PMA-Pupil Map

The Pupil Map (PMA) option displays functions in the exit pupil: wave aberrations, pupil intensity, surface codes for ray failure, HOE spatial frequencies, and properties of polarized beams.

When to Use the Pupil Map Option

Use the Pupil Map option to display maps of functions in the exit pupil, including wave aberrations, pupil intensity, surface codes for ray failure, HOE spatial frequencies, and properties of polarized beams. The output is produced separately for each wavelength and field angle. The Pupil Map option can also be used to check pupils used in Point Spread Function (PSF), Line Spread Function (LSF), and Partial Coherence (PAR) for corresponding inputs. See those options for a more complete discussion of FFT grid adjustment. Note that PMA will not give accurate results for non-imaging systems.

Default Operation

For each field point, wavelength and zoom position, and for the depth-of-focus values defined in the LDM (FFO, IFO, NFO), the wave aberrations in the exit pupil are displayed. This is represented as a listing of waves (multiplied by 100) in a 128 x 128 grid with the chief ray or optical axis as the center point on the grid. PMA uses Gaussian and user-defined apodization and polarization ray tracing if it is activated.

Command Mnemonics
(alphabetical)

ADD	ADW	BAC	COM	CON	DIS
GRI	HFR	LEV	LIS	NRD	PIN
PLO	PPH	RAC	RAN COL	RAN SCA	ROT
SIZ	SSI	TGR	TIT	WIN	WBF
XSC	Y	YC	ZFR	ZRN	

Defining Display Settings

You can define settings that change the Pupil Map default display from wave aberration to one of the following: pupil intensity, ray failure, HOE spatial frequency, or polarization phase effects.

To define these display settings, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays with the **Display** tab in the foreground. Define the controls on the **Display** tab as described in the table below.

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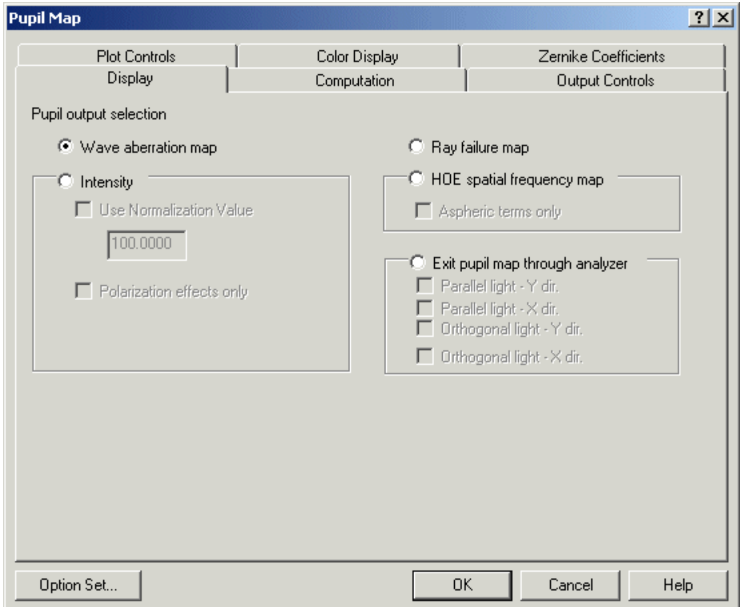

Command Syntax		
Screen Control	**Explanation**	**Default**
PIN [POL] Yes | No | norm_value....z		
Pupil Output Selection: Wave aberration map Intensity	**Wave aberration map** Specifies that the default wave aberration map is generated. **Intensity** Selects pupil intensity map, replacing the default wave aberration map. Includes effects of Gaussian and user-defined apodization, and diffraction efficiency for all blazed grating types (kinoform, step, sinusoid, volume hologram). If polarization ray tracing is active (POL in LDM), polarization-dependent transmission effects (e.g. Fresnel losses) are included. **Use Normalization Value** Specifies scale of pupil intensity map. Range: 1-9999. Default: 100. **Polarization effects only (POL)** Displays **only** polarization-dependent losses.	Wave aberration map (PIN No).
RAC Yes | No....z		
Ray failure map	Selects ray failure map (replaces wave aberration map). Maps the surface numbers at which rays failed to pass through to the image surface; obscurations are indicated by negative surface numbers. Is a zoomable parameter; right-click over the button to access the **Zoom Editor**.	No.

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<table>
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<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">HFR [ASP] Yes | No....z</td></tr>
<tr><td>HOE spatial frequency map</td><td>Selects HOE spatial frequency map (replaces wave aberration map). Maps lines/mm measured on the HOE surface for the surface area used by the beam at each field as projected on the exit pupil; assumes only one HOE is in the system. Is a zoomable parameter; right-click over the button to access the Zoom Editor.

Aspheric terms only (ASP)

Specifies that only the aspheric phase terms (departure from two point HOE) are displayed.</td><td>No.</td></tr>
<tr><td colspan="3">PPH [YP1] [XP1] [YP2] [XP2]</td></tr>
<tr><td>Exit pupil map thru analyzer</td><td>Selects polarization phase effects map (replaces wave aberration map), the result of phase differences between S and P components at each interface, introduced by coatings, metallic reflectors, and polarization operators. In general, all 4 maps are needed to characterize fully phase behavior over the pupil when input light is partially polarized, as defined by PTP, POR, PRO (in LDM):

YP1

Specifies exit pupil analyzer assumed to be parallel to Y axis (default).

XP1

Specifies exit pupil analyzer assumed to be parallel to X axis.

For input light orthogonal to the state defined by PTP, POR, PRO:

YP2

Specifies exit pupil analyzer assumed to be parallel to Y axis.

XP2

Specifies exit pupil analyzer assumed to be parallel to X axis.

Results are displayed in waves of phase difference modulo ± 0.5 wave.</td><td>Not run by default.</td></tr>
</table>

Note: If you submit multiple PIN, RAC, HFR, PPH commands on the command line, only the last of these commands given is executed.

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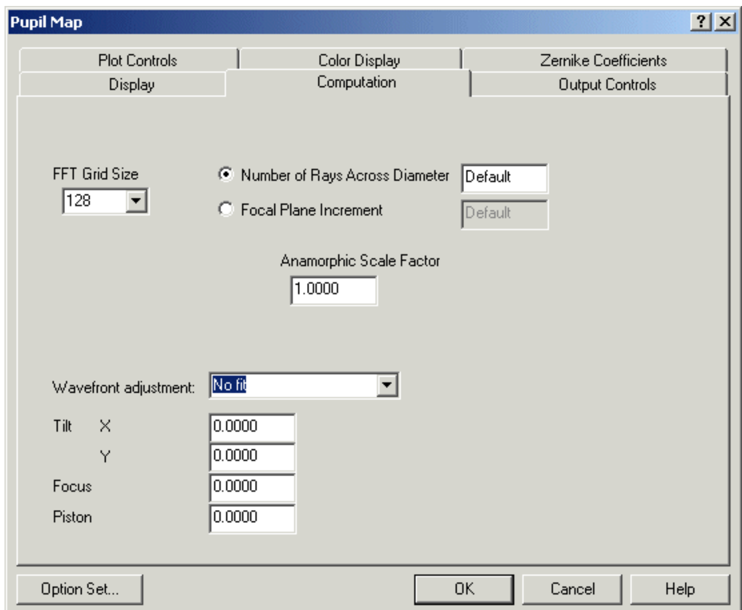
Defining Computation Controls

There are several computation controls that you can modify for the Pupil Map option, including altering the pupil grid, reducing pupil sampling points in the X or Y directions, and modifying the wavefront. You can also specify how you want the option's text output to be displayed.

To define these computational controls, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays. Click the **Computation** tab. Define the controls on the **Computation** tab as described in the following table.



Command Syntax		
Screen Control	**Explanation**	**Default**
TGR num_fft_grid_pow_of_two		
FFT grid size (power of 2)	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. Can be adjusted to match operating conditions of PSF, LSF, or PAR options.	128
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. Can be adjusted to match operating conditions of PSF, LSF, or PAR options. Use either this setting or **Focal plane increment** (GRI), but not both. Is a zoomable parameter; right click over the field to access the **Zoom Editor**.	TGR/2 at short wavelength.

