BIO-Biocular Analysis

The Biocular Analysis (BIO) option computes chief ray behavior, in one zoom position, relative to a reference system which may be a correction polynomial, another zoom position, or a paraxially perfect lens of the same or different focal length.

When to Use the Biocular Analysis Option

Use the Biocular Analysis (BIO) option when you have an optical system that is to be looked through from different eye locations and you wish to find out how well the images presented to the two eyes match one another. Typical optical systems which would be analyzed with the BIO option include simulators, bioculars (large eyepieces viewed through both eyes), head-up displays (HUDs), and head-down displays.

BIO was originally developed for use with head-up display (HUD) systems. Determining parallax (different apparent object locations for the two eyes) and image doubling errors for such systems is still its principal use. It has been expanded to handle a variety of other related problems such as distortion analysis, aircraft windscreen analysis, and simulator analysis.

This option computes and plots the difference in chief ray angles for different eye locations (convergence, divergence, and dipvergence). To determine the field of view from different eye locations, use the Biocular Field of View Plot (FOV) option.

Default Operation

A single page table is listed for the first zoom position. The maximum and minimum elevations are obtained from the last YAN, by assigning a minus sign and plus sign, respectively; this span is divided into 21 total elevations. At 0 azimuth and each of these elevations, chief rays are traced and the deviations from equivalent paraxial rays are calculated in lens units on the image surface; these are tabulated vs. azimuth and elevation of the chief rays in object space. Clipping for a single eye view is shown by the absence of data. Note that BIO ignores all CRA values.

Command Mnemonics
(alphabetical)

AZC	AZI	COR	ELC	FTT	LAB
MNE	MXE	NEL	OFS	PLO	RAC
RET	SAP	SSI	SUR	TIT	UNI
WED	XLA	XLE	XOF	YLA	YLE
ZCA	ZPO				

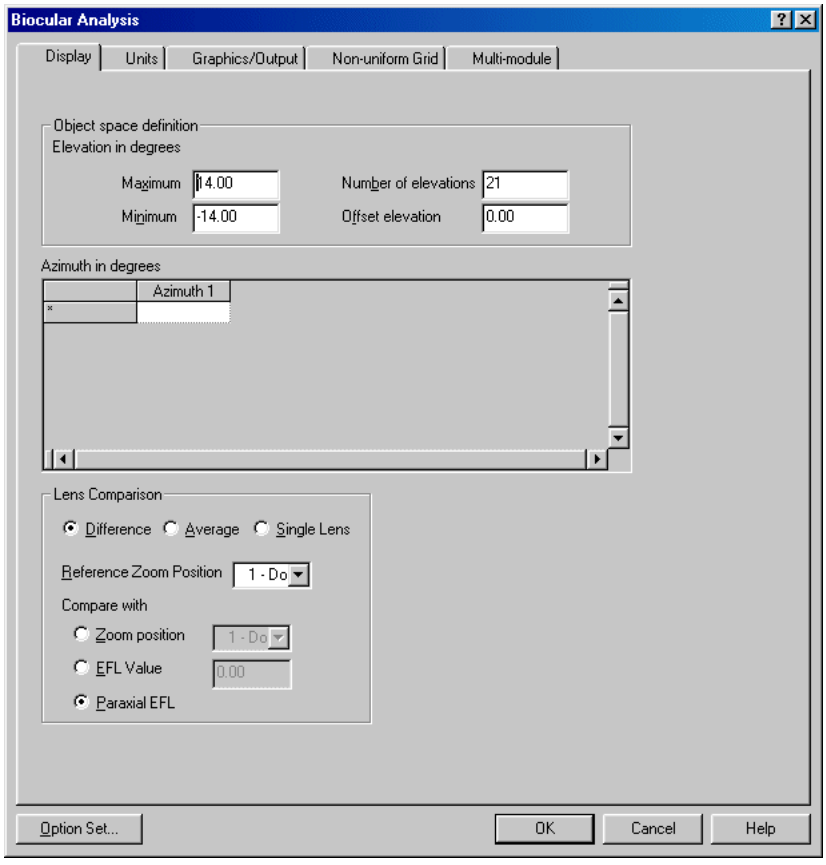
Defining Display Settings

To define display settings for the Biocular Analysis (BIO) option, choose the **Analysis** > **Geometrical** > **Biocular Analysis** menu. The **Biocular Analysis** dialog box displays, with the **Display** tab automatically selected.

There are two types of display settings you can define for Biocular Analysis:

- Object space grid settings. Go to “Object Space Grid Settings” on page 19-11 for details about how to define these controls.
- Lens comparison settings. Go to “Lens Comparison Settings” on page 19-11 for details about how to define these controls.

For more details about how this option works, go to “Usage” on page 19-21.



Object Space Grid Settings

Command Syntax		
Screen Control	**Explanation**	**Default**
MXE max_elevation_degr		
Elevation in degrees: Maximum	Specifies most positive object space elevation. Use with **Minimum** (MNE), **Number of elevations** (NEL), and **Offset elevation** (OFS) to define Y components of object space grid.	From last YAN, using + sign.
MNE min_elevation_degr		
Elevation in degrees: Minimum	Specifies most negative object space elevation. Use with **Maximum** (MXE), **Number of elevations** (NEL), and **Offset elevation** (OFS) to define Y components of object space grid.	From last YAN, using - sign.
NEL num_elevations		
Number of elevations	Specifies total number of elevations from **Minimum** (MNE) to **Maximum** (MXE). **Range**: 1 to 21.	21
OFS offset_elevation_degr		
Offset elevation	Specifies elevation of optical axis (in degrees) in the object space - subtracted from grid elevations to define traced object points.	0.0
AZI azimuth_degr....7		
Azimuth	Defines X component of object space grid. You can specify up to 7 values, each establishing an azimuth to be computed (in degrees).	0.0

Lens Comparison Settings

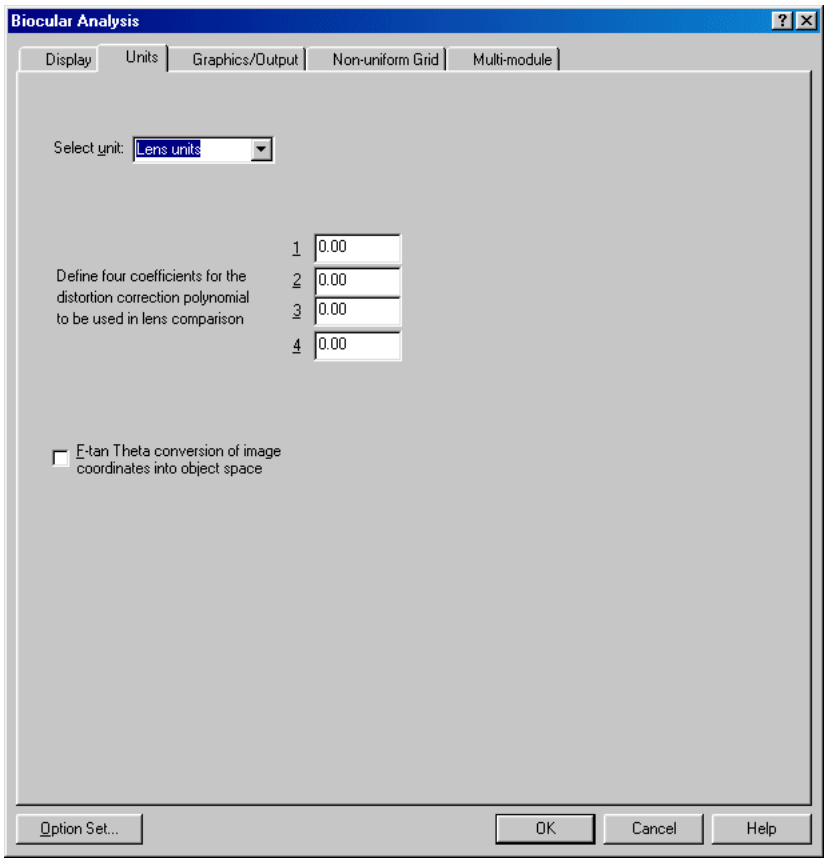
Command Syntax		
Screen Control	**Explanation**	**Default**
ZPO SIN Zk or **ZPO** [DIF | AVE] Zk Zn | PAR | subs_lens		
Single Lens	Produces Biocular Analysis output in the form of absolute coordinates. No comparison to a zoom position, EFL value, or paraxial EFL value is done; the chief ray coordinates for the specified **Reference Zoom Position** are provided without processing. **From the command line:** Use ZPO SIN Zk.	ZPO DIF Z1 PAR. Display values for (Zk - paraxial equivalent for Zk).

