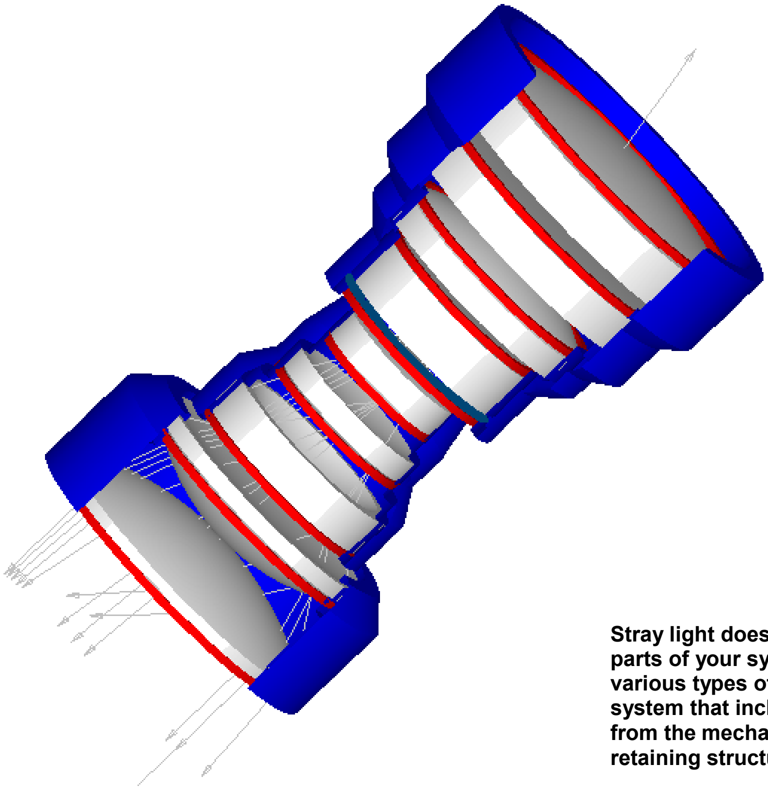
ASAP Procedural Note
October, 2001
BRO-PN-1157(10/01)

Stray Light Analysis with ASAP



Stray light doesn't come just from the glass parts of your system. ASAP lets you perform various types of analysis of an optical system that include reflections and scatter from the mechanical mounting elements and retaining structures.

This procedural note describes how ASAP™, the Advanced Systems Analysis Program from Breault Research Organization (BRO), simulates stray light in optical systems. ASAP combines 3D geometrical optical and mechanical systems modeling with detailed optical properties simulations. These simulations include isotropic and anisotropic surface scatter, volume scatter, and an efficient method for modeling scattered light. ASAP also models other stray light phenomena including ghost imaging, diffraction, and thermal emission. ASAP has been used to simulate scattered light in everything from automotive headlamps to zoom lenses, while spanning the electromagnetic spectrum from the x-ray (X-ray Multiple Mirror Telescope-XMM) and ultraviolet regions (micro-lithography systems) through the visible to the far infrared (thermal emissions).

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Stray light is unwanted light. It is light that leads to poor system performance and possibly product, or mission, failure. Stray light obscures faint signals, decreases the signal-to-noise ratio, reduces contrast, creates inaccurate radiometric, and photometric results, and in high-energy laser systems destroys optical elements and detectors. Stray light is caused by a number of phenomena including light scattered from optical and mechanical surfaces, ghost reflections from transmissive optical elements like lenses, edge diffraction from stops and baffles, unwanted diffraction orders from gratings, and thermal emission.

Stray light analysis determines not only how unwanted light gets to your detector but also how much stray light makes it to the detector of your optical system. Stray light analysis allows you to examine if stray light is a problem and how to fix it during the design phase of the project before building your optical system. This prevents costly redesigns and potentially fatal design mistakes before tooling hardware.