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<table>
<tr><th colspan="3">Command Syntax</th></tr>
<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">GRI image_grid_spacing....z</td></tr>
<tr><td>Focal plane increment</td><td>Specifies grid spacing measured on the image surface. Is an alternative to Number of rays across diameter (NRD). Can be adjusted to match operating conditions of PSF, LSF, or PAR options. Use either this setting or Number of rays across diameter (NRD), but not both. Is a zoomable parameter; right-click over the field to access the Zoom Editor.</td><td>Shortest wavelength * fnumber/2. (Airy disc diameter for shortest wavelength spans 4.88 grid increments regardless of TGR value.)</td></tr>
<tr><td colspan="3">XSC scale_x_psf_by_factor....z</td></tr>
<tr><td>Anamorphic scale factor</td><td>Scales X dimension of image by specified factor. Used to handle highly anamorphic exit pupils. The largest (X or Y) numerical aperture of the exit pupil is used to establish default values for Focal plane increment/Number of rays across diameter settings (GRI/NRD); this may lead to insufficient sampling in either the X or Y dimension, depending on which was largest. Use anamorphic scale factor setting (XSC) to scale up the X dimension of the image, which correspondingly reduces the number of pupil sampling points in the X direction, and vice versa. Ex: XSC 2 scales the X dimension of the image by 2, GRI is also scaled by 2, or NRD by 0.5. The value will be written to the header of any files created with WIN.

Is a zoomable parameter; right-click over the field to access the Zoom Editor.</td><td>1.0</td></tr>
<tr><td colspan="3">ADW x_tilt_waves [y_tilt_waves [focus_waves [piston_waves]]]
or ADW TIL | FOC [x_tilt_waves [y_tilt_waves [focus_waves [piston_waves]]]]</td></tr>
<tr><td>Wavefront adjustment</td><td>Adds tilt, focus, and piston to the wavefront; permits a match to measured maps or changes to a more useful display. Units are waves in the traced wavelength at the edge of the paraxial entrance pupil. Select one of the following Wavefront adjustment options before entering values into the data fields:

• Select Best fit tilt (TIL) to find the best-fit tilt and piston.

• Select Best fit focus (FOC) to find the best-fit focus, tilt and piston.

Tilt X/Tilt Y

Specifies tilt value added to wavefront in X and Y directions.

Focus

Specifies focus value added to wavefront.

Piston

Specifies piston value added to wavefront.</td><td>Not done.</td></tr>
</table>

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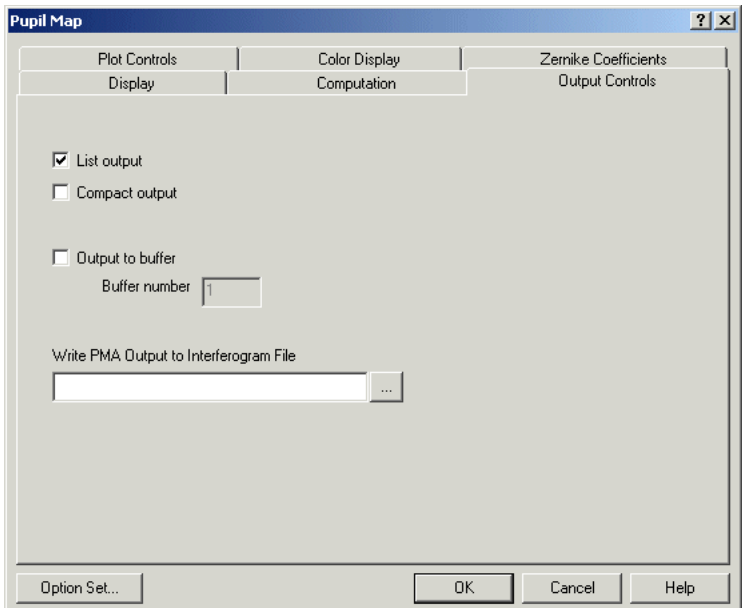
Defining Output Controls

The output controls available for the Pupil Map option allow you to specify how the listed grid is displayed, as well as specify when you want to write PMA output to a buffer or interferogram file.

To define these output controls, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays. Click the **Output Controls** tab. Define the controls on this tab as described in the following table.



Command Syntax		
Screen Control	**Explanation**	**Default**
LIS Yes | No....z		
List output	Turns off listed output when only plotting is wanted (No). Is a zoomable parameter; right-click over the button to access the **Zoom Editor**.	Yes.
COM Yes | No....z		
Compact output	Cancels blank lines between grid rows that make vertical and horizontal scales equal (Yes). Is a zoomable parameter; right-click over the button to access the **Zoom Editor**.	No.

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Command Syntax		
Screen Control	**Explanation**	**Default**
WBF Bk		
Output to buffer/ Buffer number	Writes the PMA output to the specified buffer (except B0). Buffer will contain header information and PMA output. The default is to write wavefront aberration output, consisting of a grid of OPDs across the pupil. In addition, the following output is written when these commands are specified: – Pupil intensity (PIN Y) – Ray failure (RAC Y) – HOE spatial frequency (HFR Y) – Polarization phase effects (PPH) Note that WBF acts independently of LIS.	Not done.
WIN int_filename		
Write PMA Output to Interferogram File	Writes wavefront aberration, pupil intensity (**PIN**), or wavefront phase (**PPH**) data to a file named *int_filename*.INT (see “Generating Files for Other Programs” on page 18-144). If you selected **Standard** (ZRN) or **Fringe** (ZFR) on the **Zernike Coefficients** tab (see “Defining Zernike Coefficients Controls” on page 18-138), the file format will be in Zernike coefficient form. If you used neither of these settings, the file format will be grid type, which is mapped to the exit pupil sphere (EXS). Generates separate maps, with ascending version numbers, for each successive field and wavelength. Inoperative if **Ray failure map** (RAC) or **HOE spatial frequency map** (HFR) outputs are requested.	No files written.

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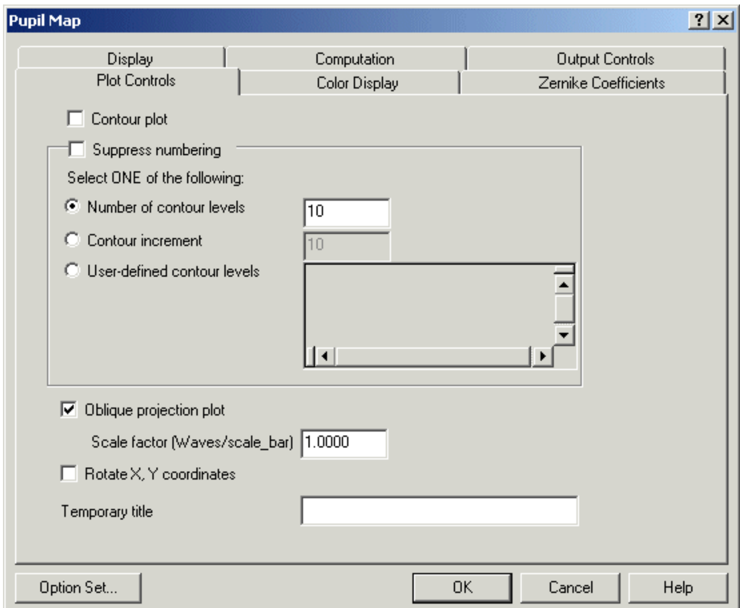
Defining Plotting Controls

The plotting controls available for the Pupil Map option allow you to specify how you want graphical output to be displayed.

To define these plotting controls, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays. Click the **Plot Controls** tab. Define the controls on the **Plot Controls** tab as described in the table below.



<table>
<tr><th colspan="3">Command Syntax</th></tr>
<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">CON [SUP] Yes | No....z</td></tr>
<tr><td>Contour plot</td><td>Plots wavefront aberration, pupil intensity (PIN), or wavefront phase (PPH) as a single page contour plot for each wavelength, field, and zoom position (not turned off with No), with numbered contours. Contour numbers are 100 x the plotted quantity. Is a zoomable parameter; right-click over the button to access the Zoom Editor.</td><td>No.</td></tr>
<tr><td>Suppress numbering</td><td>Suppresses display of contour numbering (SUP).</td><td>Yes.</td></tr>
</table>

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Command Syntax		
Screen Control	**Explanation**	**Default**
LEV [contour_level...30] or **LEV INC** contour_increment or **LEV NUM** num_contour_levels		
Select ONE of the following:	Use only with **Contour plot** (CON). Specify contours with one of the following settings: **Number of contour levels** (LEV) Specifies up to 30 values for plotted contours. Omitting values returns the field to the default: 10. **Contour increment** (LEV INC) Specifies equal separation of contours between minimum and maximum levels. **User-defined contour levels** (LEV NUM) 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.	Number of contour levels: 10 (LEV NUM 10)
PLO Yes | No....z		
Oblique projection plot	Plots wavefront aberration, pupil intensity (**PIN**), or wavefront phase (**PPH**) as a single page oblique projection plot for each wavelength, field, and zoom position (not turned off with No). Is a zoomable parameter; right-click over the button to access the **Zoom Editor**.	Yes.
SSI quantity_per_scale_bar....z		
Scale factor (Waves/scale bar)	Use only with **Oblique projection plot** (PLO). Specifies vertical scale size in datum quantity per scale bar length (25 mm for M, C lens units, 1 inch for I lens units when printed or plotted). Will be automatically reduced if vertical excursion of worst wavelength and field exceeds 2 scale bars. Is a zoomable parameter; right-click over the field to access the **Zoom Editor**.	Automatically scaled so maximum excursion for all wavelengths and fields is 1 scale bar.
ROT Yes | No....z		
Rotate X, Y coordinates	Use only with **Oblique projection plot** (PLO). Rotates oblique projection plot 90° in X-Y plane, to reveal hidden features. Is a zoomable parameter; right-click over the button to access the **Zoom Editor**.	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 designated, the title is applied to all. To zoom, right-click over the field to access the **Zoom Editor**.	Uses the first 40 characters of the system title.