Command Syntax		
Screen Control	**Explanation**	**Default**
Difference	Produces Biocular Analysis output that compares differences between the lens in the selected zoom position (**Reference Zoom Position** field) and the lens in another zoom position (**Zoom position** field), a substitute lens (**EFL Value** field), or a paraxial EFL value (**Paraxial EFL** field). **From the command line:** Use the ZPO command as follows: ZPO DIF Zk Zn | PAR | subs_lens compares lens in zoom position Zk with: Zn — lens in zoom position Zn PAR — paraxial EFL (or RED, if |RED| >1.0 E-5) of lens in zoom position Zk subs_lens — substitute lens: enter value for EFL (or RED, if |RED| > 1.0E-5) DIF — Zk - second value (Zn, PAR, or subs_lens) AVE — average Zk with second value neither — defaults to DIF	ZPO DIF Z1 PAR. Display values for (Zk - paraxial equivalent for Zk).
Average	Produces Biocular Analysis output that compares averages between the lens in the selected zoom position (**Reference Zoom Position** field) and the lens in another zoom position (**Zoom position** field), a substitute lens (**EFL Value** field), or a paraxial EFL value (**Paraxial EFL** field). **From the command line:** Use the ZPO command as follows: ZPO AVE Zk Zn | PAR | subs_lens See the ZPO command description under the **Difference** control for more details.	ZPO DIF Z1 PAR. Display values for (Zk - paraxial equivalent for Zk).
Reference Zoom Position	Specifies the lens zoom position that is compared to another zoom position. **From the command line:** Equivalent to using the Zk qualifier in the ZPO command.	1
Compare with: Zoom position	Specifies a zoom position that is compared to the **Reference Zoom Position**. **From the command line:** Equivalent to using the Zn qualifier in the ZPO command.	

Command Syntax		
Screen Control	**Explanation**	**Default**
Compare with: EFL Value	Specifies a substitute lens that is compared to the current lens. Enter a value for the EFL, or effective focal length (or for the RED, or reduction ratio, if |RED| > 1.0E-5). **From the command line:** Equivalent to using the sub_lens qualifier in the ZPO command.	
Compare with: Paraxial EFL	Specifies a paraxial EFL (or RED, if |RED| >1.0 E-5) value that the current lens, in the specified **Reference Zoom Position**, is compared to. **From the command line:** Equivalent to using the PAR qualifier in the ZPO command.	

Defining Units Settings

To define units settings for the Biocular Analysis (BIO) option, choose the **Analysis** > **Geometrical** > **Biocular Analysis** menu. The **Biocular Analysis** dialog box displays. Click the **Units** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
UNI LNS | MIC | MIL | AMI | ASE | MLR | MCR		

Select unit	Selects units for distortion display values.
	On Image Surface:
	`Lens units (LNS)`
	`Microns (MIC)`
	`Mils (MIL)`
	In Object Space:
	Arc minutes (AMI)
	Arc seconds (ASE)
	Milliradians (MLR)
	Microradians (MCR)
		Lens units (LNS)

COR a_coeff b_coeff c_coeff d_coeff		
Define four coefficients for the distortion correction polynomial to be used in lens comparison	Defines distortion correction polynomial to be subtracted from the **Reference Zoom Position** (Zk in ZPO) of the form: R = A∗T + B∗T**3 + C∗T**5 + D∗T**7 where: T = tan (object space angle with respect to optical axis) R = radius adjustment on image surface in lens units A, B, C, D are the four coefficients (fields labeled **1**, **2**, **3**, **4**) in lens units. R is converted, as needed, according to units selected in the **Select unit** field (UNI command). This setting is ignored if the **Calibration system for lens comparison** setting (ZCA command) on the **Multi-module** tab is used.	No correction polynomial used.
FTT Yes | No		
F-tan Theta conversion of image coordinates into object space (Y/N)?	Select to use a perfect lens (with field height defined by f * tan Θ) as the definition of local magnification when converting image space coordinates into object space coordinates (UNI with AMI, ASE, MLR, MCR), instead of using differential rays traced through the actual, aberrated lens.	No.

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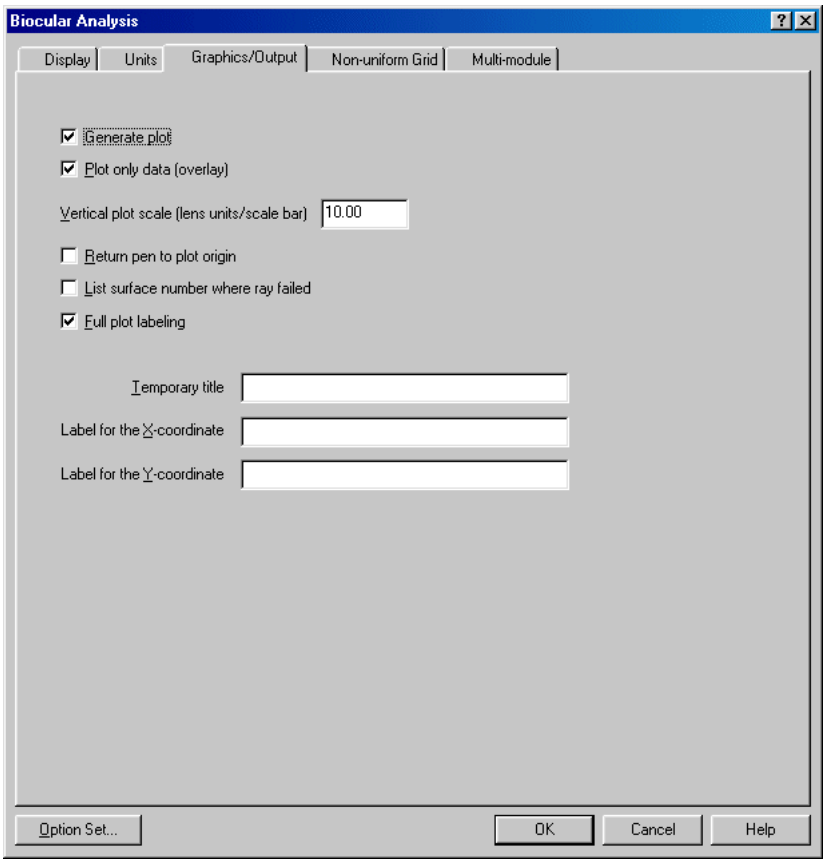
Defining Graphics/Output Settings

To define graphics/output settings for the Biocular Analysis (BIO) option, choose the **Analysis** > **Geometrical** > **Biocular Analysis** menu. The **Biocular Analysis** dialog box displays. Click the **Graphics/Output** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
PLO [OVE] Yes | No		
Generate plot	Select to plot **Lens Comparison** (ZPO) result. Both X and Y components are plotted on a single page plot, Y in the top half, X in the bottom half. Each azimuth has a different linestyle; a legend identifies them.	Yes.
Plot only data (overlay)	Select to draw only the curves in the plot; allows overlaying on top of a prior Biocular Analysis plot done with the **Return pen to plot origin** setting (RET). **From the command line:** Equivalent to using the OVE qualifier with the PLO command.	

