Polarization

Improved simulation of real-world devices in ASAP

This technical publication describes new polarization features in the Advanced Systems Analysis Program (ASAP®) from Breault Research Organization (BRO). A compressed file of ASAP scripts related to this document is available for download from the Knowledge Base. Please refer to ASAP Help for more complete conceptual, task-oriented, and reference content on polarization commands and on features of the Poincaré Sphere Visualization Tool (PSVT).

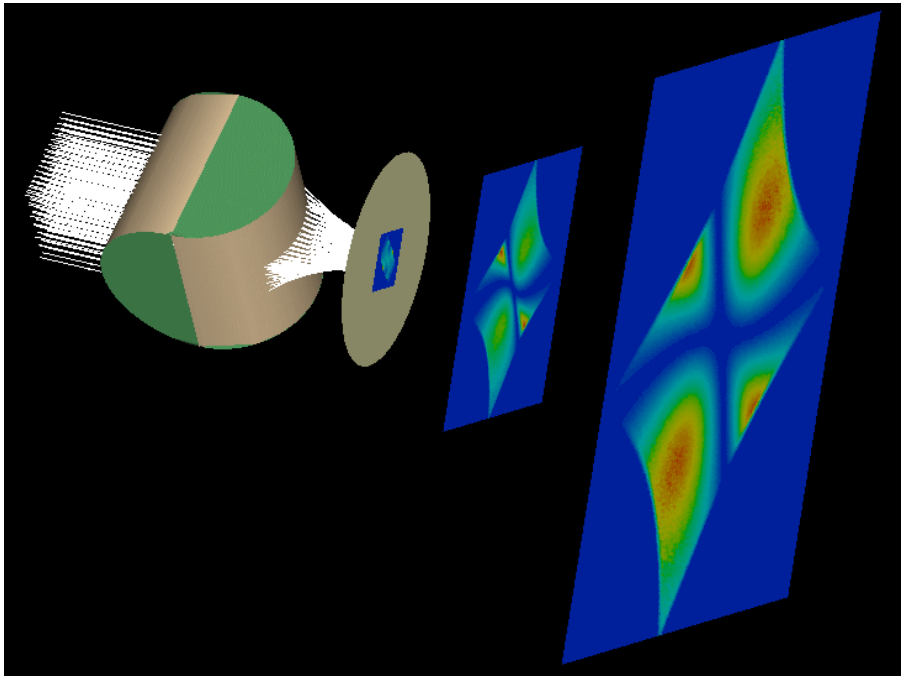

Figure 1 Transmitted energy through crossed cylindrical polarizers

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POLARIZATION IN ASAP

Analysis of polarization has been a part of ASAP for much of its history. With the advent of ASAP 2008 and continuing in subsequent releases for 2009 and 2010, significant new features have enhanced this capability. New classes of polarization elements have been added that improve the simulation of a range of real-world devices. Source polarization may be controlled using an explicitly defined reference ray, and randomization of source polarization makes it possible to model effects that idealized sources cannot produce. Ray distribution files can now include polarization data, and these files can be loaded to re-create a polarization field from previous ray trace results. Ray polarization data may be tracked in Jones vector mode or in Stokes vector mode, with the latter enabling modeling of partial polarization effects. Analysis features include output of polarization data in Jones or Stokes vector form, and a Poincaré Sphere Visualization Tool to show polarization state data and to allow exploration of the relationship among polarization, flux, position, and direction of rays.

Polarization phenomena have been observed for centuries, and the analysis of these effects began developing even before the foundation of electromagnetism was established. Although polarization is a characteristic of electromagnetic waves, it is not necessarily tied to the branch of optics commonly named “wave optics”, which deals with the finite wavelength of radiation, and the effects of diffraction and interference that follow. Polarization is crucial in many problems of wave optics, but many important problems in polarization analysis do not require a wave-optic analysis.

Although ASAP has allowed polarization analysis in its incoherent mode before, there were cases where coherent mode was required to achieve the desired result. BRO relaxed this restriction by implementing new features in ASAP for setting up polarization devices, polarized sources, tracing of polarized sources, and analysis of polarization states. The techniques pioneered by these changes are a sound foundation for enhanced polarization simulation.

The approach used to solving problems in ASAP is often described in terms of the so-called “four-step process”. Since this process has served many ASAP users well, we examine the polarization features as they relate to these steps.

Four-step process for polarization enhancements

When we discuss the four-step process in ASAP, we are just trying to help organize our analysis. It is a practice to focus on the fundamental challenges of a problem, and to reduce them to the necessary tasks. The four steps are:

1. System
2. Source
3. Trace
4. Analysis

System commands are those that are used to build the physical parts of an optical system. *Source* commands impose the light that we want to follow through the components of the physical system. The *Trace* step is the way the source light is moved into, through, and possibly out of the system. Finally, *Analysis* is the process of asking

what happens to light in the system. A summary of the process and the commands that support it is shown in .

Table 1. Process and commands supporting polarization in ASAP

System	Source	Trace	Analysis
JONES	POLARIZ MODE	No change	LIST RAYS POLARIZATION
MUELLER	POLARIZ K		
RPM	POLARIZ TREF		
RRM	POLARIZ p q		
GUM	POLARIZ RANDOM		
LCC			
CPE			PLOT POLARIZATION
BIC			
MEDIA BIAXIAL			Poincaré sphere visualization tool (PSVT)
INTERFACE POL	DUMP EMITTING RAYS		DUMP

POLARIZATION FEATURE ENHANCEMENTS

Now, we take the steps into the actual commands of the new polarization features.

System commands

To accurately simulate polarization effects in systems, the dependence of surface behavior upon the angle of incidence must be properly enabled.

***NOTE* For models using the new polarization devices described here, a global setting of FRESNEL BOTH is strongly recommended.**

The new device types are used in a similar manner to coatings, but they are a new class of object modifiers. The system commands include commands that define the behavior of the devices themselves, and a command to attach these device definitions to an object.

DEVICE DEFINITION COMMANDS

JONES COMMAND

The **JONES** command allows a device to be described in terms of the interface reflected and transmitted polarization using a local Jones matrix. Each matrix element may be a complex number. The syntax is:

```
JONES T11 T12 T21 T22 [R11 R12 R21 R22] [REFL] ['name']
```

The **Tij** are transmission elements, and the **Rij** are reflection elements. Transmission is the default if only four elements are specified. The **REFL** option modifies this default behavior. To retain both transmitted and reflected components, all eight elements are needed. For example, using the fact that transmission is the default when only four matrix elements are provided, a transmissive quarter-wave plate can be described by:

```
!! QUARTER-WAVE PLATE, FAST AXIS HORIZONTAL
JONES COS[45]`SIN[45] 0 0 -SIN[45]`COS[45] 'QWP_FASTHORIZONTAL'
```

For further information of the syntax, please refer to the topic, “JONES (ASAP Command)” in ASAP Help.

MUELLER COMMAND

The **MUELLER** command allows a device to be described in terms of the interface reflected and transmitted polarization using a Mueller matrix. One syntax is:

```
MUELLER M11 {value} M12 {value}...M44 {value} RM11 {value}...RM44 {value} 'name'
```

The **Mij** are transmission element keywords, each of which is followed by its assigned value; the **RMij** define reflection elements. All unspecified elements are assumed to be zero, making this syntax useful for sparse Mueller matrix descriptions. The keywords may be omitted if the elements are specified in precisely this row-echelon order. Transmission is the default if 16 or fewer elements are specified in this way. The **REFL** option modifies this default behavior. Another syntax includes the elements on subsequent lines without keywords:

```
MUELLER
m11 m12 m13 m14   rm11 rm12 rm13 rm14
m21 m22 m23 m24   rm21 rm22 rm23 rm24
m31 m32 m33 m34   rm31 rm32 rm33 rm34
m41 m42 m43 m44   rm41 rm42 rm43 rm44    `name'
```

where the **mij** and **rmij** are the actual values of the matrix coefficients. On each line, trailing coefficients that are omitted are assumed to be zero. For example, a free-space matrix may be defined:

```
MUELLER
1 0 0 0    0 0 0 0
0 1 0 0    0 0 0 0
0 0 1 0    0 0 0 0
0 0 0 1    0 0 0 0   `FREESPACE'
```

or, taking advantage of the trailing zeros:

```
MUELLER
1
0 1
0 0 1
0 0 0 1    `FREESPACE'
```

Of course, the previous keyword syntax can be useful and compact here, as well.

For more information on the syntax, please refer to the topic, “MUELLER (ASAP Command)” in ASAP Help.

RPM COMMAND

The **RPM** command is an abbreviation of “Realistic Polarizer Model”. It is based on common real polarizers that operate by absorption in a birefringent material. These devices are classified as O-type or E-type, for the *ordinary* or *extraordinary* transmitted components through the devices.