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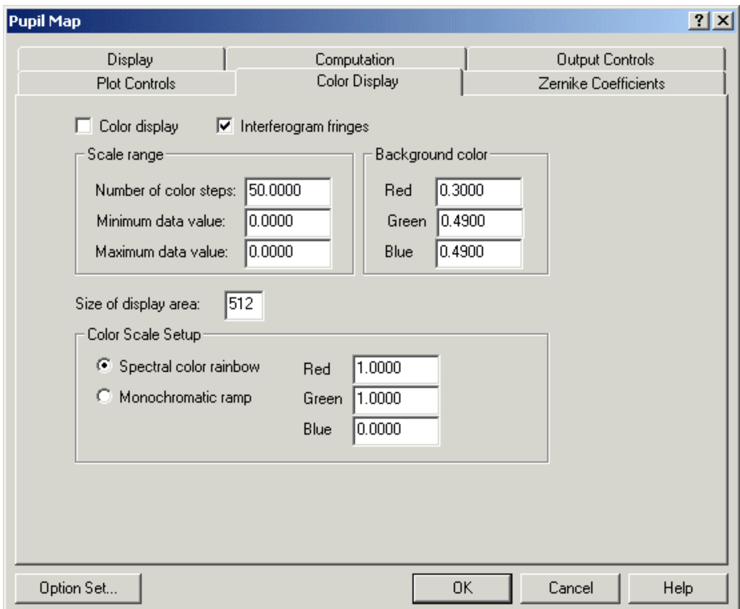
Defining Color Display Settings

The color display settings available for the Pupil Map option allow you to control the colors used for graphical output.

To define these color display settings, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays. Click the **Color Display** tab. Define the controls on the **Color Display** tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
DIS [INT] Yes | No....z		
Color display	Displays wavefront aberration, pupil intensity (**PIN**), or wavefront phase (**PPH**) as a colored contour map for each wavelength, field and zoom position (No suppresses for that zoom position). Different values are represented by different colors. This may only be displayed on devices that support color raster displays.	No.
Interferogram fringes	Displays data as interference fringes, where the reference is uniformly flat (INT). Use a monochromatic color ramp (RAN COL RGB) for best appearance.	Yes.

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Command Syntax		
Screen Control	**Explanation**	**Default**
RAN SCA num_steps [min_value max_value]		
Scale range	Use only with the **Color display** setting (DIS). Specifies the scaling of the data range. **Number of color steps** Specifies number of color steps into which the data range is divided. **Minimum data value** Specifies minimum data value included in data range. **Maximum data value** Specifies maximum data value included in data range. If the minimum and maximum values are omitted, the entire data range is shown. For interferogram-like displays (DIS INT), the min_value is ALWAYS 0.0 and max_value is used to determine the datum quantity/fringe to be displayed. For example, when wavefront aberrations are plotted, RAN SCA 50 0.0 0.1 will display a pattern with one fringe for every tenth of a wave of aberration; the default is one fringe per wave.	Number of color steps: 50 (RAN SCA 50)
RAN COL SPE | RGB [r_value g_value b_value]		
Color scale setup	Use only with the **Color display** setting (DIS). Specifies the type of color scale to be used to display the data. **Spectral color rainbow** (SPE) Selects a spectral color rainbow (blue to green to red). **Monochromatic ramp** (RGB) Selects a monochromatic color ramp from black to the specified **Red**, **Green**, and **Blue** values. Using this setting with the **Color display** and **Interferogram fringes** settings (DIS INT) creates the appearance of an actual interferogram. **Red/Green/Blue** Adjusts the individual red, green, and blue components used in the monochromatic color ramp. The default red, green and blue values are 1.0, 1.0 and 0.0, which creates a yellow ramp.	Spectral color rainbow (RAN COL SPE)
SIZ max_pixels		
Size of display area	Use only with the **Color display** setting (DIS). Specifies the maximum dimension, in pixels, of the rectangular area into which the data is drawn.	512
BAC r_value g_value b_value		
Background color	Use only with the **Color display** setting (DIS). The **Red**, **Green**, and **Blue** fields specify 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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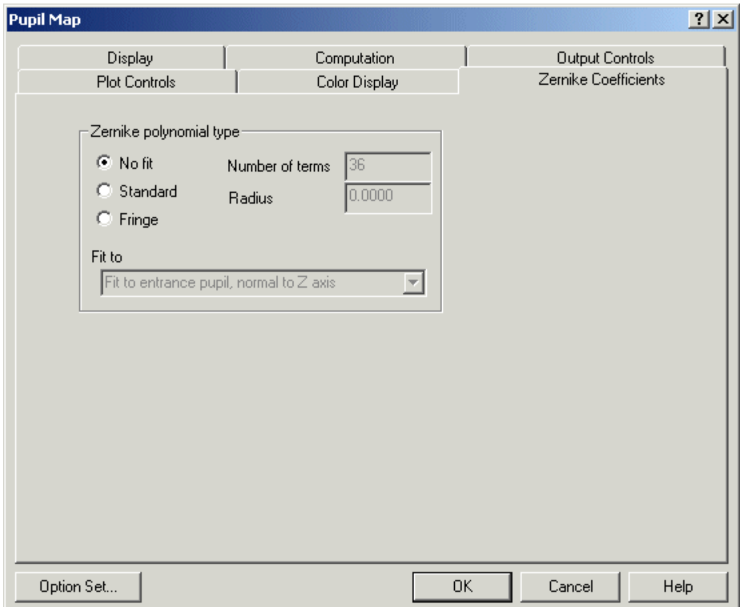
Defining Zernike Coefficients Controls

To define controls that fit PMA’s wavefront aberration, pupil intensity, or wavefront phase data to a Zernike polynomial, choose the **Analysis** > **Diagnostics** > **Pupil Map** menu. The **Pupil Map** dialog box displays. Click the **Zernike Coefficients** tab. Define the controls on this tab as described in the following table.



<table>
<tr><th colspan="3">Command Syntax</th></tr>
<tr><th>Screen Control</th><th>Explanation</th><th>Default</th></tr>
<tr><td colspan="3">ZRN [EXP | EXS] num_terms [radius]
or ZFR [EXP | EXS] num_terms [radius]</td></tr>
<tr><td>Zernike polynomial type</td><td>Fit the wavefront aberration, pupil intensity (PIN), or wavefront phase (PPH) for each field and wavelength to a Zernike polynomial.
No fit
Specifies that no fit is performed (default).
Standard (ZRN)
Selects standard Zernike polynomial.
Fringe (ZFR)
Selects fringe Zernike polynomial.
Note: Zernike polynomials are listed in “Zernike Polynomials” on page C-1.</td><td>No fit done.</td></tr>
<tr><td>Number of terms</td><td>Specifies number of terms in Zernike polynomial (see description in “Defining Interferometric Deformations and Intensity Apodization” on page 10-9).</td><td>1</td></tr>
<tr><td>Radius</td><td>Normalizes the polynomial with respect to the radius value (in lens units). If radius value is omitted, the polynomial is normalized with respect to the pupil radius.</td><td>0.00</td></tr>
</table>

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Command Syntax		
Screen Control	**Explanation**	**Default**
Fit to	Selects how the wavefront aberration, pupil intensity, or wavefront phase for each field and wavelength are fitted to a Zernike polynomial. **Fit to entrance pupil, normal to Z axis** Fit with respect to normalized **entrance** pupil coordinates centered on and measured in a direction perpendicular to the Z axis. **Fit to exit pupil plane, normal to chief ray (EXP)** Fit with respect to normalized **exit** pupil coordinates centered on and measured in a direction perpendicular to the chief ray. **Fit to exit pupil sphere (EXS)** Fit with respect to normalized **exit** pupil sphere coordinates centered on and measured in a direction perpendicular to the image surface normal at the chief ray intersection.	Fit to entrance pupil, normal to Z axis.