Command Syntax		
Screen Control	**Explanation**	**Default**
SSI vert_units_per_scale_bar		
Vertical plot scale (lens units/scale bar)	Used only with the **Generate plot** setting (PLO). Specifies vertical scale size of **Lens Comparison** (ZPO) values in the number of units specified in the **Select unit** field (UNI). When printed or plotted, scale bar length is 25 mm for M, C lens units, 1 inch for I lens units.	10 (UNI per scale bar).
RET Yes | No		
Return pen to plot origin	Used only with the **Generate plot** setting (PLO). When finished with plot, returns to original origin; allows overlaying by later Biocular Analysis plots.	No.
RAC Yes | No		
List surface number where ray failed	In listing tables, replaces blank for rays that don't pass the system with the number of the surface at which the ray is clipped or has failed.	No. Only display values for rays that pass through the lens.
LAB Yes | No		
Full plot labeling	Labels plot in standard manner. If not selected, eliminates plotting of border, scale, and azimuth, elevation labels - 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)		
Temporary title	Specifies up to 40 characters are plotted (in two 20 character lines) and listed for the title.	Uses the first 40 characters of the system title.
XLA 'x_coord_label' (40)		
Label for the X-coordinate	Specifies special 40-character label for listed and plotted X-coordinate output.	Blank.
YLA 'y_coord_label' (40)		
Label for the Y-coordinate	Specifies special 40-character label for listed and plotted Y-coordinate output.	Blank.

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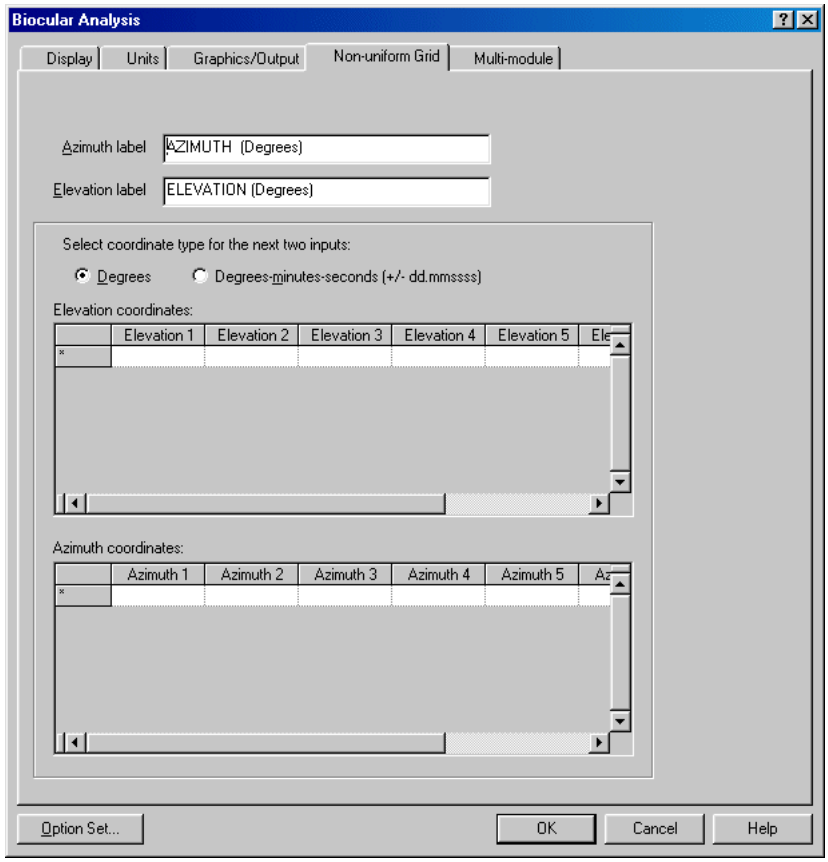
Defining Non-uniform Grid Settings

To define non-uniform reference grid settings for the Biocular Analysis (BIO) option, choose the **Analysis** > **Geometrical** > **Biocular Analysis** menu. The **Biocular Analysis** dialog box displays. Click the **Non-uniform Grid** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
XLE 'replace_azimuth_label'(30)		
Azimuth label	Replaces, in one 30 character line, the default azimuth legend.	A Z I M U T H (DEGREES)
YLE 'replace_elevation_label'(15+15)		
Elevation label	Replaces, in two 15 character lines, the default elevation legend.	ELEVATION (DEGREES)

Command Syntax		
Screen Control	**Explanation**	**Default**
ELC [DMS] elevation_coordinates_degr....7		
Select coordinate type for the next two inputs	Defines units used for **Elevation coordinates** and **Azimuth coordinates**. **Degrees** Select to designate elevation and azimuth coordinate units as degrees. **Degrees-minutes-seconds (+/- dd.mmssss)** Select to designate elevation and azimuth coordinate units as degrees-minutes-seconds in format dd.mmssss, where ssss implies ss.ss. **From the command line:** Use the DMS qualifier with ELC and AZC to designate units as degrees-minutes-seconds.	Degrees
Elevation coordinates	Use only with **Azimuth coordinates** (AZC). Define non-uniform grid by designating each elevation (ELC) and azimuth (AZC) value separately. Enter up to 7 elevation coordinate values in each row. Each row of elevation coordinate values corresponds with each row of changing azimuth values in the **Azimuth coordinates** spreadsheet. You can define up to 21 rows of elevation coordinate (ELC) values and azimuth coordinate (AZC) values. **Note**: Although results are listed in uniform rows and columns they only correspond in order to the sequence of input, which is not necessarily a uniform grid in the object space.	REQUIRED WITH AZC. If neither ELC or AZC are used, use grid defined by MXE, MNE, NEL, AZI, OFS.
AZC [DMS] azimuth_coordinates_degr....7		
Azimuth coordinates	Use only with **Elevation coordinates** (ELC). Define non-uniform grid by designating each elevation (ELC) and azimuth (AZC) value separately. Enter up to 7 azimuth coordinate values in each row. Each row of azimuth coordinate values corresponds with each row of elevation coordinate values in the **Elevation coordinates** spreadsheet. You can define up to 21 rows of azimuth coordinate (AZC) values and elevation coordinate (ELC) values. **From the command line:** Use the DMS qualifier with AZC to designate units as degrees-minutes-seconds. **Note**: Although results are listed in uniform rows and columns they only correspond in order to the sequence of input, which is not necessarily a uniform grid in the object space.	REQUIRED WITH ELC. If neither ELC or AZC are used, use grid defined by MXE, MNE, NEL, AZI, OFS.

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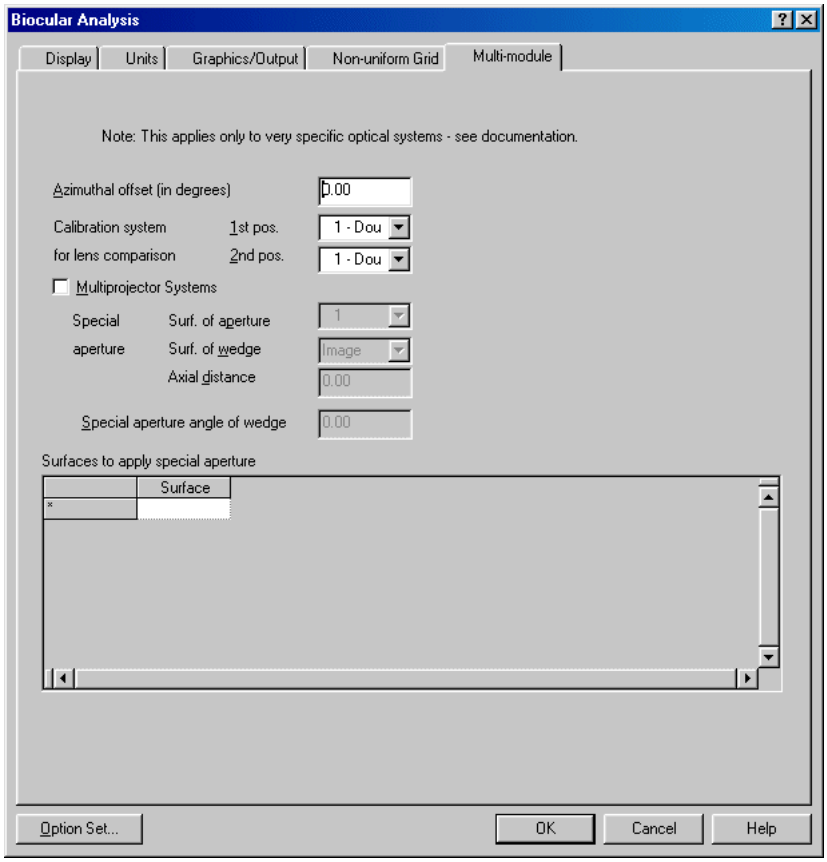
Defining Multi-Module Display Settings

To define multi-module display settings for the Biocular Analysis (BIO) option, choose the **Analysis** > **Geometrical** > **Biocular Analysis** menu. The **Biocular Analysis** dialog box displays. Click the **Multi-module** tab, and define the controls on this tab as described in the table below.