Different techniques and procedures are required for different stray light analyses. This necessitates optical engineering software that has a wide variety of powerful, general, and specialized features. For example, scattering and ghost images usually comprise the largest portions of stray light in optical systems and most of the optical engineering effort is put into analysis of, and ultimate suppression of, these phenomena. Both images require different simulation procedures and features. ASAP is flexible enough to simulate both of these types of stray light phenomena and many others. Furthermore, ASAP combines powerful geometrical optical and mechanical systems modeling capability, sophisticated optical properties models (including Fresnel reflection and transmission coefficients, isotropic and anisotropic surface scatter, volume scatter, and importance area sampling—scattered ray targeting) with flexible numerical and graphical analysis tools to facilitate efficient stray light analyses.

The most common types of computational techniques for stray light analysis are ray tracing and radiosity. ASAP is a ray tracing program that combines geometrical optical simulation with a physical optics calculation (see the Procedural Note “Physical Optics in ASAP,” BRO-1151) that allows you to model a wide variety of optical phenomena and processes including stray light in a wide variety of optical systems. Ray tracing simulates the propagation of light in an optical system with a ray, which is a vector representation of light as a normal to a wavefront. Radiosity is a finite-element radiometry method that uses the power transfer equation to propagate stray light from object to objects within your optical system model. However, the radiosity technique usually has limited geometrical modeling and visualization capabilities. You cannot graphically represent stray light propagation with this technique because it does not have a graphical representation such as a ray. It requires you to almost know the stray light behavior before you perform the analysis. The radiosity technique is computationally more efficient for simulating stray light from sources out of the field view of the optical system. However, ray tracing can handle a more general case of problems including a wider variety of systems. It is also computationally better for simulating stray light in the field of view of the optical system. Furthermore, ray tracing is operationally easier to use to find stray light problems. Rays are lines in space that graphically help determine stray light problem areas.

Scattered Light Analysis

The quality of an image produced by an optical system is a function of diffracting, aberrating, and scattering processes. All these processes cause light to spread out from a point source (an infinitesimal, self-luminous point) or a point object (an infinitesimal, illuminated point). Extended sources, such as fluorescent lamps, or extended objects such as scenes we see, are made up of collections of point sources and objects. Imaging optical systems are required to image points on the object to points in the image whose collective nature results in the scene or object image. Similar processes also affect non-imaging optical systems such as illuminations systems. However, in the case of illumination systems like automotive head and tail lamps, you are usually concerned with spreading a point over a larger area or into a larger solid angle in order to properly illuminate a lighting task.

Optical engineers often compute the spread and shape of a point of light, imaged through an optical system, to asses the image-forming qualities of the optical system in terms of the effects of diffraction and aberrations. Diffraction is the natural spreading of a point of light. Even in a perfect optical system you cannot focus a beam of light to a point, because it spreads out as it is focused. Aberrations are departures from ideal behavior. These non-ideal behaviors are introduced by the optical elements of an optical system that prevent a point on the object to be perfectly imaged through the optical system to a point on the image. The image point is aberrated or spread out, but the spreading is due to the non-ideal behavior of the optical system, as opposed to the spreading due to diffraction. The spreading of a point of light is called the point-spread function. Diffraction and aberrations cause local spreading of image points. Optical systems whose aberrations are corrected are called diffraction limited because the size of a point of light is limited to the size imposed by diffraction and not aberrations. Optical system aberrations can be eliminated or reduced by the choice of appropriate lens designs. Diffraction and scatter, however, are inherent parts of the imaging process. In addition to simulating scatter phenomena ASAP can simulate diffraction and aberration phenomena in optical systems. See the Procedural Notes "Physical Optics in ASAP," BRO-1151 and "Imaging and Non-imaging System Modeling in ASAP," BRO-1155.