Defining a Perturbed Wavefront

Using the following commands, you can add a wavefront perturbation to the entrance pupil at a selected field and wavelength. See “Perturbed Wavefront Analysis” on page 18-145 for more details about this capability.

Command Syntax		
Screen Control	**Explanation**	**Default**
ADD Fn [Wm] [B | Q]		
Command line only.	Adds 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 Pupil Map option with the same TGR and NRD or GRI. Symmetry can be designated to reduce the number of Y, YC commands as follows: **B** Specifies bi-lateral symmetry in X; give only the left half of the pupil grid, including the center column and row (TGR/2 + 1). **Q** Specifies quadrant symmetry; give only the upper left quadrant of the pupil grid, including the center column and row (TGR/2 + 1). Use neither B nor Q for no symmetry; give all columns and rows.	No perturbation.

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Command Syntax		
Screen Control	**Explanation**	**Default**
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

In general, no additional LDM data needs to be entered for the Pupil Map option; if the effect of polarized input beams is to be analyzed (intensity, or **PIN**; exit pupil map through analyzer, or **PPH**), then the POL flag should be turned on in the LDM to activate this extra computation; if the input beams have apodization, and/or are polarized, the effects will be included. If you wish to do through-focus analyses, enter the LDM data for depth of focus (FFO, IFO, NFO).

Display Selections

You can change the PMA default display of wave aberration to one of the following (only the last will be executed if more than one is requested):

- **Pupil intensity (PIN).** Includes effects of Gaussian and/or user-defined apodization, Bragg diffraction efficiency in volume HOEs, if any, and polarization, if POL switch in the LDM is on. Note that the scale of values can be selected. The **Polar. effects only** button (POL qualifier) permits display of the effect on pupil intensity of polarization only. Pupil intensity can be used to analyze "leakage" in a system with crossed polarizers, by you including the analyzer in the system as a surface polarizer on an appropriate dummy surface, entered in the LDM.

- **Ray error code (RAC).** Displays an entrance pupil map showing the surface numbers at which each ray is clipped by the system by vignetting or obscuration. Negative numbers indicate obscurations.

- **HOE spatial frequency (HFR).** Displays a map of the spatial frequency of the fringes (phase terms), in lines/mm as a function of projected position in the exit pupil; it is assumed that there is only one HOE in the system. With the **Aspheric terms only** setting (ASP qualifier), only the aspheric phase terms (departure from two point HOE) are displayed.

- **Polarization phase effects (PPH)**. Displays, in 4 maps as projected on the exit pupil, the wavefront for X and Y polarization in waves, caused by coatings, metallic reflectors, surface polarizers or retarders; includes any polarization of the input beam. The intensity of the light over the pupil is given with the **Polar. effects only** button (**PIN** POL command), described above. Without you doing it, the 4 maps of polarization phase automatically assume a polarization analyzer (linear polarizer) has been added in the exit pupil to sort out the components parallel to X and Y axes; in combination, input beams can be assumed to be as defined or orthogonal to that defined in the LDM. See Chapter 9, *Defining Polarization* for details and examples regarding polarized light.

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In PMA, the polarization phase maps combine the geometrical optics phase with the polarization phase. This can result in multiple 2π (1 wave) phase discontinuities that can cause errors when fitting wavefronts to Zernike polynomials. CODE V attempts to remove these phase discontinuities when polarization ray tracing is activated (POL Y). This allows CODE V to fit wavefronts with Zernike polynomials more accurately. Note that phase unwrapping can sometimes fail when the pupil intensity at sample points is very small. CODE V will detect where the phase unwrapping fails, and will issue a warning message. PMA will then list and/or plot the wrapped phase map.

Grid Alteration

Though the Pupil Map option does not actually perform an FFT, its pupil grid can be specified as if an FFT were done in order to match the operating conditions of FFT-based options (Point Spread Function (PSF), Line Spread Function (LSF), and Partial Coherence (PAR)). Thus we can speak of the "image grid spacing" even though Pupil Map does not actually calculate anything on the image surface.

The FFT grid size (**TGR**), number of rays across the pupil diameter (**NRD**) or its alternate, the image grid spacing (**GRI**), can all be adjusted as in actual FFT-based options. Use either **GRI** or **NRD**, but not both. Refer to the Point Spread Function documentation for a more complete description on choice of values for these parameters.

Anamorphic Pupils

The largest (X or Y) numerical aperture of the exit pupil is used in establishing default values for **GRI**/**NRD**. This may lead to insufficient sampling in either X or Y, depending on which is larger. You can scale up the X dimension of the image (**XSC**), which correspondingly reduces the number of pupil sampling points in the X direction, and vice versa.

Example:	XSC 2	! Scales the X dimension of the
		! image by 2, and the GRI or NRD by 0.

Modifying the Wavefront

In the Pupil Map option, tilt, focus, and piston can be added to the wavefront (with the **Wavefront adjustment** setting, or **ADW** command) prior to display or plotting. This can be used, for example, to simulate the appearance of an interferogram with tilt, focus, or piston. Units are in waves (in the traced wavelength) at the edge of the paraxial entrance pupil. Tilt is equivalent to shifting the image location by Δx and/or Δy on the image surface. Focus corresponds to a Δz shift of the image point. Piston corresponds to a uniform shift of the OPD across the whole pupil. The amount of waves to be added with the wavefront adjustment corresponding to these linear shifts is given by:

$$\text{Tilt\_x (waves)} = \Delta x/(2F\lambda)$$

$$\text{Tilt\_y (waves)} = \Delta y/(2F\lambda)$$

$$\text{Focus (waves)} = \Delta z/(8\lambda F^2)$$

where λ is the traced wavelength and F is the paraxial f/number. Select **Best fit tilt** in the **Wavefront adjustment** field (or use the TIL qualifier with the **ADW** command) to remove average tilt. Or select **Best focus/tilt** in this field (FOC qualifier) to remove average tilt and focus. Either one of these selections, or one or more of the tilt/focus/piston values, or both, must be given to modify the wavefront.

Fitting Data to Zernike Polynomials

Within the Pupil Map option, you may fit the wavefront aberration (Default), pupil intensity (**PIN**), or wavefront phase (**PPH**) data to a standard Zernike (**ZRN**) or FRINGE Zernike (**ZFR**) polynomial. This can be done in the GUI on the **Interferogram** tab in the **Diagnostic Option PMA** dialog box. A separate fit is done for each field and wavelength. For either type of Zernike fit, the coordinate system used depends on the qualifier given.

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If no qualifier is given, the Zernike fit is done with respect to normalized entrance pupil coordinates. These entrance pupil coordinates are located on a plane perpendicular to the Z axis in object space and located at the real entrance pupil (where the chief ray crosses or comes closest to the Z axis). The radius used for the Zernike fit, unless otherwise specified, is the paraxial entrance pupil radius.

If you select **Fit to exit pupil plane, normal to chief ray** (EXP qualifier) in the **Fit to** field, the Zernike fit is done with respect to normalized exit pupil plane coordinates. This is shown in Figure 1. The exit pupil plane is tangent to the reference sphere where the chief ray crosses it. The exit pupil plane Z axis is located along the chief ray and the exit pupil plane X and Y axes are perpendicular to the chief ray. The exit pupil plane coordinates for an arbitrary ray are where the ray intersects the exit pupil plane.

