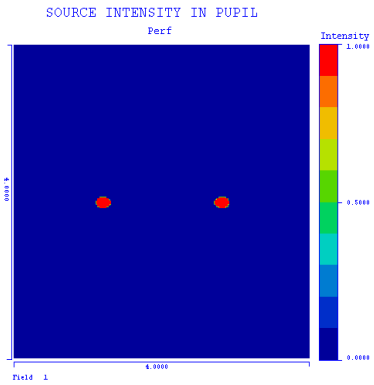


SRC SEC 4 .7 .9 45

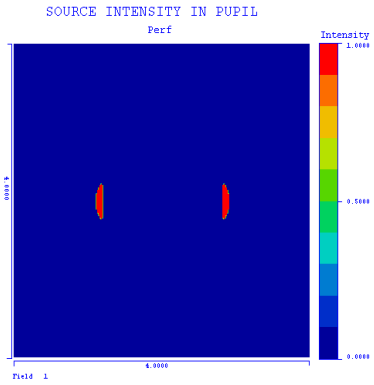
Intensity Distributions of Sources with Bun-Shaped Poles



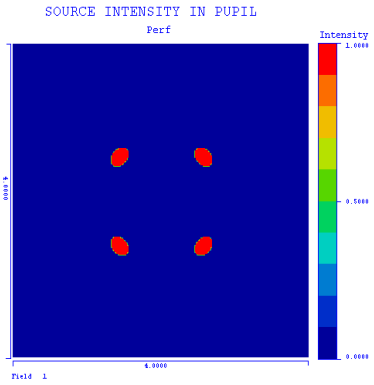
SRC BUN 2 .7 .9 10 90



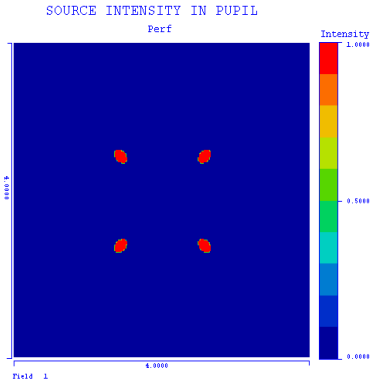
SRC BUN 2 .7 .9 30 90



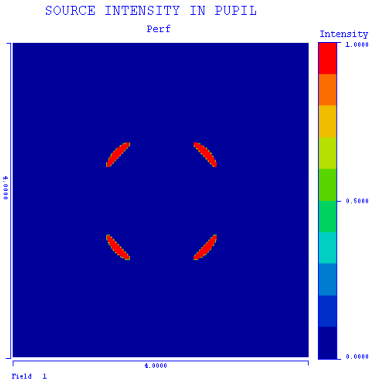
SRC BUN 2 .8 .9 30 90



SRC BUN 4 .7 .9 20 45



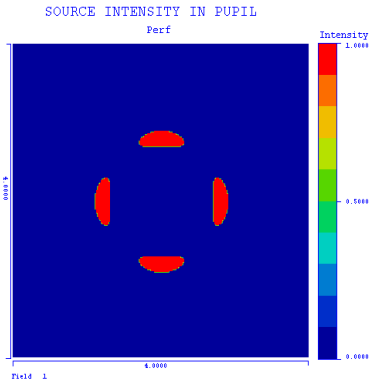
SRC BUN 4 .7 .9 10 45



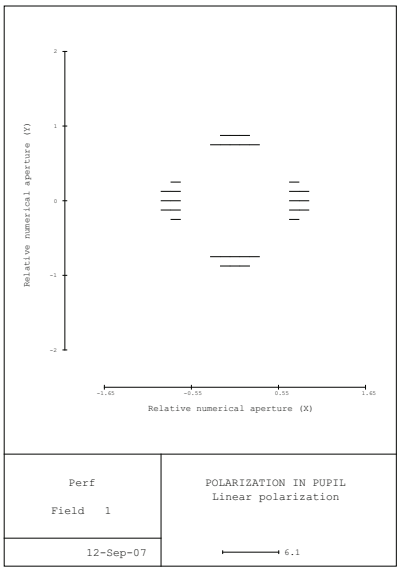
SRC BUN 4 .8 .9 30 45

Intensity Distribution and Polarization for Bun-Shaped Poles

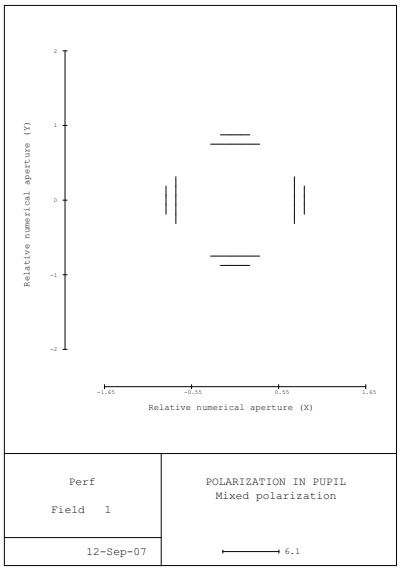
The following figures show the intensity distribution of a quadrapole illumination for a source with bun-shaped poles, along with three examples of polarization for this illumination: linear, mixed, and circular.



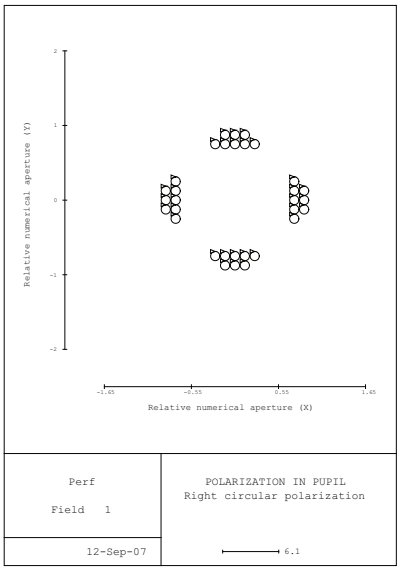
SRC BUN 4 .7 .9 45



SRC POL LIN



SRC POL MIX



SRC POL CIR

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 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 the reciprocal of the f-number). 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.

Bossung Calculation

A common experiment is to produce a focus-exposure matrix that illustrates the sensitivity of a lithography process away from some nominal dose and focus. In this case, one determines the dose-to-size for a desired critical dimension (CD) through some desired focus range. The best focus is then the focus at which there is a maximum or minimum (depending on the parity of the feature, line, or space) of the dose-to-size through-focus. Once these are determined, then the CDs are computed through the focus and the dose ranges are specified. (The dose ranges are expressed in percent deviations from the nominal dose-to-size, as the dose-to-size is not yet known.)

Curves of CD vs. focus for each dose are called Bossung curves, and are a common means to evaluate process sensitivities.

The Bossung calculation (BOS command) uses the dose-to-size computed at best focus for the center bar, even when a different bar is selected with the BOS command. If this is not an appropriate dose-to-size, you may enter the reciprocal of the desired dose-to-size using the BOS CDT command form.