Stray light is created by light scattering off mechanical and optical elements. Stray light from mechanical elements is sometimes more intuitive to visualize than scattering off optical elements. Light incident on painted mechanical mounts in the field of view of the optical system has a high probability of scattering to the image plane. But high-quality optical elements have an even higher probability of scattering light to the image plane, although perhaps at smaller orders of magnitude than mechanical surfaces. Highly polished optical elements are unable to produce perfectly specularly reflected or regular transmitted images. The process of manufacturing the lenses, such as grinding and polishing, causes micro-cracks at the optical surfaces that create scattered light. If the optical elements had perfect transmission, you would not even see them. These optical elements scatter light incident on them just as every optical system scatters light. Even more scattered light is produced from contaminated surfaces. ASAP can simulate painted mechanical surfaces and smoothly polished surfaces with a wide and flexible variety of scattering models that use measured data.

Scattered light from optical surfaces in imaging systems is part of the incident light from a point source that is removed from its normal imaging path and redistributed or spread out over an area. Scattering causes light to spread out but over much larger areas than diffraction or aberrations. Scattered light, stray light in general, might be considered a type of aberration because it is a departure from ideal behavior. Although the magnitude of light scattered is smaller than diffraction or aberrations, its effect is much broader and additive across the detector or image plane. Moreover, scattered light in a high-energy laser system can destroy optical elements and detectors.

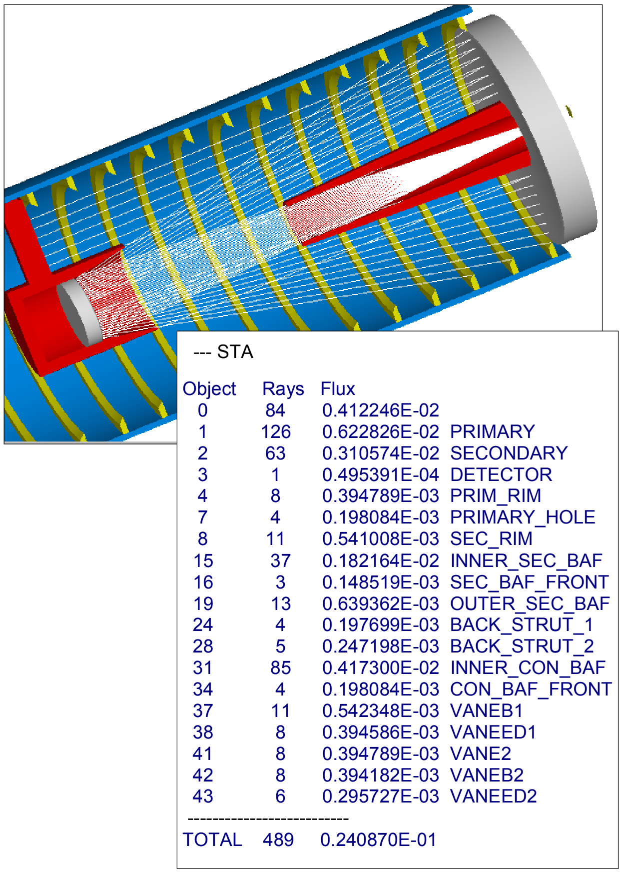
Scattered light is not only caused by subsurface damage created by manufacturing processes and surface contamination, but also by scratches and pits on lens and mirror surfaces. Scatter can also be caused by inhomogenieties in the volume of the glass such as bubbles, pits, and striae. All these effects primarily contribute to scatter in the field of view of the optical system. In-field scatter is typically caused by scatter from the optical components illuminated by sources in the field of view of the imaging system. Contamination causing in-field scatter can be reduced by carefully cleaning the optics, but cleaning can also damage the optical surface, creating even more scattered light.

The procedure for calculating stray light from scattering objects is a straightforward process where the analysis actually starts not at the input but at the detector. It simplifies the analysis while directing attention to the best solutions. This procedure requires first calculating critical and illuminated objects. Critical objects are objects that are directly seen by the detector or whose images are seen by the detector. Critical objects account for 100% of the scatter light reaching the detector. Illuminated objects are objects in the optical system illuminated by external sources of light. Optical system elements that include both critical and illuminated objects form a direct, first-order stray light path to the detector, and are typically the largest scattered light contributors.