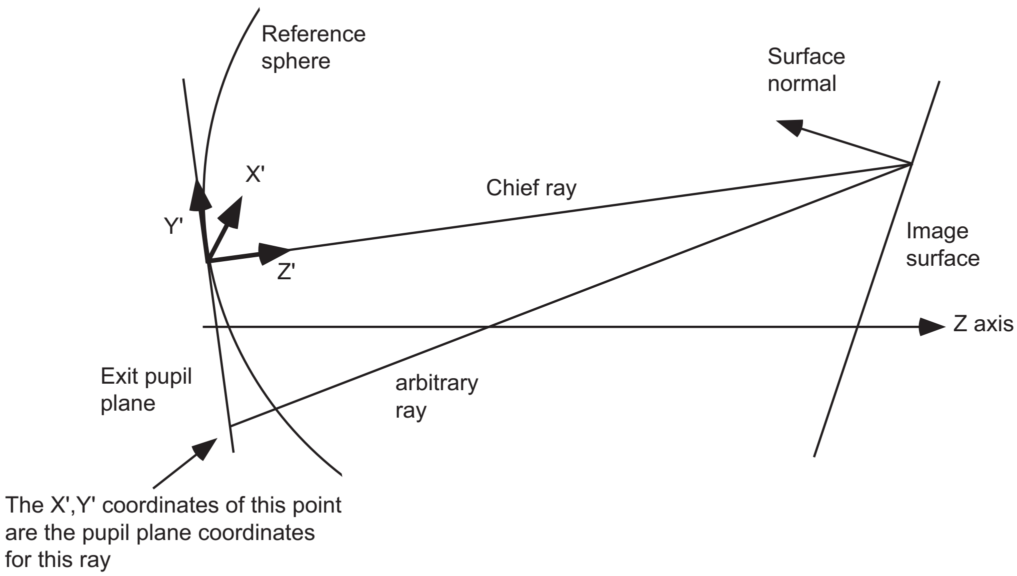

Figure 1. Exit pupil plane coordinates used for Zernike fits

If you select **Fit to exit pupil sphere** in the **Fit to** field (EXS qualifier), the fit is done with respect to exit pupil sphere coordinates. This is shown in Figure 2. The origin of the exit pupil sphere coordinate system is where the chief ray crosses the reference sphere. The pupil sphere Z axis is parallel (or antiparallel) to the vector normal to the image surface at the point where the chief ray intersects the image surface. The pupil sphere X and Y axes are perpendicular to the pupil sphere Z axis. The exit pupil sphere coordinates for an arbitrary ray are the coordinates where the ray intersects the reference sphere. These are essentially direction cosine coordinates with respect to the chief ray.

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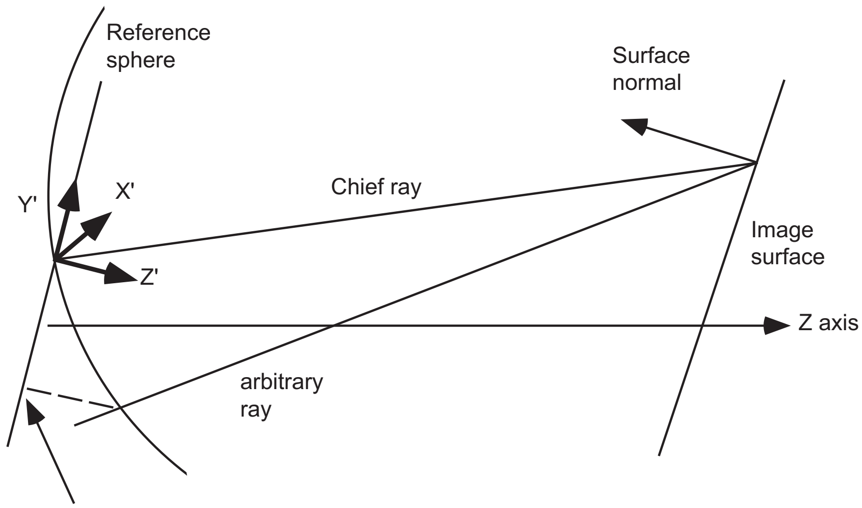

Figure 2. Exit pupil sphere coordinates used for Zernike fits

For both the EXP and EXS Zernike fits, the normalization radius used, unless otherwise specified, is based on the reference rays. The four outer reference rays are traced to the appropriate coordinate system, and the radial dimension of the reference ray with the largest radial dimension is used as the normalization radius. Thus, in general, the default normalization radius will be different for each field and wavelength. For all Zernike fits, the normalization radius used is listed; in addition for EXP fits the reference ray information is listed.

If Zernike outputs are produced for attaching to the exit pupil at a later time, then the EXP form is preferred, as CODE V attaches interferograms to the exit pupil plane. If the Zernike outputs are to be used by a macro or an external program to compute PSF or some other diffraction-based image metric, then it is more useful to use the EXS form. Note that there should only be significant differences between the two forms for fast systems.

The behavior of the coordinate system used for Zernike fitting should be noted. In order for the reference rays maintain a consistent definition as the rays propagate through the system, we define the coordinate system for the pupils such that it rotates by 180 degrees when the pupil moves through infinity. It should also be noted, however, that the coordinate systems that are used for constructional surfaces of the system (lenses, mirrors, as well as dummy surfaces) do **not** flip or rotate when you go through focus.

Note: Either **ZFR** or **ZRN** may be entered on the command line, but not both. Polynomial fitting is done using traced rays which are typically distributed over a rectangular grid. Since Zernike polynomials are defined on a unit circle, the fit is an approximation to a Zernike fit, usually a very good one. In some cases, small discrepancies from expected results may arise. For example, for a rotationally symmetric axial wavefront, the Zernike fit in PMA sometimes shows small, non-zero values for coefficients 11, 23, etc., in the standard Zernike polynomial. These are terms which depend on cos (4θ), cos (8θ), etc., and the non-zero values are attributable to a square grid being used. The terms become smaller as more rays are traced.

See also: “Zernike Polynomials” on page C-1.

Generating Files for Other Programs

Images sometimes need to be analyzed by other programs outside of CODE V. To facilitate this, use the **Write PMA Output to Interferogram File** field on the **Output Controls** tab (**WIN** command). This feature allows writing of wavefront aberration (default), pupil intensity (**PIN**), or wavefront phase (**PPH**) data to a file. There is one file for each field point and wavelength, separated as files only by ascending version numbers. Be careful about purging files before renaming them, if you want to keep them. The file format will be Zernike coefficients if you have used **ZRN** or **ZFR**, or grid form otherwise. If **XSC** is used, the value is written to the interferogram file header.

See“INT File Format” on page 10-30 or the *CODE V Prompting Guide* for more information on file formats.

PMA output (wavefront aberration, intensity, ray failure, HOE spatial frequency, and polarization phase effects) can also be written to a buffer (**WBF** command). The data in the buffer can then be utilized by a macro, or exported (BUF EXP) for further analysis outside of CODE V. The WBF command writes the PMA output to the specified buffer (not B0). The buffer will contain header information (e.g., grid size grid increment, and wavelength identifier) and PMA output. The default behavior is to write wavefront aberration output. The WBF command acts independently of the LIS command.

Listing Controls

The listed grid displays include two blank lines between grid rows to make the vertical and horizontal scales equal. These blank lines can be cancelled for a more compact output matrix with the **Compact output** setting (**COM**). The listed output can be suppressed altogether by de-selecting the **List output** checkbox (LIST N) when only plotting is wanted.

Plotting Controls

Three types of graphical output are available in the Pupil Map option:

- A “three-dimensional” oblique projection plot (**PLO**)
- A contour “map” (**CON**)
- A color display of the contour “map” (**DIS**)

These commands can be used for plotting wavefront aberration (Default), pupil intensity (**PIN**), or wavefront phase (**PPH**) data.

3-Dimensional Oblique Projection Plots

When a 3-D projection plot is requested (**Oblique projection plot** setting, or **PLO**), the Pupil Map option scales the vertical height so that maximum deviation for all field angles of a zoom position is one inch. This may be reduced to improve visibility of the plotted data or altered to match a desired scale. This vertical scale factor is entered in the **Scale factor (Waves/scale bar)** field on the **Plot Controls** tab, or with the **SSI** command, as the datum quantity to correspond to one scale bar of vertical height in the field corresponding to the desired zoom position (note: 1 scale bar = 1 inch or 25mm when printed or plotted). These values will be overridden if any entered value would cause a vertical excursion of greater than 2 scale bars. In this case the scale is reduced to allow 2 scale bars as the maximum value (see Figure 3 in *Description of Output*).

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

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Contour Plotting

As an alternative to the projection plot, contour mapping of the data can be requested (**Contour plot** setting, or **CON**). The contour lines will be numbered unless suppressed (**Suppress numbering** setting, or **CON** SUP). Ten levels between minimum and maximum with reasonable rounding of the increment are the default. The user may specify up to 30 contour levels (**LEV** n..30), the **Contour increment** (**LEV** INC n) and override the number of contour levels (**LEV** NUM n). Levels will be integral multiples of the contour increment. The number of levels plotted may change by one due to rounding.