In O-type polarizers, the absorption is in the extraordinary index, and the extraordinary component is absorbed. However, in E-type polarizers, the absorption is in the ordinary index and the ordinary component is absorbed. The device may be described by its extinction ratio, transmission and reflection coefficients, acceptance angle, and real indices. If no parameters are provided, it is still a valid definition for a transmissive polarizer with fixed indices of n_o=1.5, n_e=2.1. The syntax is:

```
RPM [extinction ratio] [Tp] [Rp] [Rs] [acceptance angle] [no] [ne] [PRE] '[name]'
```

The **Rp** is the reflectance of light polarized along the transmission axis, while the second, **Rs**, is the reflectance of light polarized normal to the transmission axis. The pre-polarizer **PRE** option causes the input to be assumed unpolarized for a positive propagation direction. Here are several examples of polarizer definitions using this model.

```
RPM  1E4  'POL_O'                 !! simple O-type polarizer
RPM -1000 'POL_E'                 !! simple E-type polarizer
RPM  300 0.95 0.1 0.05 'POL_ETR' !! O-type with extinction, T, R
RPM 1500 0.8 'POL_ET'             !! O-type with extinction, T only
```

These models can be used to produce many classical results of polarization physics, including the variations on the “Maltese cross” pattern that occur when crossed polarizers are in a non-collimated beam. As illustrated in Figure 2, a lens is placed in a collimated beam to produce a beam that passes through focus.

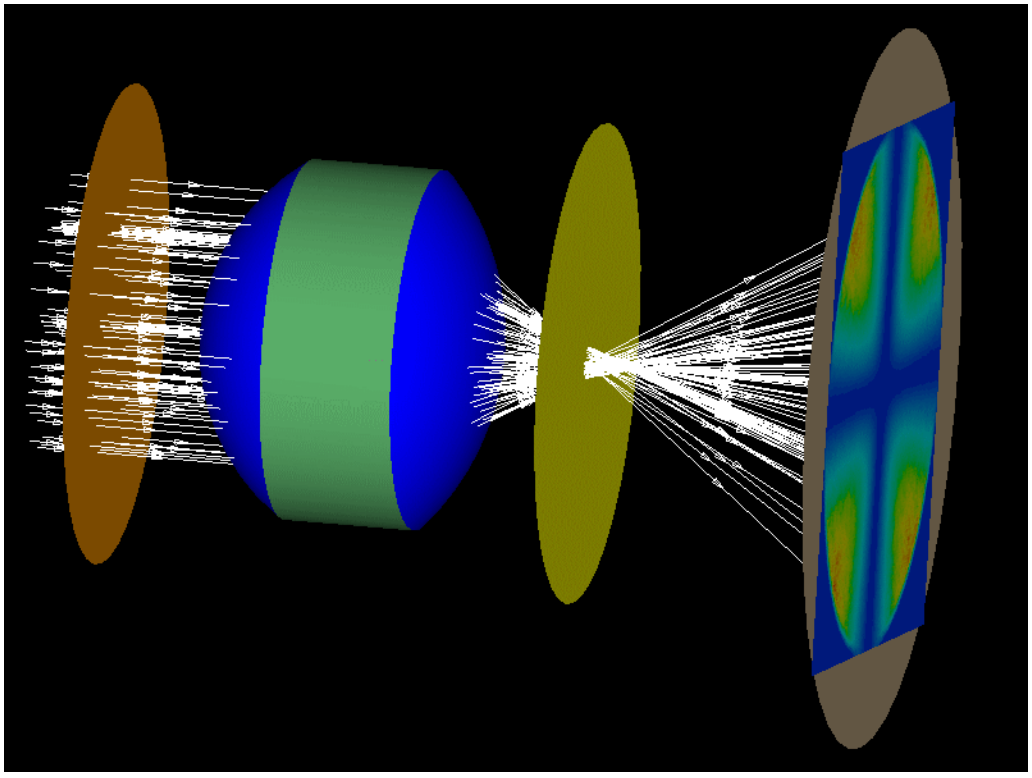


Figure 2 Lens test between crossed polarizers

By placing a crossed polarizer pair around the lens, such a pattern is observed in the transmitted irradiance. See Figure 3.

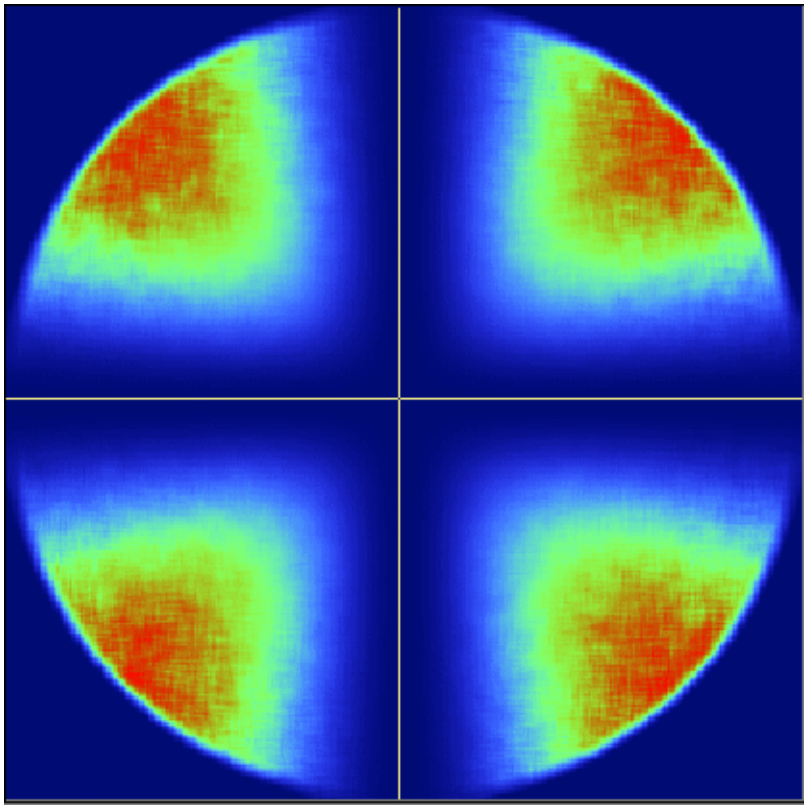


Figure 3 Polarization interference test result of a lens

For more information on the syntax, please refer to the topic, “RPM (ASAP Command)” in ASAP Help.

RRM COMMAND

The **RRM** command is an abbreviation of "Realistic Retarder Model", and is based on the behavior of uniaxial birefringent materials under a small-birefringence approximation. The device may be described by its retardance, design wavelength, nominal thickness (the retarder does not have to be zero-order), transmission and reflection coefficients, and the two refractive indices. If no parameters are provided, it is still a valid definition for a transmissive quarter-wave retarder, at a design wavelength of 0.633 μm, with fixed indices of n_o=1.543, n_e=1.552. The syntax is:

```
RRM [retardance[wavelength [thickness [transmission [no [ne [Ro Re ]]]]]]]
'[name]'
```

Its arguments are described as follows:

- The on-axis retardance is given in waves.
- The design wavelength is specified in μm, as is the nominal thickness of the retarder.
- The fourth argument is the power transmittance of the device.
- The ordinary and extraordinary refractive indices, **no** and **ne**, respectively, may be prescribed next, or the name of a previously-defined **CRYSTAL** medium may be used to provide the index information for both.
- The **Ro** is the reflectance of the ordinary eigenmode, and **Re** is the reflectance of the extraordinary eigenmode; the default for these is zero.

Here are several examples of definitions using this model:

```
!!quartz quarter-wave at 0.633 um wavelength
RRM  'RET_DEFAULT'

!!half-wave plate at 0.552 um; nominal thickness 120 um
RRM  0.50 0.552 120.0 'RET_HW'

!!quarter-wave plate with specified no and ne
RRM  0.25 0.660 80.0 1.0 1.537 1.548

!!half-wave plate using previously-defined media indices
RRM  0.50 0.550 75.0 CRYST_QUARTZ
```

This model is generally intended to model physically thin devices. An example of this is the insertion of a retarder between crossed polarizers to compensate for the off-axis polarizer behavior. A retarder with its extraordinary axis along the system axis, known as a c-plate, may be inserted in such a system as part of a more extensive compensation scheme.

The result of inserting an optically thick (~5 wave retardance) c-plate between crossed O-type polarizers is shown in Figure 4.

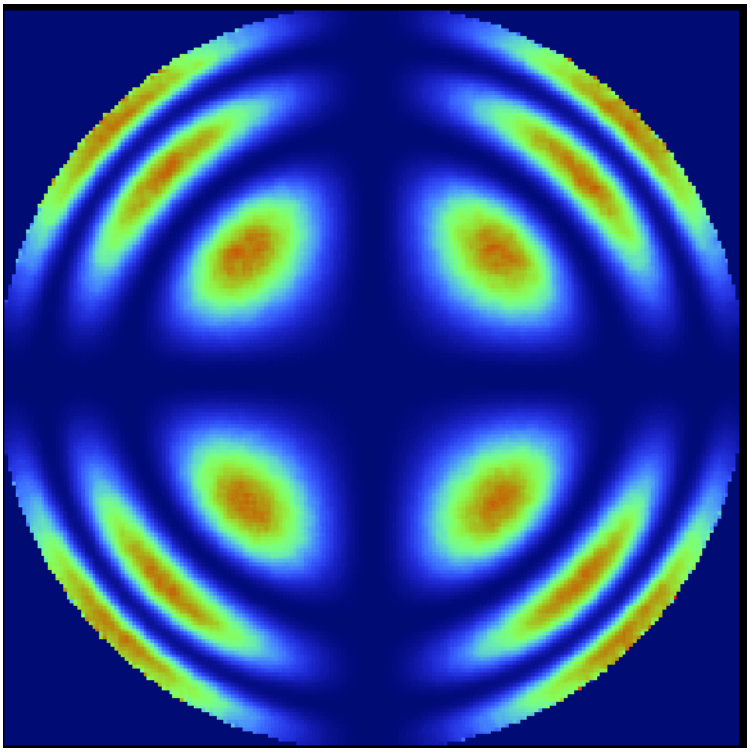


Figure 4 Polarization interference when a thick c-plate retarder is inserted between crossed polarizers

The result exhibits multiple transmitted orders through the system, replacing the Maltese cross pattern for the crossed polarizers alone. Note that since the extraordinary axis of the c-plate is along the system axis, there is no retardance on-axis, but retardance off-axis varies to produce polarization interference.