Command Syntax		
Screen Control	**Explanation**	**Default**
XOF azimuth_offset_degr....z		
Azimuthal offset (in degrees)	Specifies increment in pointing angle azimuth for each zoom position. For each azimuth to be analyzed, the azimuthall offset (XOF) value is subtracted to determine the traced azimuth. This is done only in the second zoom position of the pair of zoom positions specified in the **Lens Comparison** area on the **Display** tab (ZPO). Used for multi-module projectors to analyze the overlap region. Is a zoomable parameter; right-click over this field to access the **Zoom Editor**.	0.0

Command Syntax		
Screen Control	**Explanation**	**Default**
ZCA Zi [Zj]		
Calibration system for lens comparison	Defines calibration system for lens comparison (ZPO) calculations. The chief ray at each azimuth and elevation is first traced through the lens represented by the first zoom position **(1st pos.** field or Zi); this result is then subtracted from the **Reference Zoom Position** and **Zoom position** specified in the **Lens Comparison** area on the **Display** tab (Zk and Zn position of ZPO) before any comparison is made. If a second zoom position is given (**2nd pos.** field or Zj), separate operations are done on the **Reference Zoom Position** and **Zoom position** specified in **Lens Comparison** (Zk and Zn of ZPO): the chief rays in positions Zi and Zj are subtracted from Zk and Zn respectively - (Zk - Zi), (Zn - Zj). Used for multi-module projectors. **Note:** When this setting is used, the **Define four coefficients for the distortion correction polynomial to be used in lens comparison** setting (COR) is not applied.	**N/A**
SAP Si Sj wedge_aperture_distance		
Special aperture	Used for multi-module projectors. Defines a special azimuthal wedge aperture for a selected surface. The **Special aperture angle of wedge** setting is **required** with this setting. **Surface of aperture** (Si) Selects the surface where special azimuthal wedge aperture is defined. **Surface of wedge** (Sj) Selects the surface from which the point of the wedge is defined by the **Axial distance**. **Axial distance** (wedge_aperture_distance) Specifies wedge aperture distance along Z axis from the **Surface of wedge**.	No wedge aperture imposed.
WED wedge_aperture_degr....z		
Special aperture angle of wedge	**Required** with **Special aperture** (SAP) setting. Specifies vertex angle between the two sides of the azimuthal wedge.	Use XOF.
SUR Si....7		
Surfaces to apply special aperture	Used only with **Special aperture** (SAP) setting. Applies wedge aperture on up to 7 surfaces instead of the selected surface (Si) in **Special aperture** (SAP).	Si on SAP.

Discussion of Input and Computations

What to Include in the LDM Data

Since the eye accepts collimated or near-collimated light, optical systems designed for the eye are usually designed at infinite conjugates (or long finite conjugates). The aperture stop is usually external to the optical system and is placed where the eye would be located. Different eye locations are modeled for the Biocular Analysis (BIO) option via two zoom positions with the aperture stop decentered. Typically zoom position 1 decenters the stop 1.25" to the left while zoom position 2 decenters it to the right 1.25" to correspond to the standard 2.5" eye separation.

For BIO to execute, it must be able to trace all of the reference rays for each specified field. Because most biocular systems do not allow viewing of the total field of view from all eye positions, it is best to specify a small entrance pupil diameter, EPD (or NAO), and to reduce the field of view substantially. Reducing the field of view or entrance pupil size can have an impact on any solves in the system, so they should be deleted (DEL SOL SA).

Because the BIO option includes the effect of clipping by system apertures, they must be set properly. Thus, user-defined apertures should be entered on all surfaces (such as with SET APE) prior to decentering the stop surface or reducing the entrance pupil and object point specifications, or the CA APE command can be used to restrict clipping to user-defined apertures only. If there is a field stop at the image (e.g., the edge of a CRT screen), a dummy surface should be inserted in contact with the image with the appropriate aperture specified, since the image surface ignores apertures. Note that since BIO generates intermediate field points, it ignores CRA values for all fields.

Usage

The Biocular Analysis (BIO) option traces chief rays on an azimuth/elevation grid, and displays the results in linear units on the image surface or in angular units in object space. Most often the desired output is the difference of the chief ray behavior in two modified lens configurations, but the results can be in any of the following forms:

1. Absolute coordinates. (Use the **Single Lens** setting in the **Lens Comparison** area or the **ZPO** SIN command.)

2. Differences with respect to another chief ray position (in another zoom position), the paraxial chief ray location, or a position computed according to a correction polynomial (**Define four coefficients for the distortion correction polynomial to be used in lens comparison** setting or the **COR** command). (Use the **Difference** setting in the **Lens Comparison** area or the **ZPO** DIF ... command.)

3. Averages with another chief ray position (same choices as in #2). (Use the **Average** setting in the **Lens Comparison** area or the **ZPO** AVE ... command.)

The output units can be linear units (lens units, mils [thousandths of an inch], or microns) on the image surface, or angular units (arc minutes, arc seconds, milliradians or microradians) in object space. Angular errors are exact (to within local differential ray trace estimates) and are not simple scaling conversions via the lens focal length.

Only those rays which pass all apertures will be used. If two zoom positions have been selected in the **Lens Comparison** area (**ZPO**), corresponding chief rays must pass in both zoom positions. Selecting the **List surface number where ray failed** setting (**RAC**) will indicate (on the printout) at which surface each clipped ray has been blocked.

The object space coordinate angles of the incoming chief rays are specified by the user in terms of azimuth and elevation. Elevation is the angle between the incoming chief ray and the X-Z plane. Azimuth is the angle between the projection of that ray on the X-Z plane and the Z axis, and is the same as XAN. Elevation, however, is NOT the same as YAN, the relationship being:

$$\tan(YAN) = \tan(\varepsilon)/\cos(\alpha)$$

where α is azimuth and ε is elevation.

Azimuths (up to seven) are specified with the **AZI** command, elevations (up to 21) with **MXE**, **MNE**, **NEL**, and **OFS**.

Description of Output

As shown, the printed output consists of two tables, one each for the X and Y components. Each column is one of the requested azimuths. X and Y labels (if input) appear above the corresponding tables. There is also a header which indicates the operation performed on the chief ray data (e.g., POSITION 1 - POSITION 2 for **ZPO** Z1 Z2 input). The data in the table is in the requested **UNI**ts. Where either chief ray is blocked at an aperture, the table entry is blank, or, if **RAC** has been requested, it is the surface number where the blockage occurs. At the bottom of each table are the minimum, maximum, mean, standard deviation, and RMS of the table entries. Note that the minimum and maximum often occur at the edge of an aperture, and thus are likely to be sensitive to the azimuth/elevation sampling density.

In the plotted output, X and Y components are plotted on separate axes, with elevation as the abscissa and a different line style for each azimuth. The ordinate axis goes from plus to minus **SSI**. **LAB** NO (not used in the examples) will delete most of the labeling for a quicker plot.

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Examples

Example 1. Distortion analysis for a "mapping" camera

We want to convert the distortion of a lens (the sample triplet) into microradians in object space, making allowance for the defocus (THI SI) of the lens from the paraxial focal plane. (The sample triplet has a PIM solve.) BIO's default operation is to subtract the paraxial chief ray heights from the real-ray heights, and we can use the **COR** command to accomplish the desired correction for defocus. Since the chief rays appear to emanate from the exit pupil, the linear (A) term we enter with **COR** is given by:

$$A = \frac{\text{THI SI}}{\text{exit pupil distance (w.r.t.image)}} \times \text{EFL}$$

The nonlinear terms in **COR** are set to zero in this example, but could have been non-zero if the errors with respect to a correction function were desired. BIO uses the default azimuth of zero, while its maximum elevation is set to the maximum YAN. The X component of the output is identically zero because of symmetry.