Critical and illuminated objects are just parts of your opto-mechanical system simulated from the general class of objects in ASAP. General objects in ASAP can be created in a number of ways. ASAP is similar to 3D solids modeling programs in that it utilizes a powerful geometrical modeling approach. This permits a nearly limitless variety of system geometry and optical properties to be constructed in a straightforward manner in either the spreadsheet-like Geometry Builder, which is part of the user interface, through a translated CAD Initial Graphics Exchange Standard (IGES) file, or through the command language. For more information on CAD/IGES please see the Procedural Note, “CAD in ASAP,” BRO-1154.

As opposed to other ray tracing algorithms found in lens design codes, all surfaces and ray data are referenced by default to a single global coordinate system, which facilitates easy model creation and component perturbation or linear transformation. Smooth, continuous object surfaces can be represented by a sequence of simple conicoids or a general 286-term polynomial. Therefore, anything from a simple plane to an arbitrarily oriented elliptical toroid can be modeled precisely. ASAP is also one of the few codes that can simulate parametric mesh surfaces (NURBS). In fact polynomial and parametric entities can be used to trim each other. Polynomial and parametric surfaces can even be made into emitters in ASAP, which is an important requirement for thermal emission calculations.

Critical objects are initially set to be totally absorbing and are first identified by tracing rays backwards from the detector as is illustrated in *Figure 1*. ASAP allows you to create virtually any point or extended source required for backward ray tracing. For more information on modeling point and extended sources, see the Procedural Notes, “Physical Optics in ASAP,” BRO-1151, “Modeling Incoherent, Extended Sources in ASAP,” BRO-1153, and “Imaging and Non-imaging System Modeling in ASAP,” BRO-1155. Illuminated objects are identified by tracing rays forward from the front of the optical system as illustrated in *Figure 2*. Any rays that touch components in these ray traces constitute the respective critical and illuminated objects. With ASAP you can examine critical and illuminated objects numerically in a tabular format or graphically with its powerful 3D Viewer.