The retarder in this case is created using the **RRM** command:

```
RRM 505 0.55 278 1.0 1.543 1.552 'THICK_C'
```

For more information on the syntax, please refer to the topic, “RRM (ASAP Command)” in ASAP Help.

Subsequently, this device definition is applied to an object interface in the system. Applying this device to an object interface to place its extraordinary axis along the object's surface normal is demonstrated in “Device object commands” on page 22.

The RRM device type may be used to model variable-alignment of birefringent stratified media, as well. One important application of this is the simulation of liquid crystal (LC) devices by representing them as an assembly of sub-cells.

GUM COMMAND

The **GUM** command is an abbreviation of "General Uniaxial Medium". As with **RRM**, it is based on the behavior of uniaxial birefringent materials under a small-birefringence approximation. The device may be described by its thickness, two refractive indices, and optional reflection coefficients. If no parameters are provided, it is still a valid definition for a transmissive uniaxial layer with a thickness of 100 μm, with fixed indices of n_o=1.543, n_e=1.552. The syntax is:

```
GUM [thickness    no     ne   REFL  Rs  Rp  'name']
```

The arguments are described as follows. The thickness is given in micrometers. The ordinary and extraordinary refractive indices, **no** and **ne**, respectively, may be prescribed next, or the name of a previously-defined **CRYSTAL** medium may be used to provide the index information for both. The **REFL** keyword alone specifies that Fresnel reflection coefficients will be calculated and applied. Finally, the **Rs** specifies the reflectance of the *s*-polarization component, and **Rp** the reflectance of the *p*-polarization component; the default for these is zero. Here are several examples of definitions using this model.

```
!!default -- quartz 100 um layer with reflection omitted
GUM  'GUM_DEFAULT'

!!thickness 120 um, with specified indices and reflection
GUM  120.0 1.54 1.56 REFL 0.2 0.1 'GUM_PARTIAL_REFL'

!!thickness 37.6 um, with using previously-defined media indices
GUM  37.6 MY_CRYST 'GUM_CRYST'
```

This model, like the **RRM**, is intended to model physically thin devices. It provides a direct method to create devices where the physical thickness, rather than the retardance, is known. Further, the **GUM** reflection coefficients, if any, are expressed in terms of the incident *s* and *p* polarization states. Instead, the **RRM** uses reflection coefficients expressed in terms of the device ordinary and extraordinary eigenstates. Aside from these details, **GUM** applications parallel those of **RRM**.

For more information on the syntax, please refer to the topic, "GUM (ASAP Command)" in ASAP Help.

Subsequently, this device definition is applied to an object interface in the system. Applying this device to an object interface to place its extraordinary axis along the object's surface normal is demonstrated in the last syntax example under "Device object commands" on page 23.

The GUM device type, like the **RRM**, may be used to model variable-alignment of birefringent stratified media by dividing it into sub-cells.

LCC COMMAND

The **LCC** command is an abbreviation for “Liquid Crystal Cell”. It is a model for typical liquid crystal materials with spatially varying uniaxial birefringence. The device is described by its thickness and material ordinary and extraordinary indices, and by the variation in orientation of the extraordinary axis. The extraordinary axis in liquid crystal media is often called the crystal *director*, and we may use either term in this context. Two angles are used to describe the orientation of the director in the device local coordinates. This is depicted in Figure 5.

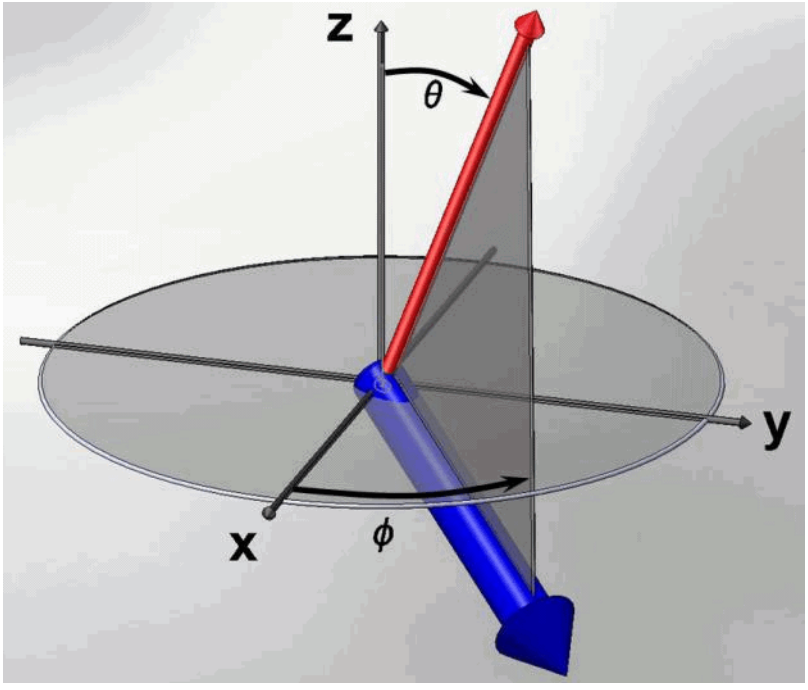


Figure 5 Orientation defined by polar angle and the azimuthal angle

The orientation in the figure is defined by the polar angle (tilt, pre-tilt), θ, and by the azimuthal angle (twist), ϕ. The **z** axis here is assumed to be a reference device axis, and the **x** axis is assumed to be the home position of the director or extraordinary axis, shown as a thick blue arrow. A perpendicular (shown as a thin red arrow) to the director is included to clarify the definition. The polar angle is both the angle of this director normal (thin red) from the local axis, and the angle of the director (thick blue, extraordinary axis) out of the local **x**-**y** plane. The azimuthal angle is defined by director rotation from the **x** axis. We could simply say that the orientation is defined by starting with the director along the local **x** axis, rotating by the angle ϕ in the **x**-**y** plane, and then tilting by the angle θ out of the **x**-**y** plane. The latter variation can be described by a linear variation between two limits, by a set of values in a table, or by equations as **$FCN**’s. If no parameters are provided, it is still a valid definition for a transmissive liquid crystal cell of 5 μm thickness, with fixed indices of n_o=1.487, n_e=1.568.

There are parameters for optional reflection behavior, but for now we are focusing on transmission. Because the model can be used to describe complex variations in orientation, there are multiple syntaxes to allow a user to choose the best one for the task at hand. The simplest syntax, suitable for a linear variation in one of the orientation angles, is:

```
LCC [ [thickness {no ne}| Crystal_Medium_index ] [ THETA|PHI start_angle end_angle
steps ]
 [REFL [Rs Rp]] '[name]'
```

These are the arguments:

- The thickness is specified in μm.
- The indices are specified either as an **no**, **ne** pair, or via a previously-defined **CRYSTAL** medium name.
- The orientation parameter to be varied is specified by the choice of **THETA** or **PHI** keyword, followed the two limits of a linear variation, and the number of discrete steps used through the thickness to vary the orientation.

Using our input of the LC pre-tilt and twist angles, corresponding to the device polar and azimuthal angles, we describe an LC cell.

For information on the reflection parameters, please refer to the topic, "LCC (ASAP Command)" in ASAP Help.

To illustrate the basic utility of such a model, consider a normally-white twisted-nematic, liquid crystal (NW TN-LC) cell.[1] We can model the liquid crystal cell birefringence by dividing the cell into sub-cells, each described by a single RRM device, but with a different extraordinary-index orientation. However, the LCC model provides a more direct way to describe this system. Here is an example of this syntax for a very simple model, ignoring a small polar angle, of a NW TN-LC cell in the "on" state.

```
!! NW-TN cell, 5.9 um thick, in its "On" state using linear phi variation
LCC 5.9 1.487 1.568 PHI 0 90 20 'LCC_CELL_ON_SIMPLE'
```

This liquid crystal cell, when placed between crossed polarizers, represents the on-state behavior of a simple liquid crystal display device.

1. Yeh, P., and Gu, C., *Optics of Liquid Crystal Displays*, John Wiley & Sons, New York, 332-337 (1999).

The directional transmission profile for such a model is shown in Figure 6.