Command inputs:

```
RES   CV_LENS:TRIPLET

BIO;COR   -.289   0   0   0;UNI   MCR;GO
```

```
CODE V> BIO
```

```
     BIO                                                ORA                          15H 11M 35S
                                          CODE V Version: 8.03          CPU clock:   0H  0M 28S
BIO> COR -.2892 0 0 0
BIO> UNI MCR
BIO> GO

     The first zoom position and the paraxial data will be differenced

     The following function will be subtracted from each zoom position

                                          3               5               7
     COR(R) =   -0.289200*R +    0.000000*R  +    0.000000*R  +    0.000000*R

     where R is the tangent of the angle in object space
```

```
                                C O D E   V

            Triplet    U.S. Patent 2,645,157
                                                                POSITION 1 - PARAXIAL
                                                                           - COR(R)
                          ANGULAR ERRORS (MICRORAD)

       ELEVATION          A Z I M U T H  (DEGREES)
       (DEGREES)               0.00

          20.00                 0.0
          18.00                 0.0
          16.00                 0.0
          14.00                 0.0
          12.00                 0.0
          10.00                 0.0
           8.00                 0.0
           6.00                 0.0
           4.00                 0.0
           2.00                 0.0
           0.00                 0.0
          -2.00                 0.0
          -4.00                 0.0
          -6.00                 0.0
```

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```
          -8.00                0.0
         -10.00                0.0
         -12.00                0.0
         -14.00                0.0
         -16.00                0.0
         -18.00                0.0
         -20.00                0.0

                        MAXIMUM =         0.0
                        MINIMUM =         0.0
                        MEAN    =         0.0
                        RMS     =         0.0
                        STD DEV =         0.0
```

```
                              C O D E   V

          Triplet    U.S. Patent 2,645,157
                                                          POSITION 1 - PARAXIAL
                                                                       - COR(R)
                          ANGULAR ERRORS (MICRORAD)

      ELEVATION          A Z I M U T H  (DEGREES)
      (DEGREES)               0.00

         20.00              -627.5
         18.00              -490.5
         16.00              -351.6
         14.00              -234.4
         12.00              -145.0
         10.00               -82.0
          8.00               -41.0
          6.00               -16.9
          4.00                -4.9
          2.00                -0.6
          0.00                 0.0
         -2.00                 0.6
         -4.00                 4.9
         -6.00                16.9
         -8.00                41.0
        -10.00                82.0
        -12.00               145.0
        -14.00               234.4
        -16.00               351.6
        -18.00               490.5
        -20.00               627.5

                        MAXIMUM =       627.5
                        MINIMUM =      -627.5
                        MEAN    =         0.0
                        RMS     =       283.3
                        STD DEV =       283.3
```

```
CODE V> OUT T
              ...
```

Example 2. Parallax and image doubling analysis of a dual-glazed heads up display

Here the Petzval sample lens is used as a HUD. Conventional (non-holographic) HUDs are often of this form. Additional surfaces have been added ahead of the lens elements for the two flat combiners, as depicted in Figure 1. In actuality, each combiner would be a flat glass plate, probably coated with a spectrally selective partially reflective multilayer coating, but for purposes of this example the back side of the upper combiner can be ignored, and only the lower combiner is modeled as a plate. In this simulation, four zoom positions have been used, two for the two eyes, times two for the two combiners. A single REFL surface serves for both combiners; to have it act as the lower combiner, the lower combiner's thickness and the airspace following it are "zoomed" to zero in positions three and four. Note that this occurs in two places (surfaces 2-3 and 4-5), since the light reflected by the upper combiner must pass twice through the lower combiner. The second REFL surface is a fold mirror. Frequently such a fold is located in the Petzval lens's large central airspace.

To represent the observer's "look direction," BIO traces chief rays, which pass through the center of the "stop" surface. The stop therefore represents the pupil of the observer's eye and must be X-decentered (and the decenter must be zoomed) to simulate left and right eyes for parallax analysis. Positive X is to the observer's left.

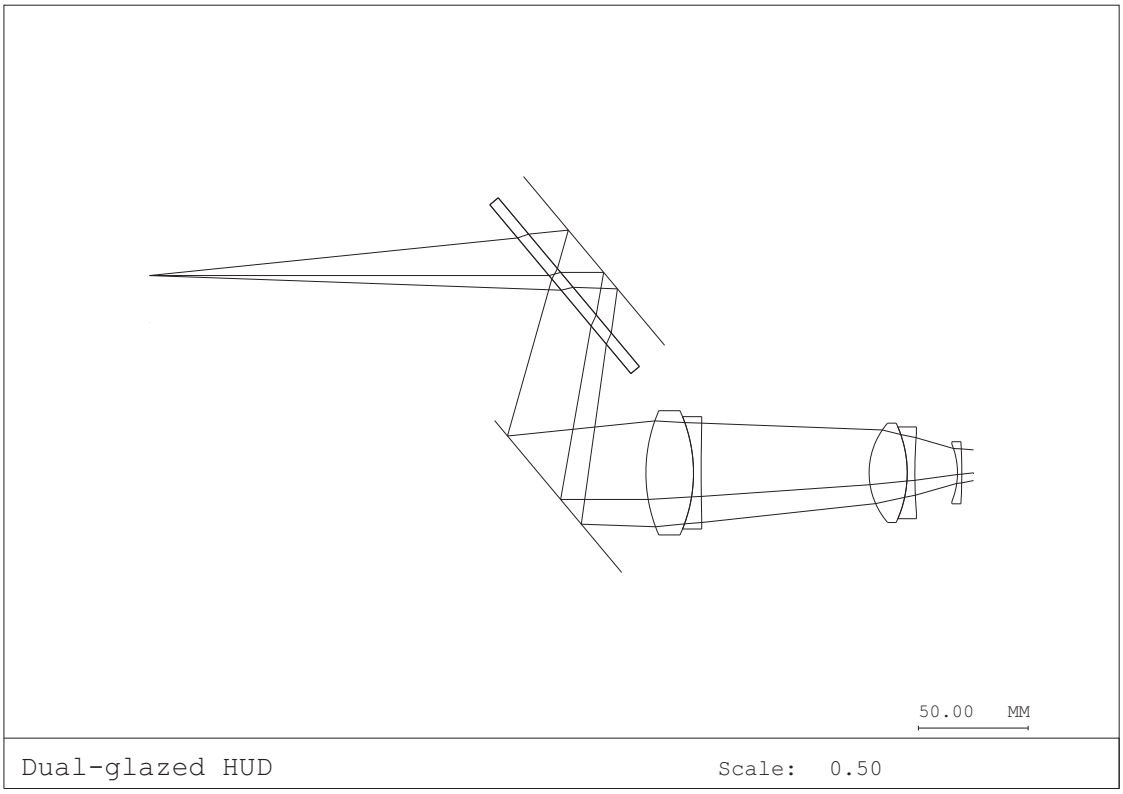

Figure 1. Dual-glazed HUD example

The range of azimuths and elevations to be used is most readily established with the FOV option. The FOV plot used for this example is shown in Figure 2. The overlap areas for parallax (upper combiner) and image doubling (left eye) are shaded (the shading was added manually; it is not part of the BIO plot). Note that positive azimuths are to the left in FOV plots in order to depict the optical system as it appears to the viewer, and that the CODE V lens set up is different between FOV and BIO.

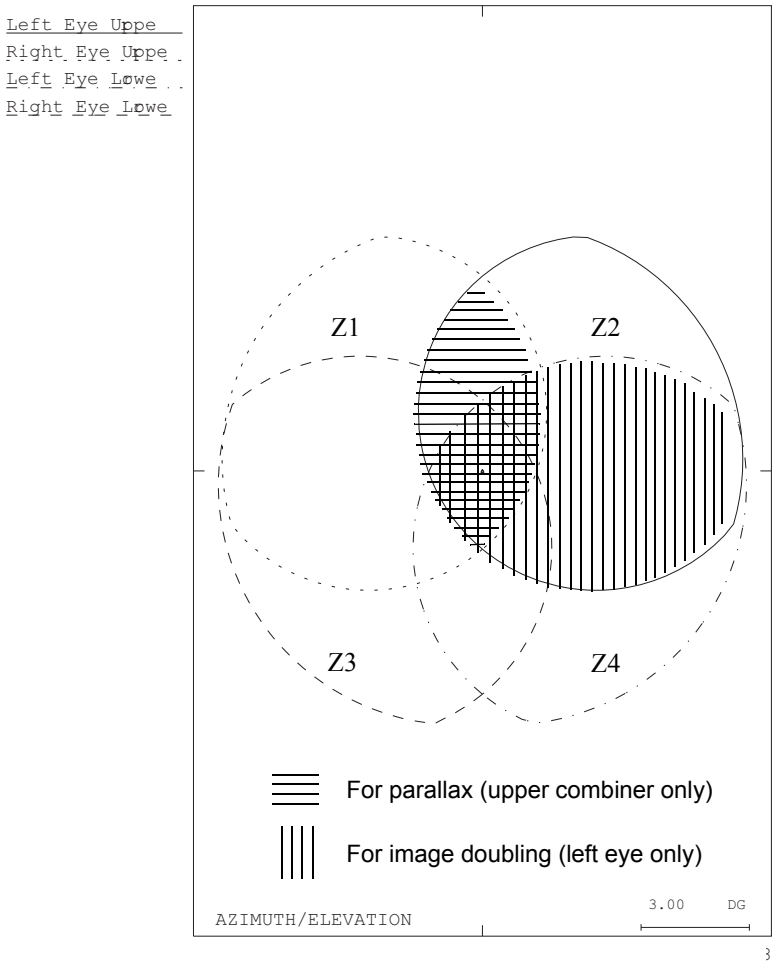

Figure 2. Petzval lens as dual-glazed HUD

Several other hints for successful use of BIO for HUD analysis are implicit in the example:

1. **Fields.** CODE V traces the reference rays at the beginning of the option in order to establish system traceability and set clear apertures. Because BIO analysis of a HUD often uses extreme eye positions, the design field points (XAN and YAN, or their equivalents) may not always be traceable in all zoom positions. Restrict yourself to a single field that you know will trace (YAN=0 is used here, but a different value might be needed in other cases), and reduce the EPD to a small fraction of its design value. If this procedure is not used, ray trace errors may occur during the reference ray trace and prevent BIO from completing the desired calculations.

2. **Apertures.** In analyzing a HUD you want consistent apertures that do not change from one BIO run to the next, as you will get if you allow CODE V's reference rays to determine the (circular) apertures for you. This is particularly true if you implement the suggestions of the above paragraph. Therefore it is best to put a CIR (or whatever other shape is appropriate) aperture on all limiting surfaces and set CA APE.

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3. Multiple BIO calls for each set of zoom parameter values. In analyzing parallax, for example, six zoom positions could be used to set three "head positions" (pairs of left and right eye positions). A single change of the zoom parameters could be followed by BIO;ZPO Z1 Z2;...;BIO;ZPO Z2 Z3;...;BIO;ZPO Z5 Z6;...

4. Checking the sign of convergence/divergence in parallax computations. This is easily accomplished by calling BIO once (a single azimuth/elevation is sufficient), changing THI SI, and calling BIO again. Then note how the X-component of parallax has changed. Moving the image surface closer to the lens will yield more convergence. If the sign is wrong, exchange the order of the zoom positions requested in **ZPO**. This will change the sign of the dipvergence as well, but that is generally immaterial.

5. Checking results with symmetry. While this example is completely asymmetric, BIO results for a system with bilateral symmetry (including the eye points, i.e., the head is not laterally [X] decentered) can be checked for consistency via symmetry. Such a system must have zero dipvergence for AZI=0, dipvergence that is antisymmetric with respect to azimuth, and convergence that is symmetric with respect to azimuth.

Input:

```
res cv_lens:petzval          ! retrieve the sample lens
sca fac spc 2                ! Scale to more realistic HUD size.
set ape                      ! Set apertures.
epd 1                        ! Reduce the EPD to small value.
yan 0                        ! Get rid of all fields.
ins s1 0 300                 ! Insert stop surface for eyepoints.
sto;dar                      ! Decenter it.
zoo 4                        ! Positions 1-2 are upper combiner, 3-4 are lower.
zoo xde s1 -7 57 -7 57       ! X-decenter for R,L,R,L eyes, 64 mm IPD.
tit '  Dual-glazed HUD,     Head Left 25mm'
ins s2 0 6 bk7;ade 40;zoo thi 6 6 0 0;cir 80   ! front of lower combiner
ins s3 0 25;zoo thi 25 25 0 0;cir 80           ! back of lower combiner
ins s4 0 -25 refl;zoo thi -25 -25 0 0;cir 70   ! upper combiner
ins s5 0 -6 bk7;zoo thi -6 -6 0 0;cir 80       ! back of lower combiner again
ins s6 0 -150;rev;ade -40;cir 80               ! front of lower combiner again
ins s7 0 50 refl;ben;ade -40;yde -20;cir 70    ! fold mirror
bio                          ! BIO for parallax.
mne -1.98;mxe 5.22           ! Elevations and
azi -1 -2 -3 -4              !   azimuths from FOV plot.
zpo z2 z1                    ! Difference R and L eyes for parallax.  (DIF is default.)
uni mlr                      ! Typical units for HUDs.
rac                          ! Will show where rays are blocked.
xla 'Convergence'            ! (Divergence is negative convergence.)
yla 'Dipvergence'
ssi 1                        ! Set the vertical plot scale size.
go
bio                          ! BIO for left eye image doubling.
mne -3;mxe 3                 ! Elevations and
azi -2 -3 -4 -5 -6 -7        ! azimuths from FOV plot.
zpo z2 z4                    ! Difference upper and lower combiners.
uni mlr
rac
xla '  Left Eye Image Doubling (Horizontal)'
yla '  Left Eye Image Doubling (Vertical)'
ssi 1                        ! Set the vertical plot scale size.
go
```

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Output:

```
res cv_lens:petzval          ! retrieve the sample lens
    File cv_lens:petzval.len has been restored
    Lens title: "Petzval lens with field flattener     U.S. Patent 2,076,190"
sca fac spc 2                ! Scale to more realistic HUD size.
    Surfaces from 0 to 9 AND specification data scaled by 2.000000
set ape                      ! Set apertures.

    The previously undesignated surface apertures have now been reset based on
         the current aperture specification (EPD) and vignetting values.
         Check newly generated surface apertures and increase them where the
         caustic can provide more than one ray at a given height on the
         surface (for example, near intermediate or last images); this avoids
         strange clipping of evaluation ray grids for the most extreme field.