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

Color Display

Another alternative in the Pupil Map option to either the projection plot or the line contour mapping is a color contour map of the data (**Color display** setting or **DIS**) or a simulation of an interferogram (**Interferogram fringes**, or **DIS** INT). For the color contour map, different colors represent different values. The number of colors used and the range of values may be controlled with the **Scale range** setting, or **RAN SCA** command. A larger number of colors will give a continuous color gradation, whereas a smaller number will show contour edges better, giving a more quantitative effect. For the interferogram simulation, the interference fringes between the data map and a uniformly flat reference are displayed. The scale range may be used to select the datum quantity per fringe to be displayed. The data values or interferogram fringes may be colored either by a **Spectral color rainbow**, red to green to blue (**RAN COL** SPE), or a monochromatic color ramp, black to a specified color (**RAN COL** RGB). For best appearance, the monochromatic color ramp should be used with the interferogram simulation (**DIS** INT). The maximum size of the rectangular plot area can be set (**Size of display area**, or **SIZ**), and the background color outside the data display area can be specified (**Background color**, or **BAC**). As with the line contour mapping, tilt and focus can be added to the wavefront with the **Wavefront adjustment** setting or **ADW** command. The plot output for this mode is controlled by the **RGR** command.

Perturbed Wavefront Analysis

A wavefront 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 prior to PSF or LSF, 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 with the Y CONTINUE command (**YC**).

Note: In many cases it is easier to define a perturbed wavefront as a simulated interferogram (.INT file) applied to a dummy surface. Zernike polynomials or grid data can be used. (See “INT File Format” on page 10-30).

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Description of Output

Each computational sub-option in the Pupil Map option (default, pupil intensity, ray failure map, HOE spatial frequency map, exit pupil map) produces its own labeled two-dimensional grid display representing the particular function in the exit pupil, for each field and zoom position. Plots of the wavefront aberration (default), pupil intensity (**PIN**), or wavefront phase (**PPH**) data can be added. The plot options are contour (**CON**), oblique projection (**PLO**), or color display (**DIS**). The coordinate system employed in the displays and plots is +Y in the vertical direction, and +X horizontally to the right, as viewed looking from behind the image surface, into the lens toward the -Z direction. Listings can be suppressed (**LIS** N) or compressed (**COM**). See Examples below.

Examples

Example 1. Pupil map (oblique projection) of a Cassegrain system, including obscuration.

Only output for field 2 is shown. (Text output not shown) (Figure 3).

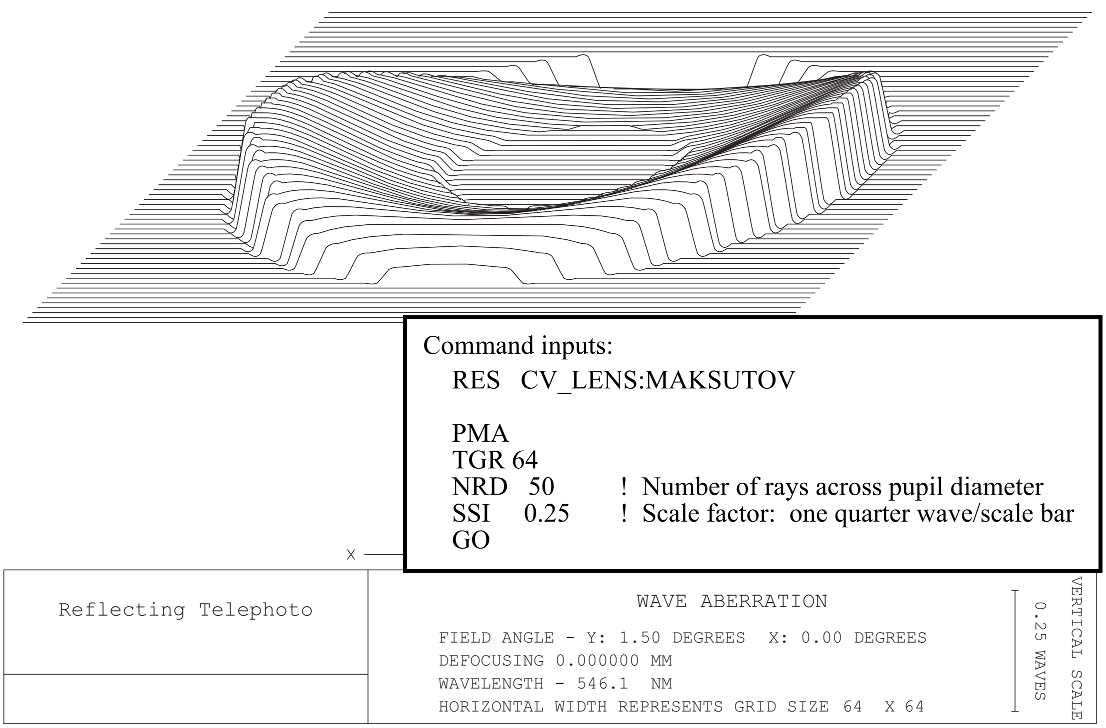

Figure 3. PMA perspective plot

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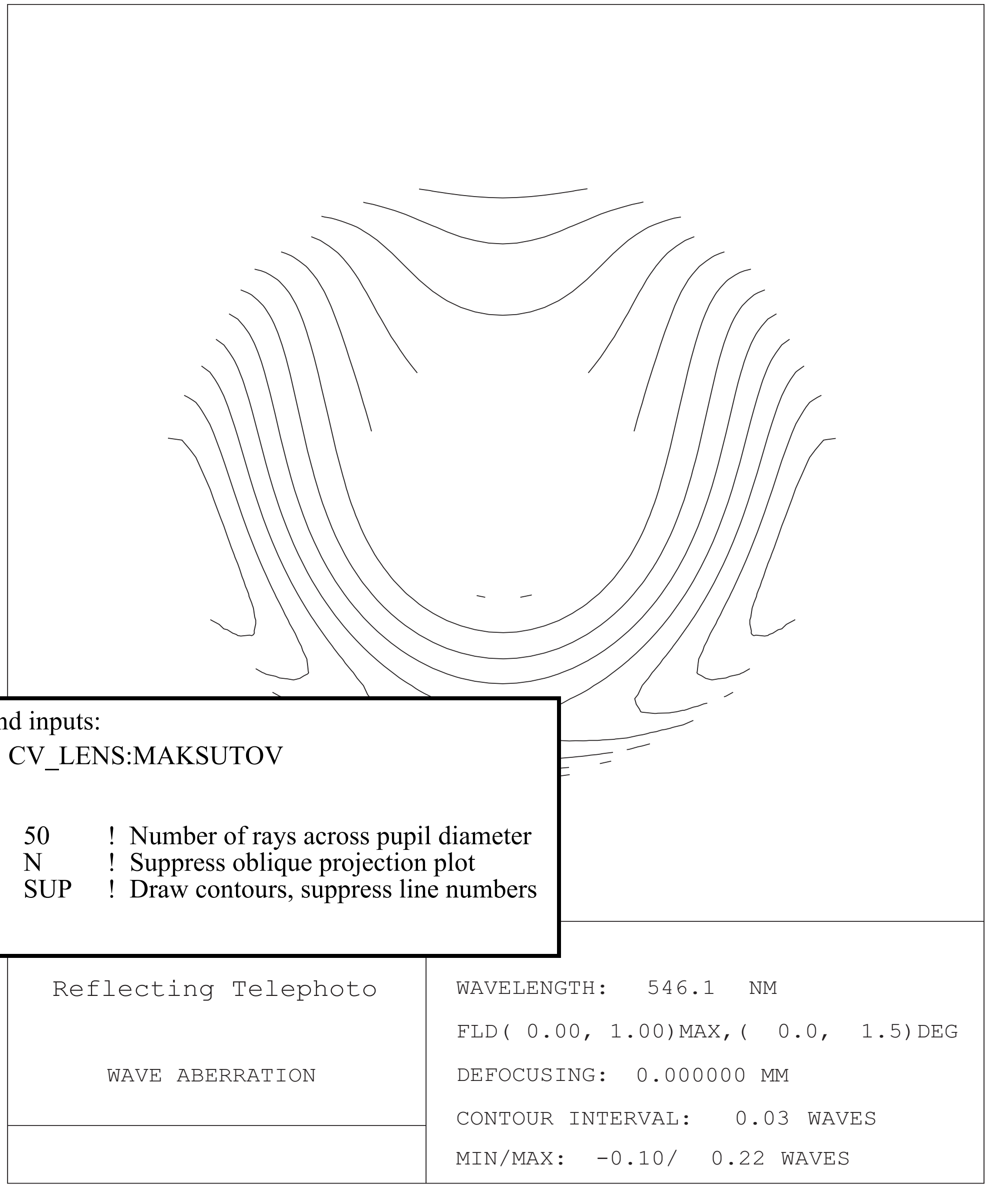
Example 2. Pupil map (contour) of the same Cassegrain system, including obscuration.