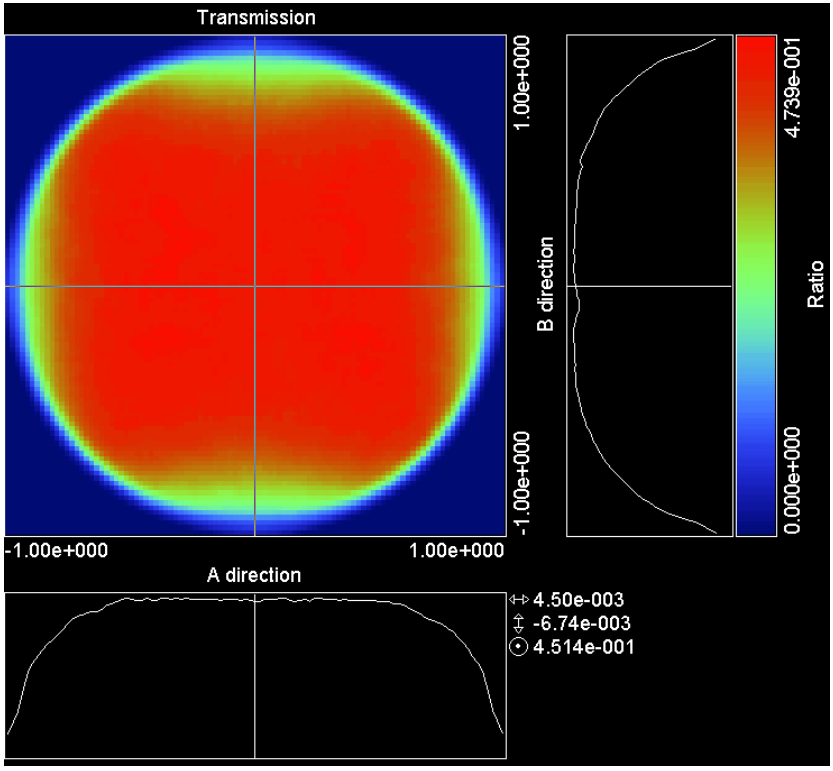


Figure 6 On-state intensity transmittance of a Normally White TN-LC cell, using an LCC model with only variation in azimuthal angle orientation, enclosed between crossed O-type Realistic Polarizer Models (RPM)

A more accurate model requires variation of both orientation angles. This may be done using a table (see ASAP script excerpt below) or equations.

```
!! NW-TN cell, 5.9 um thick, in its "On" state using a theta-phi table
LCC 5.9 1.487 1.568 BOTH TABLE 20 'LCC_CELL_ON'
0.295   2     2.25     !! 01
0.590   2     6.75     !! 02
0.885   2     11.25    !! 03
1.180   2     15.75    !! 04
1.475   2     20.25    !! 05
1.770   2     24.75    !! 06
2.065   2     29.25    !! 07
2.360   2     33.75    !! 08
2.655   2     38.25    !! 09
2.950   2     42.75    !! 10
3.245   2     47.25    !! 11
3.540   2     51.75    !! 12
3.835   2     56.25    !! 13
4.130   2     60.75    !! 14
4.425   2     65.25    !! 15
4.720   2     69.75    !! 16
5.015   2     74.25    !! 17
5.310   2     78.75    !! 18
5.605   2     83.25    !! 19
5.900   2     87.75    !! 20
```

The keyword, **BOTH** is followed by the keyword, **TABLE**, and then the number of steps. In this case, this means that both orientation angles are varied through 20 steps. This requires a table with 20 lines. Each line contains a depth for that step, the polar angle, and the azimuthal angle. Angles are in degrees.

Each depth entry must be within the range from zero (0) through the specified total thickness. The transmission profile for this model is shown in Figure 7.

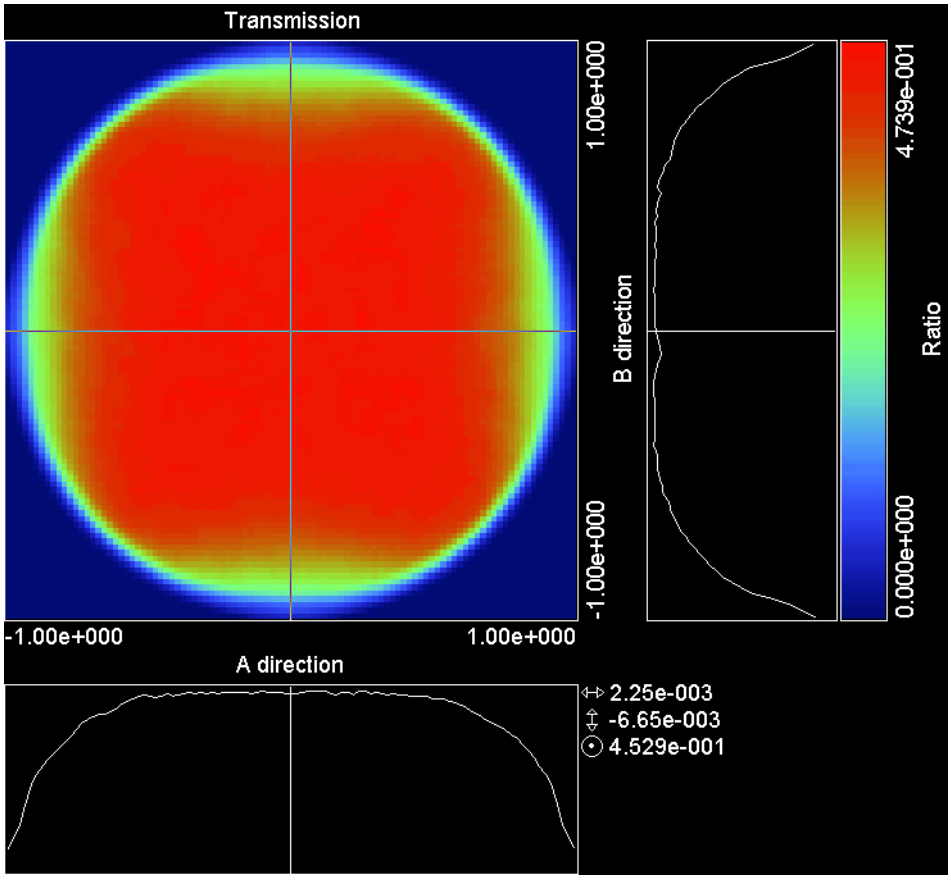


Figure 7 On-state intensity transmittance of a Normally White TN-LC cell, using an LCC model with variation in both orientation angles described by a data table, enclosed between crossed O-type Realistic Polarizer Models (RRM)

If the orientation is known in closed form from physical analysis, or measurement data have been fitted to equations, we may use the functional form. The “Off” state orientation requires nonlinear variation in both orientation parameters, so this is a good application for a **$FCN**-driven model. The definition is below.

```
!! define the $FCNs for the parameters (NW-TN in "Off" state)
$FCN LC_TILT 90*((1-(ABS((_/COMP_THICKNESS)-0.5))^6/0.5^6))
$FCN TANH (EXP(_)-EXP(-_))/(EXP(_)+EXP(-_))
$FCN LC_TWIST 90*(1+TANH(11*((_/COMP_THICKNESS)-0.5)))/2

!! NW-TN cell, 5.9 um thick, in its "Off" state using theta-phi $FCNs
LCC 5.9 1.487 1.568 BOTH LC_TILT LC_TWIST 101 'LCC_CELL_OFF'
```

This syntax uses a defined **$FCN** function for each of the orientation angles, rather than the table used before. The function for theta is named first, then the function for phi, followed by the number of steps used for evaluation. This is quite compact, but of course it requires previous analysis. It is useful for testing published results, or for applying results from other modeling tools to analysis in ASAP. The performance for this system is shown in Figure 8.

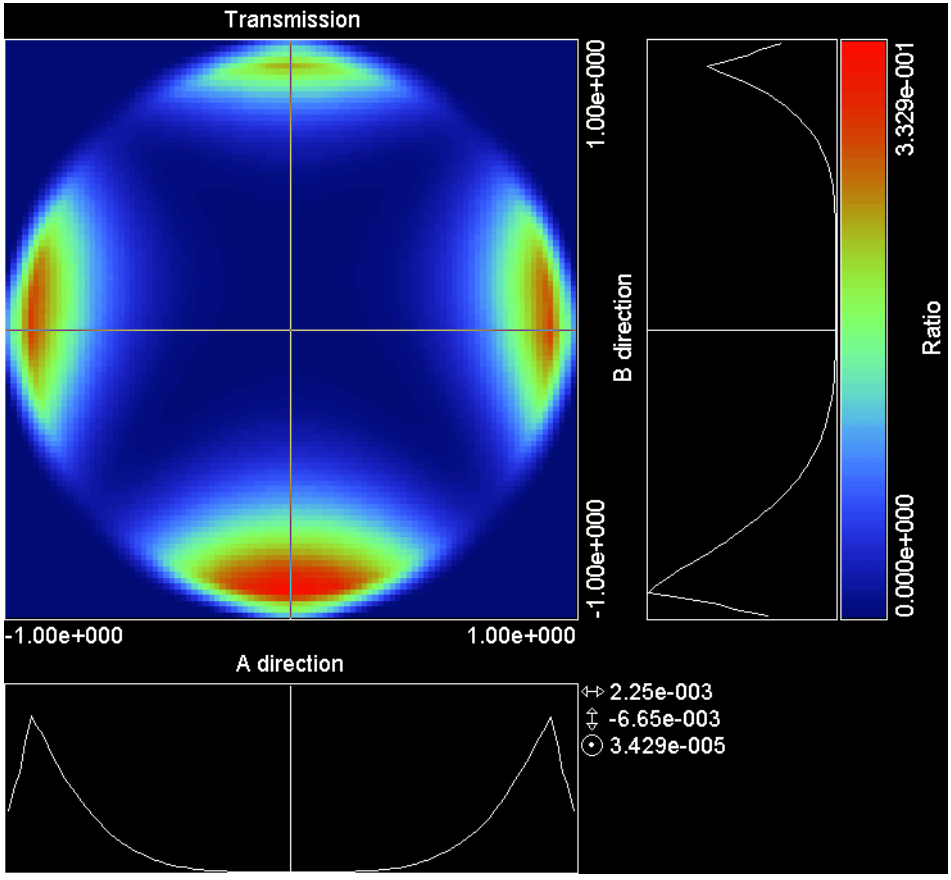


Figure 8 Off-state intensity transmittance of a Normally White TN-LC cell, using an **LCC** model with variation in both orientation angles described by **$FCN**'s, enclosed between crossed O-type Realistic Polarizer Models

These models are starting points for more detailed design studies of liquid crystal display devices. Typical analyses might include, for example, compensator design to improve off-state extinction or angular coverage, color transmission examination, and optimization for a specific range of viewing angles.