epd 1                        ! Reduce the EPD to small value.
yan 0                        ! Get rid of all fields.
ins s1 0 300                 ! Insert stop surface for eyepoints.
 SURFACE   1:
          RDY 0.000000     ; THI    300.000000 ; GLA  AIR
sto;dar                      ! Decenter it.
zoo 4                        ! Positions 1-2 are upper combiner, 3-4 are lower.
zoo xde s1 -7 57 -7 57       ! X-decenter for R,L,R,L eyes, 64 mm IPD.
tit '  Dual-glazed HUD,     Head Left 25mm'
ins s2 0 6 bk7;ade 40;zoo thi 6 6 0 0;cir 80   ! front of lower combiner
17:52:59  Warning: Glass BK7 is no longer available from SCHOTT
               A replacement glass is NBK7
 SURFACE   2:
          RDY 0.000000     ; THI      6.000000 ; GLA  BK7_SCHOTT
ins s3 0 25;zoo thi 25 25 0 0;cir 80           ! back of lower combiner
 SURFACE   3:
          RDY 0.000000     ; THI     25.000000 ; GLA  AIR
ins s4 0 -25 refl;zoo thi -25 -25 0 0;cir 70   ! upper combiner
 SURFACE   4:
          RDY 0.000000     ; THI    -25.000000 ; GLA  REFL
ins s5 0 -6 bk7;zoo thi -6 -6 0 0;cir 80       ! back of lower combiner again
17:53:00  Warning: Glass BK7 is no longer available from SCHOTT
               A replacement glass is NBK7
 SURFACE   5:
          RDY 0.000000     ; THI     -6.000000 ; GLA  BK7_SCHOTT
ins s6 0 -150;rev;ade -40;cir 80               ! front of lower combiner again
 SURFACE   6:
          RDY 0.000000     ; THI   -150.000000 ; GLA  AIR
ins s7 0 50 refl;ben;ade -40;yde -20;cir 70    ! fold mirror
 SURFACE   7:
          RDY 0.000000     ; THI     50.000000 ; GLA  REFL
```

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```
bio                          ! BIO for parallax.

    BIO                                                              17H 53M  0S
                                                 CODE V PC (09CPU clock:  6H 32M 11S
    Active zoom positions are : 1, 2, 3, 4
    User-entered and default apertures are active
mne -1.98;mxe 5.22           ! Elevations and
azi -1 -2 -3 -4              !   azimuths from FOV plot.
zpo z2 z1                    ! Difference R and L eyes for parallax.  (DIF is default.)
uni mlr                      ! Typical units for HUDs.
rac                          ! Will show where rays are blocked.
xla 'Convergence'            ! (Divergence is negative convergence.)
yla 'Dipvergence'
ssi 1                        ! Set the vertical plot scale size.
go


    The two zoom positions will be differenced

                                C O D E   V

          Dual-glazed HUD,     Head Left 25mm

                                                        POSITION 2 - POSITION 1


           Convergence
                        ANGULAR ERRORS (MILLIRAD)

     ELEVATION          A Z I M U T H  (DEGREES)
     (DEGREES)              -1.00       -2.00       -3.00       -4.00


         5.22                8          10          10           8
         4.86                8        -0.0226      0.6578       8
         4.50                8        -0.2072      0.3774       9
         4.14                9        -0.3291      0.1738       9
         3.78                9        -0.4065      0.0271       9
         3.42               10        -0.4532     -0.0778      10
         3.06            -0.5010      -0.4798     -0.1529      0.7544
         2.70            -0.5271      -0.4942     -0.2071      0.5963
         2.34            -0.5411      -0.5021     -0.2474      0.4751
         1.98            -0.5477      -0.5080     -0.2788      0.3837
         1.62            -0.5500      -0.5146     -0.3048      0.3171
         1.26            -0.5498      -0.5237     -0.3275      0.2722
         0.90            -0.5474      -0.5358     -0.3479      0.2477
         0.54            -0.5419      -0.5504     -0.3656      0.2440
         0.18            -0.5312      -0.5660     -0.3791      0.2630
        -0.18              10         -0.5799     -0.3855      10
        -0.54               9         -0.5881     -0.3806       9
        -0.90               8         -0.5847     -0.3582       9
        -1.26               8         -0.5620     -0.3098       8
        -1.62               8         -0.5097     -0.2245       8
        -1.98               6           9           9           8


                           MAXIMUM =      0.7544
                           MINIMUM =     -0.5881
                           MEAN    =     -0.2377
                           RMS     =      0.4392
                           STD DEV =      0.3693
```

```
                              C O D E   V

        Dual-glazed HUD,     Head Left 25mm

                                                          POSITION 2 - POSITION 1

         Dipvergence
                     ANGULAR ERRORS (MILLIRAD)

ELEVATION          A Z I M U T H  (DEGREES)
(DEGREES)              -1.00       -2.00       -3.00       -4.00


    5.22                8          10           10          8
    4.86                8        -0.5273     -1.2821       8
    4.50                8        -0.4433     -0.9967       9
    4.14                9        -0.3672     -0.7676       9
    3.78                9        -0.2990     -0.5861       9
    3.42               10        -0.2385     -0.4438      10
    3.06             -0.0788     -0.1851     -0.3335     -0.6922
    2.70             -0.0665     -0.1381     -0.2487     -0.5274
    2.34             -0.0459     -0.0968     -0.1839     -0.4010
    1.98             -0.0205     -0.0605     -0.1344     -0.3033
    1.62              0.0067     -0.0285     -0.0961     -0.2258
    1.26              0.0331     -0.0004     -0.0652     -0.1606
    0.90              0.0558      0.0242     -0.0384     -0.1006
    0.54              0.0720      0.0456     -0.0123     -0.0383
    0.18              0.0784      0.0639      0.0164      0.0338
   -0.18               10         0.0790      0.0513      10
   -0.54                9         0.0908      0.0964       9
   -0.90                8         0.0985      0.1563       9
   -1.26                8         0.1015      0.2362       8
   -1.62                8         0.0981      0.3426       8
   -1.98                6           9           9          8


                      MAXIMUM =      0.3426
                      MINIMUM =     -1.2821
                      MEAN    =     -0.1510
                      RMS     =      0.3332
                      STD DEV =      0.2971
```