Only the output for field 2 is shown (Figure 4).



Command inputs:

```
RES   CV_LENS:MAKSUTOV

PMA
NRD   50    ! Number of rays across pupil diameter
PLO   N     ! Suppress oblique projection plot
CON   SUP   ! Draw contours, suppress line numbers
GO
```

Figure 4. PMA contour plot with numbers suppressed

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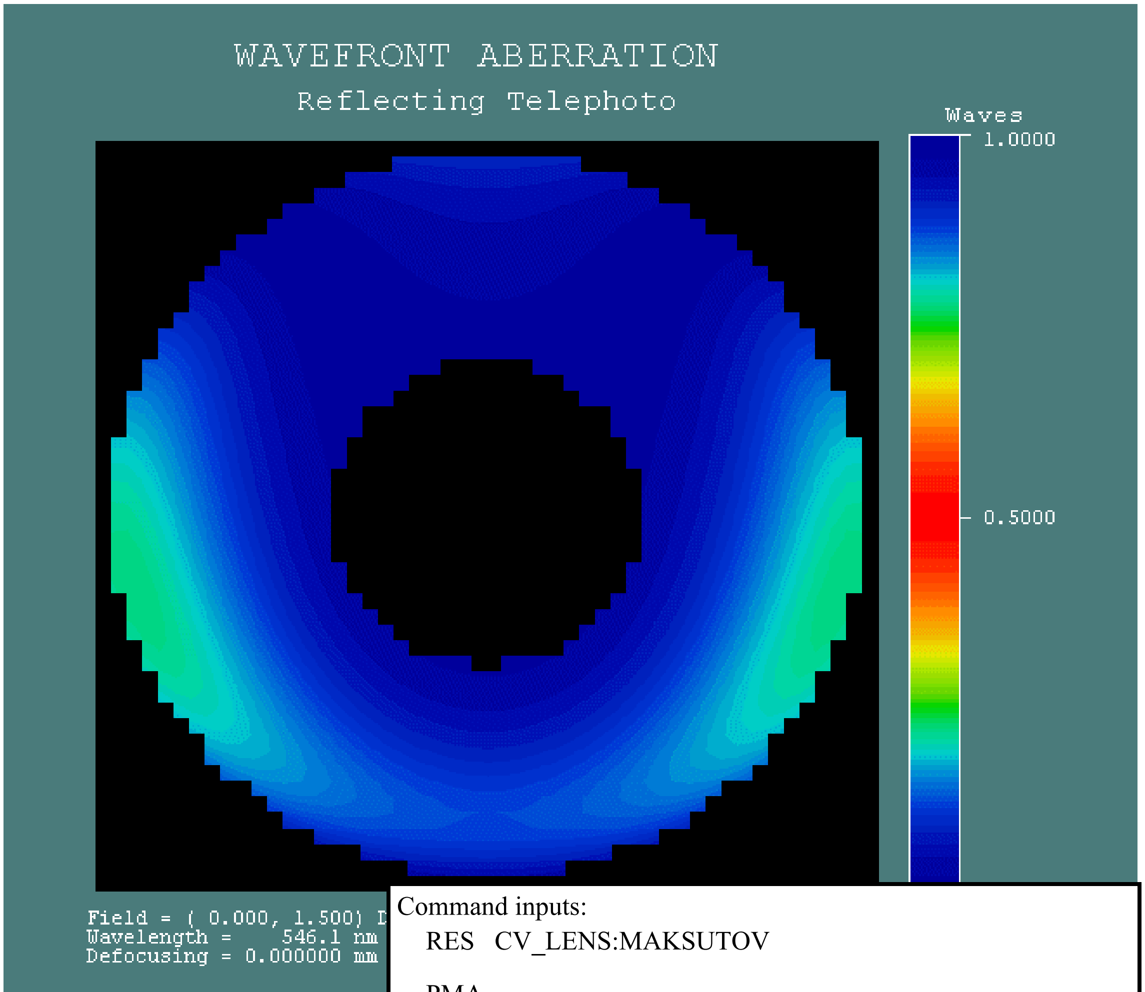
Example 3. Same as Example 2 with data drawn as interference fringes.



Command inputs:

```
RES   CV_LENS:MAKSUTOV

PMA
NRD   50
PLO   N                 !  Suppress oblique projection plot
DIS INT Y               !  Draw data as interference fringes
GO
```

Figure 5. PMA raster display output

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Example 4. Interferometric Analysis - using standard Zernike polynomial (output not shown).

```
Command inputs:
   INT   S1   MEAS1        !  Assign interfer. data file "MEAS1.INT" to surface S1
                           !  (LDM command)

   PMA
   TGR   32                !  Transform grid size adjusted
   ZRN   36                !  Fit with standard Zernike, with 36 terms
   WIN   ZRN36             !  Write coefficients to file "ZRN36.INT"
   COM                     !  Compact output (abbreviated listing)
   GO
```

Example 5. Listed output for PMA.

The listed output for PMA consists of a table of wavefront aberration (Default), pupil intensity (**PIN**), ray failure (**RAC**), spatial frequency (**HFR**), or wavefront phase (**PPH**) data across the pupil. A separate table is generated for each wavelength, through-focus position, field, and zoom position.

At the start of the output is the standard output header for all diffraction-based options with X and Y focal lengths (or magnifications) and f/numbers for each field and zoom position, plus the listing of the reference sphere values used.

After this is the table of the selected output for each grid position across the pupil at which there is data. (Note that in the default case, the **NRD** is one-half the **TGR**, and hence data are only generated for a portion of the transform grid positions).

If the PMA output is for wavefront aberration, then after the output table is a listing of the RMS OPD across the pupil. The first number listed is for the raw data. The second line lists the RMS OPD with tilt removed from the wavefront, along with the shift of the image position corresponding to the tilt removal. The third line is the RMS OPD with both tilt and focus removed, along with the corresponding shifts.

If Zernike fitting has been requested, the fit is listed below the OPD table. The coefficients are grouped by order. Refer to "Defining Interferometric Deformations and Intensity Apodization" on page 10-9 for a description of the defining equations for the Zernikes.

The following is a partial listing of the standard double Gauss lens specified at the second field for the reference wavelength, with a Zernike fit at the exit pupil.

Note: In the output, pupil increments are represented by DX and DY. These are actually direction cosine increments, and should more properly be designated DL and DM.

```
Command inputs:
   RES  CV_LENS:DBGAUSS
   YAN 10
   WL 587.6
   PMA
   TGR  32               ! Use a smaller TGR so the entire map can be seen in one table
   COM                   ! Eliminate the blank lines
   ZRN  EXP  36          ! Zernike fitting
   GO
```

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```
APERTURE STOP
              SEMI-DIAMETER =    15.910845
                (Based on the maximum reference ray height at the stop.)


    X and Y focal lengths for each field angle

       X         0.101790E+03
       Y         0.104589E+03


    X and Y F-numbers for each field angle

       X         2.035795
       Y         2.091785


    Reference sphere radius for each field angle

                0.117768E+03


    Optimum increment in image plane is  0.0005981 units.
    Actual  increment in image plane is  0.0005981 units.
    Transform grid size is   32 x   32


         POSITION 1        WAVE OPTICS WAVE ABERRATION

           Double Gauss - U.S. Patent 2,532,751
                                                                WAVELENGTH   WEIGHT  NO. OF RAYS  PUPIL GRID
     FIELD (X,Y) = ( 0.00, 1.00)MAX, (  0.00, 10.00)DEG     587.6 NM       1        205       17 x  15
     DEFOCUS =   0.000000 MM.