BIC COMMAND

The **BIC** command is used to define a layered device with birefringent media, a birefringent coating. It may include a combination of isotropic, uniaxial, and biaxial materials. The media refractive indices may be defined in line within the command structure for monochromatic analyses, or by referencing previously defined **MEDIA** definitions for monochromatic or polychromatic analyses.

We use the following syntax in this command.

```
BIC   N    ['name']
thickness n1 n2 n3                                  theta psi  phi
thickness {biaxial media name|list index number} theta psi  phi
thickness n
...
```

Parameter **N** indicates the number of layers. The layers are then defined on the lines following the **BIC** command line, with one line for each layer. The thickness of each layer is defined in μm. The parameters **n1, n2, n3** define the principal refractive indices of biaxial media; uniaxial media may be defined by making two of the indices equal. The parameters **theta, psi, phi** define the Euler angles [degrees] in the Z-X-Z Euler sequence convention. The parameter **n** is the single refractive index defining an isotropic media layer.

For more information on the syntax, please refer to the topic, "BIC (ASAP Command)" in ASAP Help.

Using in-line refractive index definitions, we can construct a new BIC device as follows.

```
!! Define a BIC element using inline principal indices as numbers
BIC 3 'BIUNISO'         !! demonstrate a biaxial, a uniaxial, and an isotropic
  0.422 1.6 1.56 1.54    30 45 60   !! biaxial
  0.633 1.56 1.48 1.48    2 15 -5   !! uniaxial
  0.211 1.62                        !! isotropic
```

In the context of the **BIC** command, we may sometimes want a convenient way to define the refractive indices of a biaxial medium and assign that a media name. This is particularly useful if the indices must be defined at multiple wavelengths for a polychromatic analysis. The **MEDIA BIAXIAL** command is designed for this purpose.

***NOTE** Though this section is for device descriptions, we introduce this special-purpose media command,* **MEDIA BIAXIAL**, *here because it is mated to the BIC device type, and is not used in any other context.*

MEDIA BIAXIAL COMMAND

At the risk of repeating the previous paragraph, the **MEDIA BIAXIAL** command is a specialized command supporting the **BIC** command. It allows the efficient entry of biaxial material refractive indices as a dummy media definition. The syntax is similar to the **MEDIA CRYSTAL** command, but with no alignment parameters. Alignment is configured by the **BIC** command, and thus is not necessary here.

The command syntax is

```
MEDIA BIAXIAL
n1|m1      n2|m2        n3|m3       ['media name']
...
```

The parameters **n1, n2, n3** define the principal refractive indices of biaxial media; uniaxial media may be defined by making two of the indices equal. The alternate parameters **m1, m2, m3** may be either the names of previously defined isotropic media, to be used for each of the principal refractive indices, or the media numbers as reported in, for example, **PRINT MEDIA**. This allows a polychromatic conventional media definition to be used as input to a biaxial media; this is convenient and it maintains consistency in the ASAP media data scheme. The ***media name*** defines a name that may be referenced in the **BIC** command, as with all other naming definitions in ASAP. If not provided, the name is automatically set with a name stem **BIAXIAL**, appended with the biaxial definition index number. Biaxial media are numbered in their own separate list, starting at 00001. Thus, the third biaxial media is named BIAXIAL00003 if the user does not specify a name.

For more information on the syntax, please refer to the topic, "MEDIA BIAXIAL (ASAP Command)" in ASAP Help.

Now that we know how a biaxial media definition works, we can demonstrate how to use the **BIC** command by media name, rather than by in-line refractive indices.

```
!! Define a BIC element using previous MEDIA BIAXIAL definitions
MEDIA BIAXIAL
1.60  1.56  1.54    'BIAX1
1.56  1.48  1.48    'UNIAX1'

MEDIA
1.62     'ISOTROP1'

BIC 3 'BIUNISO2'          !! demonstrate a biaxial, a uniaxial, and an isotropic
  0.422 BIAX1     30 45 60    !! biaxial
  0.633 UNIAX1     2 15 -5    !! uniaxial
  0.211 ISOTROP1              !! isotropic
```

TIP in both the BIC and MEDIA BIAXIAL commands, there is the potential ambiguity between specifying a media number or a numeric refractive index. Best practice is to use media names rather than media number where possible. Use a floating-point number with decimal point to specify a refractive index value, and an integer without a decimal point to specify a media number, if media numbers must be used.

To further generalize this to polychromatic media definitions, we define simple isotropic media that produce the dispersion relation for each of the three principal indices, and substitute the name of each of these simple media for the corresponding numeric indices in the previous example. This provides great flexibility in describing and analyzing the dispersion of complex birefringent stratified coatings.

CPE COMMAND

Using the basic device types described before, a composite device of “Cascaded Polarization Elements” can be defined. This works by cascading the transmission characteristics of multiple simple devices. The reflected component interactions among the multiple elements are not considered. The number of elements cascaded is limited only by system resources. Please note that cascaded devices cannot be nested; in other words, one **CPE** cannot use another **CPE** as a device in its definition.

We use the following syntax in this command.

```
CPE   n   Alignment   [STACKED]    ['name']
{type|type_ID}     {element name|list_ID}      theta     phi
{type|type_ID}     {element name|list_ID}      theta     phi
```

Parameter **n** tells the number of devices cascaded. The parameter, **Alignment** may be either **RELATIVE** to the previous entry, or **ABSOLUTE**; in which case, all subsequent elements are aligned to the first element in the CPE. Each device “layer” is then referenced in subsequent lines, including the polar angle, theta, and the azimuthal angle, phi, describing the its alignment. The type describes the specific device type corresponding to one of the device definition commands in the preceding sections. Each defined device is referenced by its name (or number in that device list).

The valid device type and type ID entries are related to their respective devices in Table 2 on page 23.

For more information on the syntax, please refer to the topic, “CPE (ASAP Command)” in ASAP Help.

Using two of the previous device definitions, we can construct a new CPE device as follows.

```
!! Define a CPE element
CPE 2 ABSOLUTE 'QWP_ISOLATOR'
  POLARIZER  POL_O                0  0
  JONES      QWP_FASTHORIZONTAL   0  45
```

The combination of a polarizer and a quarter-wave retarder is a simple isolator to control ghost reflections that might otherwise pass backwards through the device. This isolator is illustrated in Figure 9.

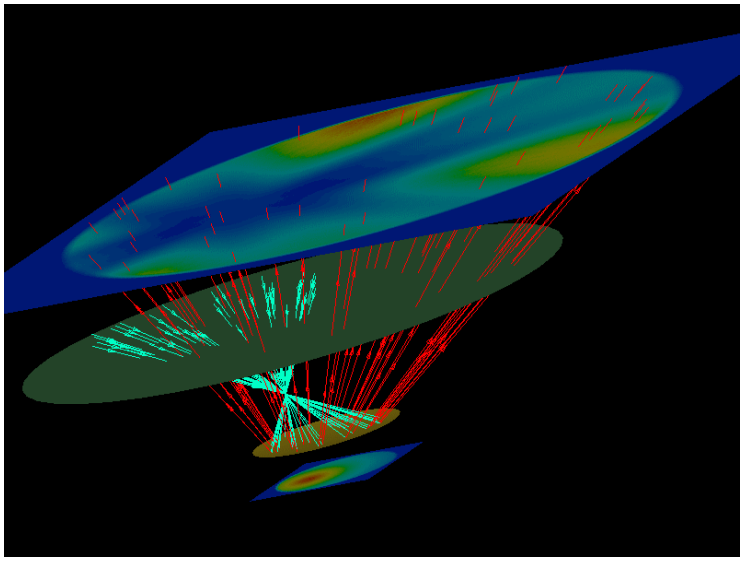


Figure 9 Simple isolator with second pass due to a mirror reflection

The green plane in the center is the isolator. A converging beam passes through the isolator, goes through focus, is then reflected by a mirror, and makes its second pass through the isolator. At the bottom is the irradiance map at the mirror, while at the top is the throughput irradiance, in a skew Maltese cross form. See Figure 10 to exam-

ine this irradiance pattern in detail.

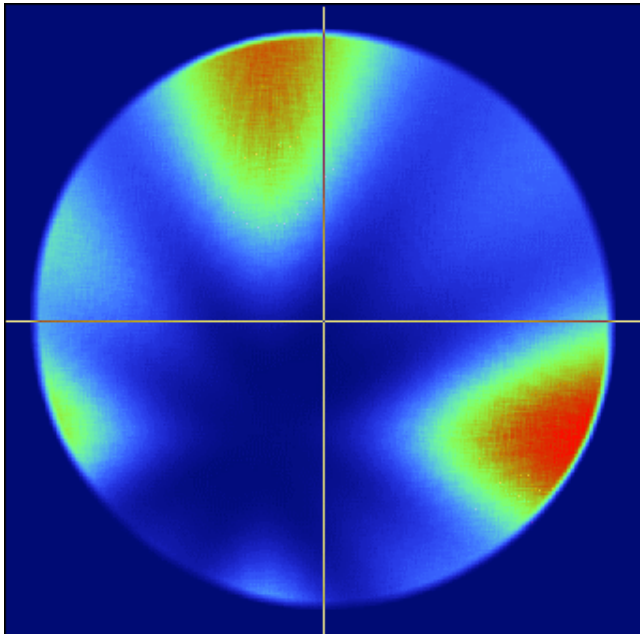


Figure 10 Detail of the isolator throughput

This cascaded element technique simplifies modeling when a large number of devices must be stacked. A common example of this is the modeling of liquid crystal cells for displays, in which the LC cell, compensator elements, and polarizers must be combined.