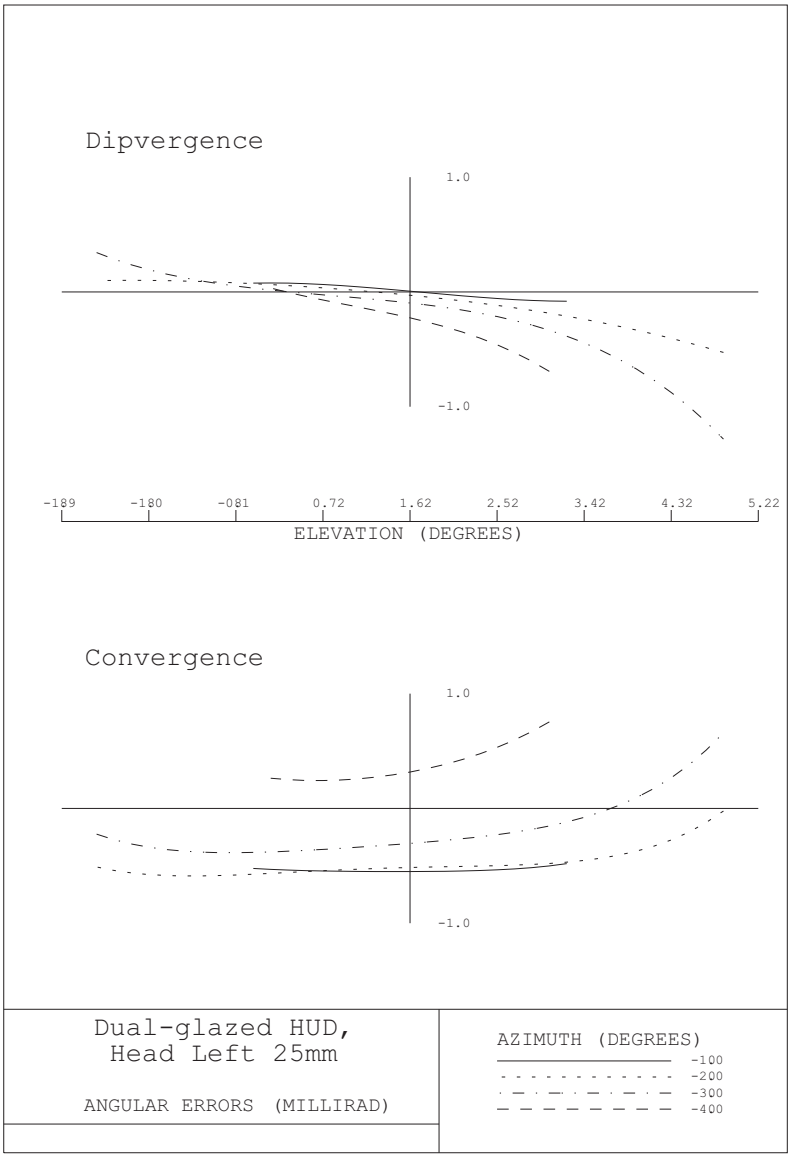

Figure 3. BIO dipvergence/convergence plot for dual-glazed HUD

```
bio   ! BIO for left eye image doubling.

    BIO                                                                  17H 53M  0S
                                              CODE V PC  Version: 10.2 (09CPU clock:  6H 32M 11S
    Active zoom positions are : 1, 2, 3, 4
    User-entered and default apertures are active
mne -3;mxe 3              ! Elevations and
azi -2 -3 -4 -5 -6 -7     ! azimuths from FOV plot.
zpo z2 z4                 ! Difference upper and lower combiners.
uni mlr
rac
xla '  Left Eye Image Doubling (Horizontal)'
yla '  Left Eye Image Doubling (Vertical)'
ssi 1                     ! Set the vertical plot scale size.
go


    The two zoom positions will be differenced

                              C O D E   V

         Dual-glazed HUD,     Head Left 25mm

                                                    POSITION 2 - POSITION 4


            Left Eye Image Doubling (Horizontal)
                       ANGULAR ERRORS (MILLIRAD)

      ELEVATION          A Z I M U T H  (DEGREES)
      (DEGREES)             -2.00       -3.00       -4.00       -5.00       -6.00       -7.00


         3.00                8           8           9         0.4912      0.7413       14
         2.70                8           8         0.2799      0.4327      0.6178      0.9157
         2.40                8           9         0.2718      0.3783      0.5102      0.7315
         2.10                8         0.1234      0.2573      0.3277      0.4162      0.5708
         1.80                9         0.1398      0.2377      0.2805      0.3338      0.4299
         1.50               10         0.1440      0.2142      0.2362      0.2609      0.3053
         1.20             -0.0207      0.1385      0.1877      0.1943      0.1955      0.1935
         0.90              0.0028      0.1254      0.1589      0.1542      0.1359      0.0913
         0.60              0.0151      0.1067      0.1282      0.1153      0.0801     -0.0045
         0.30              0.0195      0.0838      0.0960      0.0770      0.0266     -0.0971
         0.00              0.0189      0.0581      0.0627      0.0386     -0.0264     -0.1895
        -0.30              0.0161      0.0310      0.0284     -0.0005     -0.0808     -0.2850
        -0.60              0.0141      0.0037     -0.0066     -0.0412     -0.1383     -0.3870
        -0.90              0.0157     -0.0225     -0.0422     -0.0843     -0.2009     -0.4989
        -1.20              0.0243     -0.0461     -0.0782     -0.1306     -0.2709     -0.6246
        -1.50              0.0433     -0.0655     -0.1142     -0.1812     -0.3506     -0.7684
        -1.80               10        -0.0788     -0.1502     -0.2373     -0.4428     -0.9351
        -2.10                9        -0.0836     -0.1855     -0.3000     -0.5506     -1.1298
        -2.40                6        -0.0772     -0.2196     -0.3707     -0.6775     -1.3585
        -2.70                5           6        -0.2519     -0.4511     -0.8274       15
        -3.00                5           5        -0.2810     -0.5428     -1.0048       14


                             MAXIMUM =      0.9157
                             MINIMUM =     -1.3585
                             MEAN    =     -0.0244
                             RMS     =      0.3712
                             STD DEV =      0.3704
```

C O D E V

Dual-glazed HUD, Head Left 25mm

POSITION 2 - POSITION 4

Left Eye Image Doubling (Vertical)
ANGULAR ERRORS (MILLIRAD)

ELEVATION (DEGREES)	A Z I M U T H (DEGREES) -2.00	-3.00	-4.00	-5.00	-6.00	-7.00
3.00	8	8	9	-0.1667	-0.4623	14
2.70	8	8	0.1000	0.0253	-0.2245	-0.7212
2.40	8	9	0.2239	0.1491	-0.0619	-0.4769
2.10	8	0.2674	0.2971	0.2229	0.0443	-0.3027
1.80	9	0.3320	0.3347	0.2612	0.1092	-0.1823
1.50	10	0.3672	0.3483	0.2755	0.1448	-0.1025
1.20	0.3393	0.3832	0.3472	0.2748	0.1605	-0.0530
0.90	0.3747	0.3877	0.3385	0.2661	0.1636	-0.0257
0.60	0.3965	0.3867	0.3274	0.2544	0.1593	-0.0147
0.30	0.4098	0.3843	0.3176	0.2433	0.1516	-0.0161
0.00	0.4177	0.3832	0.3115	0.2351	0.1424	-0.0275
-0.30	0.4217	0.3846	0.3103	0.2307	0.1328	-0.0483
-0.60	0.4216	0.3885	0.3138	0.2301	0.1222	-0.0795
-0.90	0.4155	0.3934	0.3207	0.2315	0.1086	-0.1240
-1.20	0.3997	0.3964	0.3283	0.2321	0.0884	-0.1863
-1.50	0.3684	0.3926	0.3320	0.2273	0.0563	-0.2734
-1.80	10	0.3752	0.3257	0.2104	0.0047	-0.3945
-2.10	9	0.3346	0.3005	0.1726	-0.0766	-0.5619
-2.40	6	0.2582	0.2448	0.1020	-0.2006	-0.7912
-2.70	5	6	0.1433	-0.0169	-0.3846	15
-3.00	5	5	-0.0239	-0.2042	-0.6501	14

MAXIMUM = 0.4217
MINIMUM = -0.7912
MEAN = 0.1314
RMS = 0.3011
STD DEV = 0.2710

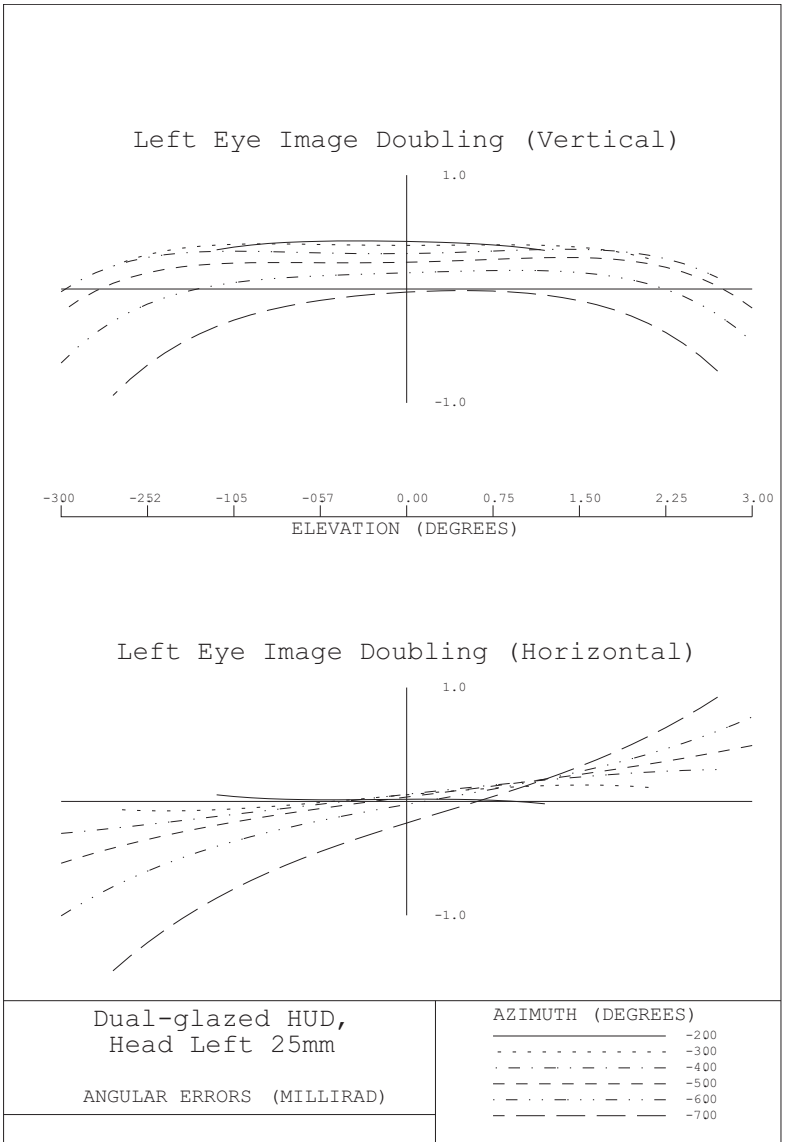

Figure 4. BIO vertical/horizontal image doubling plot

Example 3. Color fringing in a heads-up display

With the observer's eye not on the optical axis, color fringing can be due to lateral or longitudinal color or both. The lens setup from Example 2 can be analyzed for this effect by dezooming to a single position, then zooming the reference wavelength with:

```
ZOO 2;REF 1 3
```

Of course, you should make sure the wavelengths in WL are appropriate, and it is a good idea to delete a PIM solve (or any other first-order solves) before changing the reference wavelength.

The BIO analysis is then performed with:

```
BIO;ZPO Z1 Z2;AZI ...
```

A typical tolerance for color fringing is about one arc minute.