    AVERAGE INCREMENTS ON ENTRANCE PUPIL (LENS UNITS)
          DX = (  3.125010,  0.000000)
          DY = (  0.000000,  3.210957)
    Wave aberrations in hundredths of wavelength     587.6NM
         RMS =   4.045 waves       P-V =   21.029 waves
 SUM OF VALUES =  34312.
       7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26   27

 10                                   -1414 -790 -494 -408 -494 -790-1414
 11                         -1438 -399   82  287  365  384  365  287   82 -399-1438
 12                    -1044  -11  389  501  501  476  464  476  501  501  389  -11-1044
 13               -1186   69  499  567  501  412  346  322  346  412  501  567  499   69-1186
 14                -129  510  616  522  382  264  189  164  189  264  382  522  616  510 -129
 15           -802  360  648  588  425  266  149   81   58   81  149  266  425  588  648  360 -802
 16           -193  568  665  525  341  188   85   28   10   28   85  188  341  525  665  568 -193
 17            104  642  642  470  287  147   59   14    0   14   59  147  287  470  642  642  104
 18            217  651  612  433  257  128   52   14    4   14   52  128  257  433  612  651  217
 19                 620  584  412  243  122   50   15    5   15   50  122  243  412  584  620
 20                 547  552  402  241  120   47   10   -1   10   47  120  241  402  552  547
 21                 405  499  391  244  124   45    4   -9    4   45  124  244  391  499  405
 22                      383  355  243  131   49    3  -12    3   49  131  243  355  383
 23                           242  202  122   50    5  -11    5   50  122  202  242
 24                                      35    1  -29  -40  -29    1   35

              RMS Wave aberration           Shift of nominal image
                   (waves)                       point  (mm)
 ( FIT )                               X              Y            Focus
   None             4.045 (P-V = 21.029)
   Tilt             3.972              0.000000       0.003811
Tilt/Focus          3.900              0.000000       0.011295       0.048255


Exit Pupil Origin, (X,Y,Z):    (expressed in image space coordinates)
                 (   0.000000E+00,    0.000000E+00,    -116.441     )

Exit Pupil Orientation Angles (Alpha, Beta, Gamma):
                 (    8.61043     ,    0.000000E+00,    0.000000E+00 )

Reference Ray Coordinates on the exit pupil plane, (X_p,Y_p):
      R1:  ( 0.000000E+00,   0.000000E+00)
      R2:  ( 0.000000E+00,    28.6158    )
      R3:  ( 0.000000E+00,   -30.1055    )
      R4:  (  29.8325    ,  -0.642212    )
      R5:  ( -29.8325    ,  -0.642212    )
```

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```
ZERNIKE POLYNOMIAL COEFFICIENTS   (normalization radius = 30.105540)
Number   Order     Value (waves at 587.6 nm)  RMS wavefront error

   1       0           1.2611                      1.2611

   2       1           0.0000                      0.0000
   3                  -3.3164                      1.6582

   4       2           6.3200                      2.5801
   5                  -2.5703                      1.4840
   6                   0.0000                      0.0000

   7       3           0.0000                      0.0000
   8                   0.0000                      0.0000
   9                  -8.2103                      2.9028
  10                  -0.4354                      0.1539

  11       4           0.2411                      0.0763
  12                   2.1793                      0.6892
  13                  -5.8399                      2.6117
  14                   0.0000                      0.0000
  15                   0.0000                      0.0000

  16       5           0.0000                      0.0000
  17                   0.0000                      0.0000
  18                   0.0000                      0.0000
  19                  -5.2145                      1.5053
  20                  -0.2606                      0.0752
  21                   0.0158                      0.0046

  22       6          -0.0522                      0.0140
  23                   0.1184                      0.0316
  24                   0.4590                      0.1227
  25                  -2.1500                      0.8126
  26                   0.0000                      0.0000
  27                   0.0000                      0.0000
  28                   0.0000                      0.0000

  29       7           0.0000                      0.0000
  30                   0.0000                      0.0000
  31                   0.0000                      0.0000
  32                   0.0000                      0.0000
  33                  -0.7051                      0.1763
  34                  -0.1080                      0.0270
  35                  -0.0094                      0.0024
  36                  -0.0170                      0.0042

RMS of polynomial =    5.5082
  (tilt removed)       5.2527
RMS fit error     =    0.0590
```

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Technical Notes

Isoplanatism and OSC

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

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

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

F-Numbers, Focal Lengths and Reduction Ratios

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

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

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

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

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

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Coordinates Used in PMA Output

The PMA output coordinates are ray direction cosines in image space coordinates. The vertical direction corresponds to the Y-direction cosine (M) and the M < 0 values are at the top of the plot. The horizontal direction corresponds to the X-direction cosine (L) and the L < 0 values are at the right side of the plot.

To illustrate this coordinate system we will use an interferogram of the letter F, which introduces phase variation across the wavefront.

At the Entrance Pupil or Stop Surface

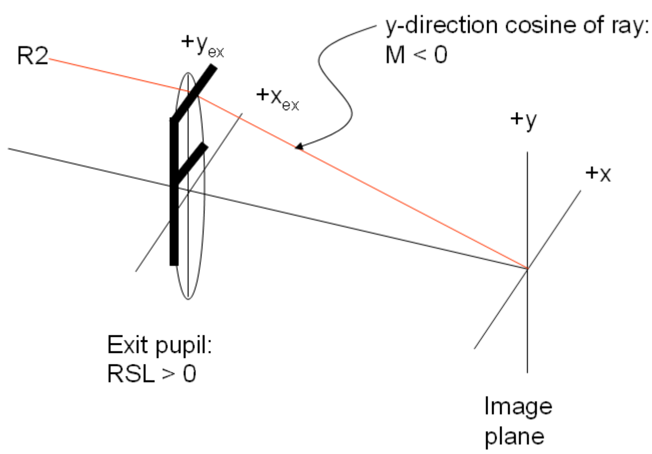
When the INT file is applied to the entrance pupil or stop surface, the pupil map shows the F in the upright orientation. The top of the F has M < 0, regardless of the reference sphere location (RSL) setting.

At the Exit Pupil

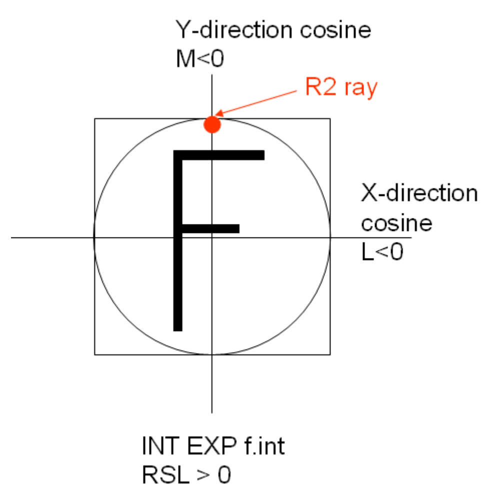
When the INT file is applied to the exit pupil, the orientation of the phase variation in the pupil map will depend on the RSL value.

RSL > 0

If the INT file is placed on the exit pupil with RSL > 0, the R2 ray goes through the top of the F and has M < 0.



As a result, the pupil map shows the F in the upright orientation.



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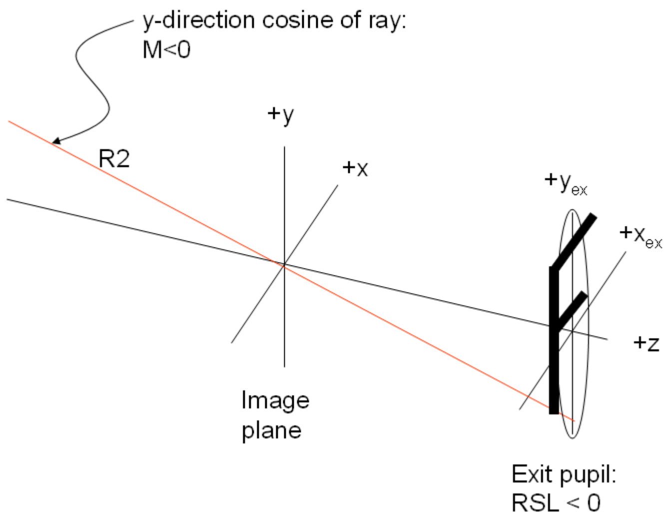
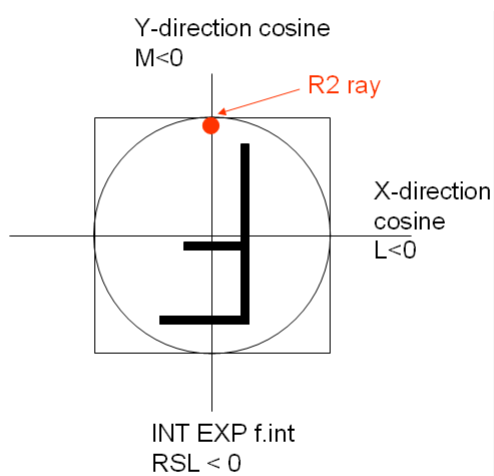
RSL < 0

If the INT file is placed on the exit pupil with RSL < 0, the R2 ray still has M < 0, but now the R2 ray intersects the exit pupil at the bottom of the F.



As a result, the pupil map shows the F rotated.



This difference in orientation is due to the different coordinate systems used for applying the INT file and displaying the pupil map. See "Coordinates Used for Applying the INT File" on page 10-18.

Note that the pupil map coordinates depend on the image space coordinates. If you apply ADE SI 180, the PMA plot will be in the rotated coordinates.