DEVICE OBJECT COMMANDS

Now that we know about the types of new polarization devices, we need to know how to apply them to an object. A familiar command, **INTERFACE**, is used, but with a new option for polarization devices.

The **INTERFACE POLARIZATION** command is used as an object modifier.

We may use the following (somewhat simplified) syntax in this command.

```
INTERFACE POLARIZATION {type|type_ID} {element name|list_ID} theta phi  media1 media2
```

The *type* describes the specific device type corresponding to one of the device definition commands in the preceding sections. Each defined device is referenced by its *element name* (or number in that device list). The orientation in device surface coordinates is described by the tilt angle *theta* and azimuthal angle *phi*, both in degrees. The media bounding the interface, *media1* and *media2*, are typical expressed as media names.

For example, the simple isolator described by a CPE device might be attached to an object by this sequence of commands.

```
!! attach a cascaded device to an object
...
OBJECT 'SIMPLE ISOLATOR'
INTERFACE POLARIZATION CPE QWP_ISOLATOR 0 30 AIR AIR
```

Here, parameters specify the device type (CPE), the polarization device name (QWP_ISOLATOR), the alignment polar (tilt or out-of-plane angle) and azimuthal angles (0 degrees and 30 degrees, respectively), and media (AIR AIR) of the interface.

The valid device type and type ID entries are related to their respective devices in Table 2.

Table 2. Polarization devices, *type* mnemonics, and numeric *type IDs* used as input

Device Type Name	Type	Type ID
Jones matrix element	`JONES`	1
Mueller matrix element	`MUELLER`	2
Realistic polarizer	`POLARIZER`	3
Realistic retarder	`RETARDER`	4
General uniaxial media	`GUM`	5
Liquid crystal cell	`LCC`	6
Birefringent coating	`BIC`	7
Cascaded polarization element	`CPE`	8

For a complete description of the syntax, please refer to the topic, “INTERFACE POLARIZATION” in ASAP Help.

In the case of the thick c-plate described in “RRM command” on page 8, the extraordinary axis must be tipped to coincide with the system axis; for example,

```
!! attach a RRM device to an object with its axis in the surface normal direction
OBJECT 'C_PLATE'
INTERFACE POLARIZATION RET THICK_C 90 0 AIR AIR   !! 90 degree polar angle
```

Source commands

Along with new classes of devices, we have commands to improve our capability to describe the polarization of light sources. ASAP has always expressed polarization in terms of a propagation direction, a reference polarization direction, and another polarization component direction orthogonal to both of these. Before ASAP 2008, the reference propagation direction was implied by the source axis, and the transverse polarization reference direction was associated to a global axis direction. These references are now made by explicit commands, using the concept of a reference ray. With ASAP 2009, polarization states may be described and traced in terms of Stokes vectors, enabling partial polarization. The previous ability to track polarization by Jones vectors is also retained, and is appropriate where partial polarization is not necessary.

In many optical systems, sources are characterized by a randomization of polarization state. While ASAP previously had a limited capability to set up such sources, source randomization is now supported by explicit and flexible commands.

POLARIZATION STATE COMMANDS

Before creating polarized sources, we must decide the polarization tracking mode that is appropriate. In versions prior to ASAP 2009, polarization is tracked internally using a Jones vector technique. As of ASAP 2009, a Stokes vector technique is available for systems where partial polarization analysis is needed. A new **POLARIZ** keyword, **MODE** allows this setting:

```
POLARIZ MODE   JONES        !! THE DEFAULT
POLARIZ MODE   STOKES       !! to allow partial polarization
```

***NOTE** Sources must be established in Stokes mode to examine subsequent partial polarization effects. A depolarization effect cannot be used to change this mode, since it concerns the actual way in which polarization data are interpreted in the device interactions of ray tracing.*

The reference ray concept chooses a propagation direction and a transverse reference direction for the fundamental polarization direction. For collimated sources, these may coincide with actual rays. For non-collimated sources, the reference directions are related to actual rays by a transformation related to an ideal, lossless, thin lens element[1]. Two new forms of the **POLARIZ** command have been added to set these reference directions.

POLARIZ K specifies the propagation reference direction. It specifies either a global axis direction or a general, global direction with direction cosines. We can remember the function of this **K** option by association with the k-vector nomenclature for propagation direction used in electromagnetic analysis.

```
!! set reference propagation direction by global axis
POLARIZ K Z


!! set reference propagation direction by general direction
POLARIZ K 0 0 1
```

1. Mansuripur, M. “Distribution of light at and near the focus of high-numerical-aperture objectives,” Journal of the Optical Society of America (JOSA) A 3, no. 12, (December 1986): 2086-2093.

The command, **POLARIZ TREF** sets the fundamental transverse reference direction for polarization:

```
!! set reference polarization direction by global axis
POLARIZ TREF X

!! set reference polarization direction by general direction
POLARIZ TREF 1 0 0
```

An **AUTO** option determines this transverse reference direction by a minimal rotation transformation from the global axes. Once these reference directions are established, the **POLARIZ** command with no directional reference specifies the complex polarization components to complete the source polarization state.

For more information on the syntax, please refer to the topics, “POLARIZ”, “POLARIZ K (Reference Ray Direction)”, and “POLARIZ TREF” in ASAP Help.

NOTE ASAP automatically enforces the orthogonality between the reference ray direction and the transverse reference direction.

POLARIZATION RANDOMIZATION

With the reference state specified, a randomization of this state may be set up by perturbing the state. The **POLARIZ RANDOM** command allows the randomization of ellipticity, principal transverse axis, initial phase, and degree of polarization (DOP). These perturbations may take either a uniform or Gaussian distribution. The form of the command is:

```
POLARIZ RANDOM UNIFORM|GAUSSIAN e1 e2 θ1 θ2 p1 p2 DOP1 DOP2
```

where

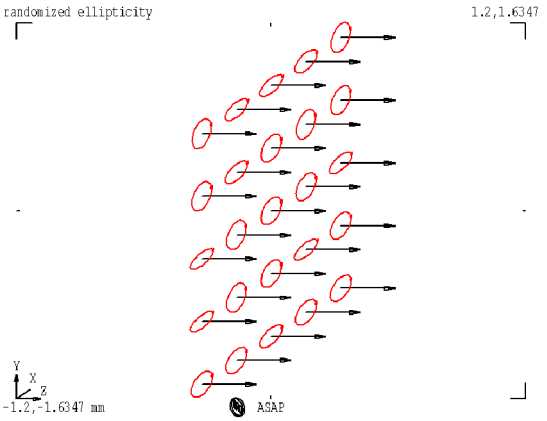
e1, **e2** are limits of ellipticity randomization,

θ1, θ2 are limits of the principal polarization direction randomization, and

p1, **p2** are limits of the polarization initial phase randomization.

DOP1, **DOP2** are limits of the degree of polarization, valid only in **POLARIZ MODE STOKES**.

These limits are the minimum and maximum values for uniform randomization, or the standard deviation for Gaussian randomization. Several examples of source randomization in terms of polarization are illustrated in Figure 11.



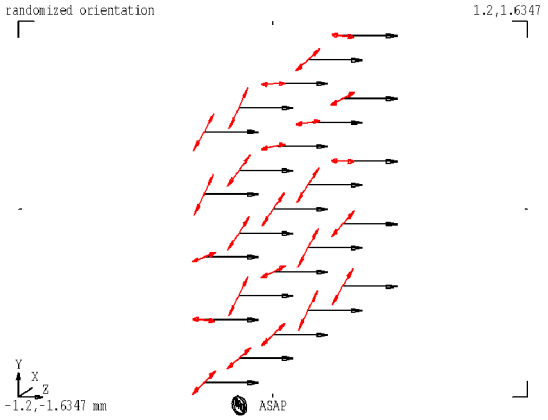

```
POLARIZ K Z
POLARIZ TREF X

POLARIZ RANDOM UNIFORM -0.3 0.8 0 0 0 0
```

Figure 11 Example of randomized ellipticity

The ray directions are plotted along with the polarization state. Though this is an example using simple grid sources with a source direction, the commands are effective for many source geometries and types. They just are not as easy to visualize. This example of randomized ellipticity, along with the reference ray command, sets the "base" state.

Figure 12 shows only the randomization of orientation with its command to perturb the base state.

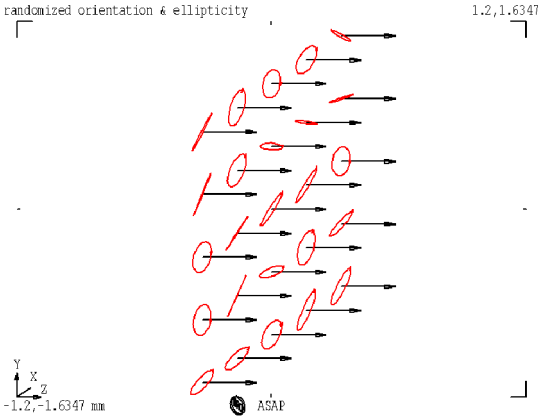



```
POLARIZ K Z
POLARIZ TREF X

POLARIZ RANDOM UNIFORM 0 0  -25 +40 0 0
```

Figure 12 Example of randomized orientation

Similarly, Figure 13 illustrates randomization of both ellipticity and orientation.




```
POLARIZ K Z
POLARIZ TREF X

POLARIZ RANDOM UNIFORM -0.9 +0.1 -35 +45 0 0
```

Figure 13 Example of randomized ellipticity and orientation

POLARIZED RAYSET STORAGE AND REUSE

With ASAP 2008 and subsequent releases, the polarization state of each ray may be included in the data saved in ray distribution files. This information allows us to reuse the rayset in another simulation, or to impose a specific polarized source condition on multiple analyses.

The **DUMP** command now has a **JONES | STOKES** option to determine the form of polarization data that are stored in a **DUMP**ed distribution file. As you might expect, either the Jones vector or Stokes vector data are stored in a polarized distribution file.

The **EMITTING DATA** command supports the reloading of raysets from dumped data with included polarization data. The **POLARIZ MODE** must conform to the form of saved polarization data.

***NOTE** If an existing* **DUMP** *file is appended, it is not possible to mix polarized and unpolarized sources.*

These commands make it possible to do a polarization trace to a specific place in a system, and then to do subsequent analyses without having to repeat the entire trace. It is also useful for producing multiple copies of a specific polarization field or source that are related by simple coordinate shifts and rotation.

Polarization raytracing

No changes are required to the raytrace process in ASAP, from a user's perspective, as a result of the new polarization constructs.

Analysis commands

The result of polarization raytracing may require a numerical or graphical summary. The existing commands, **`LIST ELLIPSE`** and **`PLOT POLARIZATION`** have given some information about polarization state. In ASAP 2008, existing commands were enhanced to provide more numerical data, and a whole new 3D graphical tool to examine polarization states.

Numerical data may now be extracted using the **`LIST RAYS POLARIZATION JONES|STOKES`** command. This adds the polarization reference direction and either Jones or Stokes vector components to the basic ray data that previously had been provided by the **`LIST RAYS`** command. When the Stokes polarization storage mode is used, the **`LIST ELLIPSE`** command now includes degree of polarization.

Polarized distribution files created by **`DUMP`** can be used in a graphical facility called the Poincaré Sphere Visualization Tool (PSVT). This sphere plots the three Stokes vector components that describe the polarization state in the 3D Viewer. It is invoked whenever a polarized DUMP distribution file is opened using **`&VIEW`**. The PSVT is automatically invoked by the **`PLOT POLARIZATION`** command when using the Stokes polarization mode, since the classic 2D plot does not depict the degree of polarization.

An example of the Poincaré tool is shown in Figure 14. There are three distinct polarization zones, one near each pole ±S3, and one near the S3=0 “equator” of the sphere, but inside the sphere.

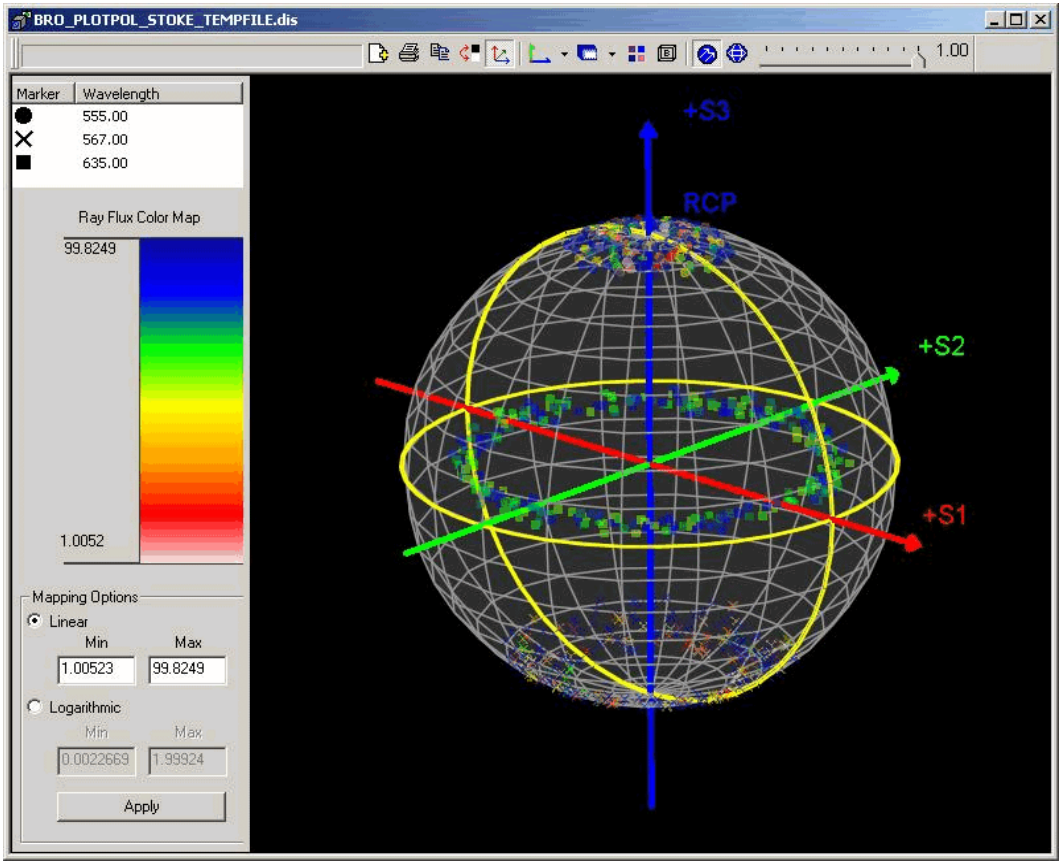


Figure 14 Poincaré Sphere Visualization Tool in the 3D Viewer window

TIP ***You may want to use different data markers or sizes on the Poincaré sphere, depending on the density of points, total number of points, or other distinctions. You can change these when the PSVT is visible, by choosing*** **File> 3D Viewer File Preferences** ***on the main ASAP menu, and then selecting the*** **Polarization** ***tab. The marker and size selection become your defaults for future PSVT displays.***

Note that a distinct marker is used for each wavelength present, and that the color of markers is mapped to flux. This flux mapping can be toggled on and off by the button in the 3D Viewer toolbar, as illustrated in Figure 15. A button on the toolbar opens the dialog, Poincaré Sphere Options, to set several options for displaying the Poi nc are sphere, such as showing meridian or equator lines.

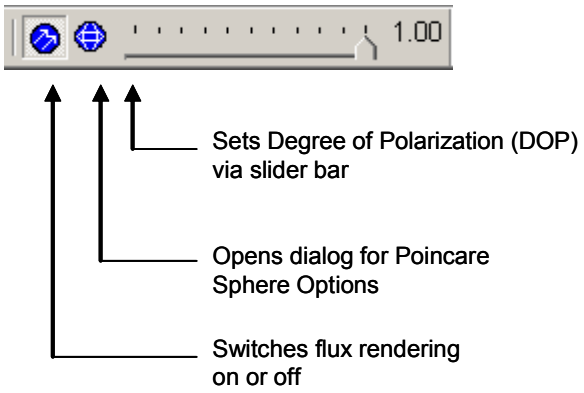


Figure 15 3D Viewer toolbar with buttons for Poincaré Sphere Visualization Tool

NOTE ***The Degree-of-Polarization (DOP) slider bar (see Figure 15) is used to indicate the maximum DOP of points to be displayed. A DOP of less than 1 can occur only when the*** `POLARIZ MODE` ***is set to*** `STOKES`.

To examine a single ray more closely, we can zoom in, using the typical 3D Viewer techniques. Cursor selecting a ray marker with a left-click produces an information box on that ray, and the cursor changes from an arrow to a cross-cursor. This result is shown in Figure 16.

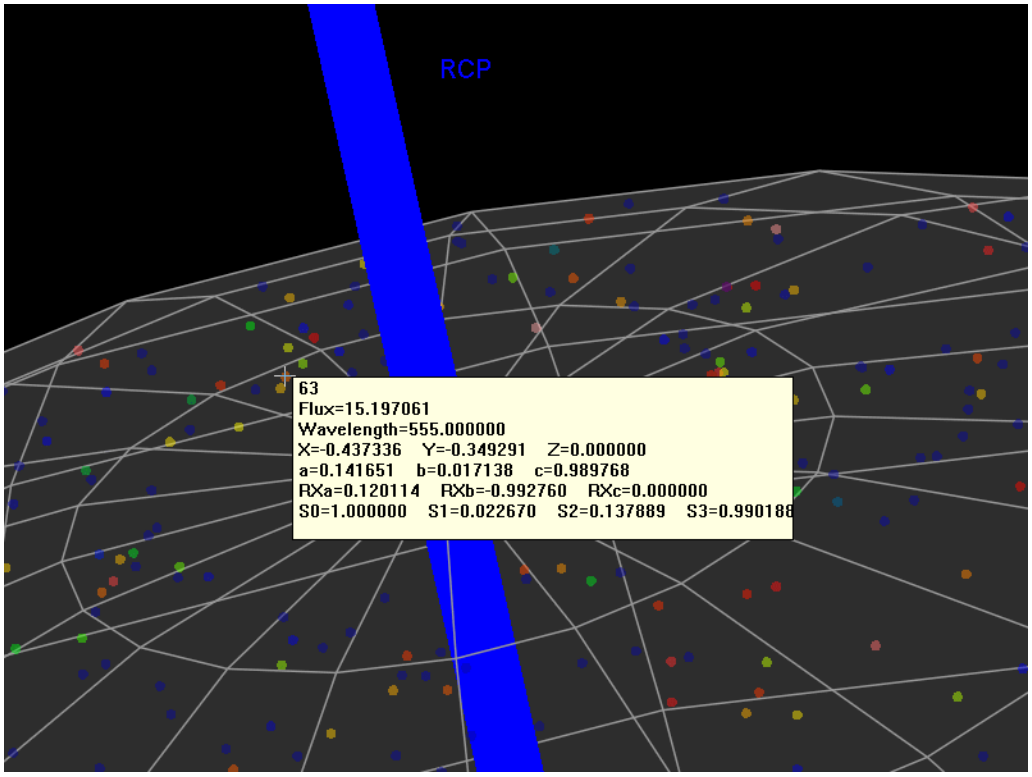


Figure 16 Selecting a ray marker in the Poincaré Sphere Visualization Tool reveals detailed information, including Stokes vector components

The information includes the ray index in the DIS file, the flux, wavelength, the position and direction ray coordinates, and the polarization data. Data may be saved to the ASAP command output window or to a file by right-clicking in the settings area on the left side of the PSVT window, and selecting **Display polarization information** or **Save polarization information**, respectively. By default, the data for the whole set of rays is saved. Rays may be selected using Ctrl-left-click to save only a small subset of the data.

In the example shown in Figure 14, moving the DOP slider to the left would allow the “equatorial” distribution to be isolated, since it has a range of DOP less than 1 (partially polarized), while the other two groups were fully polarized (DOP=1) states. This is illustrated by comparing the view in Figure 17 to that original view.

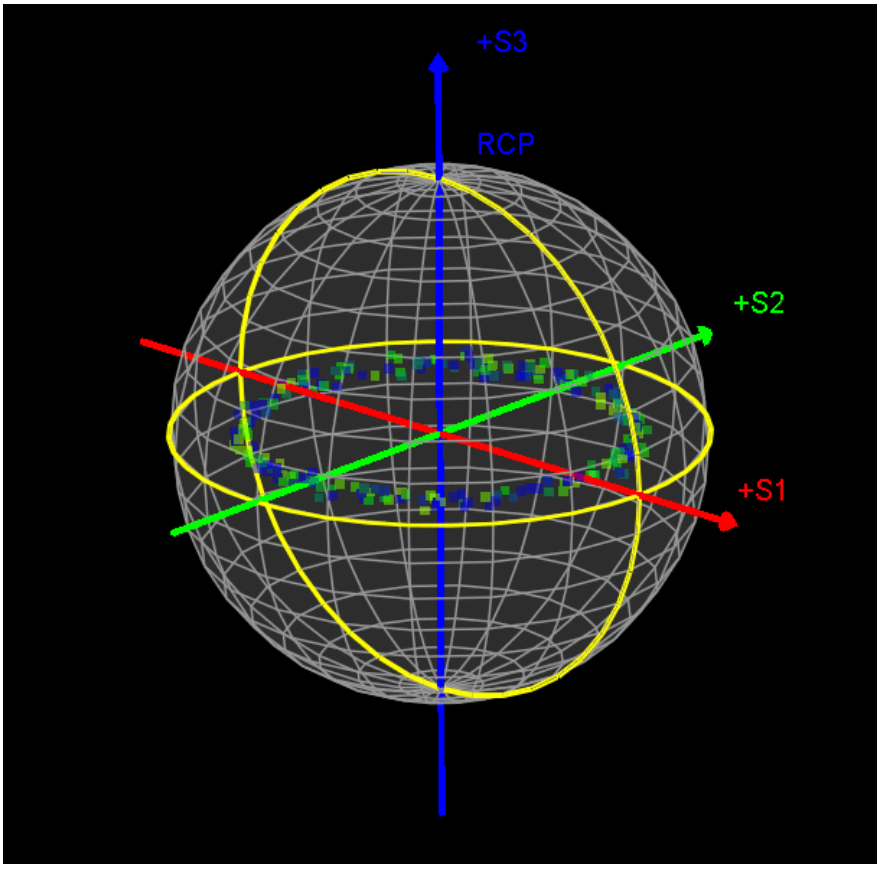


Figure 17 Original rayset in Figure 14 with DOP slider set to 0.8, eliminated fully polarized rays near either pole

These analysis tools provide greatly enhanced capability to probe polarization information, and its relation to other ray information. It should ease the investigation of a broad range of behavior and performance characteristics in polarization-critical systems.

POLARIZATION ANALYSIS WORKFLOW

Given the components of a polarization analysis, is may be useful to see how these parts work together. A flow diagram is a good way to do this. The workflow is illustrated in Figure 18, which shows commands associated with each step.

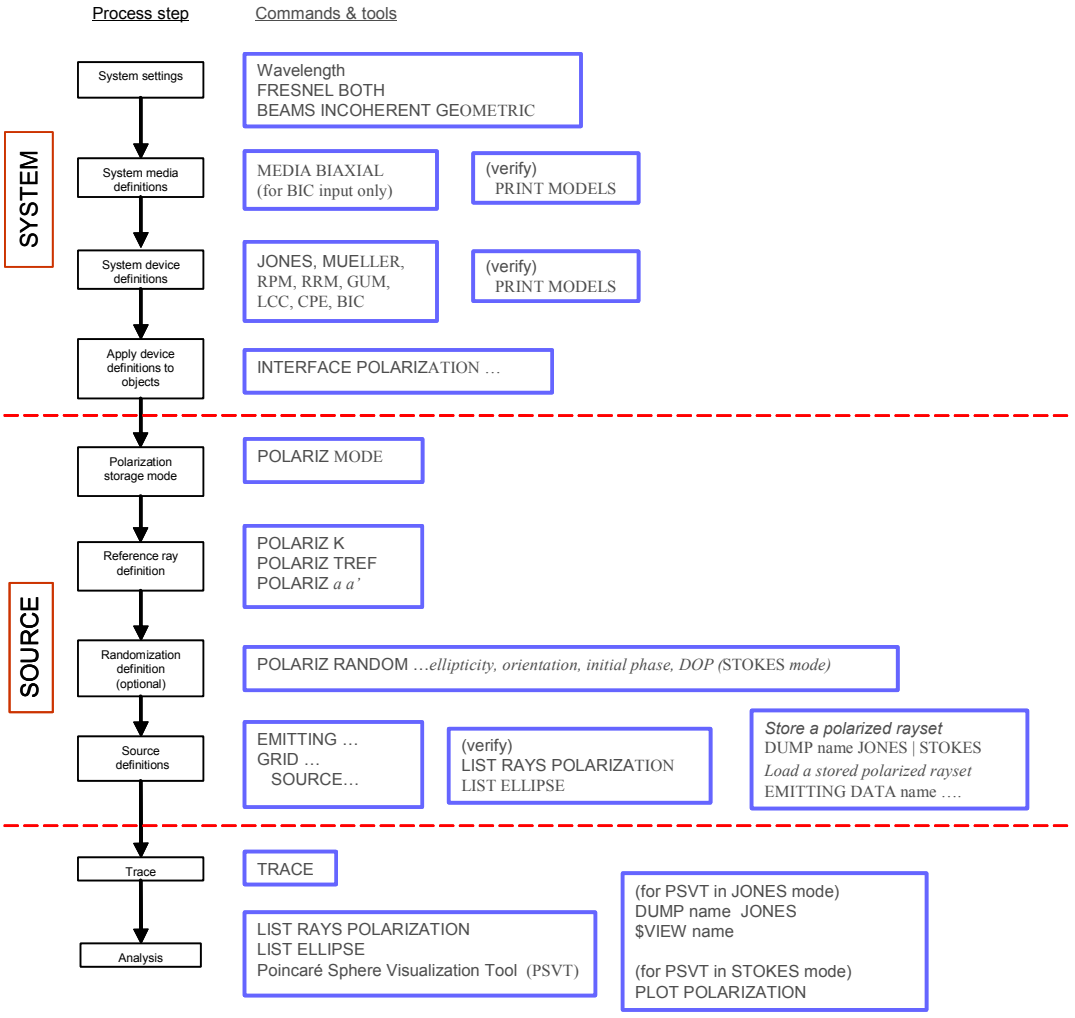


Figure 18 Polarization simulation workflow

Conceptual steps are described in the left block diagram. Key commands that support each step are outlined on the right. Though it is a simple summary, it provides the structure to solve very complex problems. In this sense, it is merely an evolutionary step in the four-step process.

SUMMARY

Many new tools have been introduced in ASAP to enhance polarization analysis. These include new classes of device models, and the ability to cascade device models. There are new controls for source polarization that allow precise control of source polarization and randomization of source states, and representation of partial polarization. Polarized raysets may now be saved and re-loaded. Polarization analysis data may now be tracked and examined in Jones or Stokes vector form, including a graphical examination using a new Poincaré Sphere Visualization Tool within the existing ASAP 3D Viewer.

These mark a notable expansion in utility for polarization simulation, and a new framework in which this capability can continue to grow.