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--- STA

Object   Rays   Flux
  0       84    0.412246E-02
  1      126    0.622826E-02  PRIMARY
  2       63    0.310574E-02  SECONDARY
  3        1    0.495391E-04  DETECTOR
  4        8    0.394789E-03  PRIM_RIM
  7        4    0.198084E-03  PRIMARY_HOLE
  8       11    0.541008E-03  SEC_RIM
 15       37    0.182164E-02  INNER_SEC_BAF
 16        3    0.148519E-03  SEC_BAF_FRONT
 19       13    0.639362E-03  OUTER_SEC_BAF
 24        4    0.197699E-03  BACK_STRUT_1
 28        5    0.247198E-03  BACK_STRUT_2
 31       85    0.417300E-02  INNER_CON_BAF
 34        4    0.198084E-03  CON_BAF_FRONT
 37       11    0.542348E-03  VANEB1
 38        8    0.394586E-03  VANEED1
 41        8    0.394789E-03  VANE2
 42        8    0.394182E-03  VANEB2
 43        6    0.295727E-03  VANEED2
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TOTAL    489    0.240870E-01
```

Figure 1 Identifying critical objects numerically and graphically

Stray light paths due to scattering are removed by blocking that path with an appropriate baffle, vane, or stop or moving the offending object so that it is no longer seen by the detector or externally illuminated by a source. The flexible geometry Builder and command language in ASAP allow you to create baffles, vanes, and stops, or you can create these in your own CAD system and import them into ASAP.

Scattered light also comes from optical elements such as mirrors and lenses and these cannot always be blocked or moved as easily as mechanical components. Also second order or higher scatter paths might affect system performance. These situations call for simulating the scatter off the optical or mechanical

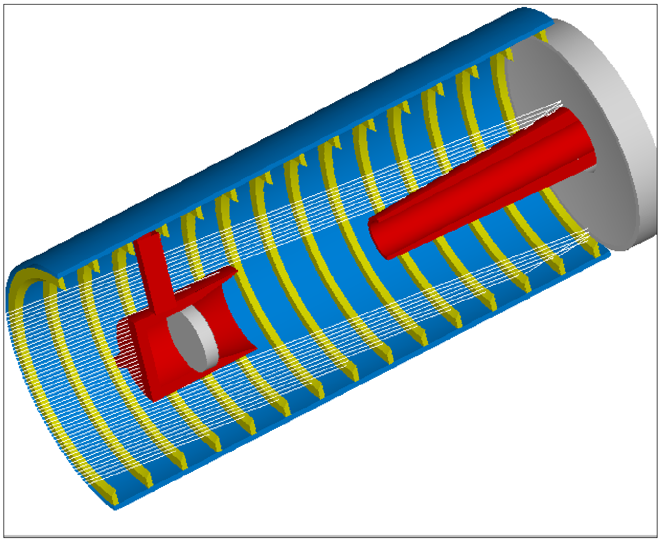


Figure 2 Identifying illuminated objects graphically

component to assess the amount of scattered light reaching your detector. Such analyses are accomplished in ASAP by using one of five approaches for simulating scattered light. ASAP also offers powerful scatter models for simulating a wide variety of surface and volume scatter, and importance area sampling for efficient stray light simulations.

Five Approaches to Simulating Scattered Light in ASAP

The ASAP scatter simulation approaches are delineated according to the specific technique they use and the number of rays generated during the scatter calculation. In some scatter applications no scattered rays are generated and the incident ray is perturbed from its specular path according to a specific scattering function. In other applications one or more rays are generated to simulate scattered light. When more than one ray is generated at an interface you can control whether or not that scattered ray in turn can be scattered at another scattering interface with the LEVEL command. In many cases, scattered rays can be generated in transmission and reflection while referencing different scatter laws. These essential features, along with importance area sampling, allow you to control the number of scattered rays, either globally or individually, at an object interface in order to maximize the efficiency of the scatter calculation.

1. **SCATTER RANDOM (surface scatter)**
   The SCATTER RANDOM technique simulates Lambertian scatter. A Lambertian scattering surface is one whose scattered radiance is constant and independent of the source's incident angle. The intensity falls off as a cosine function from the surface normal. The SCATTER RANDOM technique is useful for modeling simple diffusers. For every additional ray that hits a SCATTER RANDOM surface, additional rays are generated to simulate the Lambertian scattering characteristic. In other words, this model corresponds to a case of sending one ray in and getting many scattered rays out. The rays are by default scattered into the hemisphere each having the same flux. The Lambertian scatter pattern is created by a ray-density method. This method generates more rays per unit solid angle close to the surface normal than at grazing incidence.

2. **ROUGHNESS MODEL (surface scatter)**
   The ROUGHNESS MODEL command simulates a rough surface by inducing a random variation of the reflected or transmitted ray direction. It does this by randomly changing the surface normal at the point of ray intersection. The ray normal is sampled using an ASAP scatter model, and perturbed so that the surface will produce a normal incidence scatter behavior that mimics the assigned scatter model. The surface slope statistics are therefore the same at normal and non-normal incidence. This model does not create any scattered rays; for every ray incident on the surface only one ray leaves. This scattered light technique is useful for simulating rough surfaces commonly used in the illumination industry.

3. **SCATTER MODEL (surface scatter)**
   SCATTER MODEL scatters rays towards or away from user-defined areas or solid angles using one of the ASAP scattering models. Like SCATTER RANDOM, SCATTER MODEL can create many scattered rays for each incident ray. However, the rays created with SCATTER MODEL have different fluxes, which are determined by the scattering function and the area or solid angle in which the scattered rays propagate. In other words,

ray powers are flux weighted according to the scattering function. SCATTER MODEL and ROUGHNESS MODEL use scatter functions first defined through one of the ASAP scatter models. This technique is by far the most used scatter technique in ASAP.

4. **SCATTER BSDF or SCATTER RMS (surface scatter)**
   The SCATTER BSDF and SCATTER RMS commands are special scatter tools for simulating in-field scatter created by optical elements in imaging systems. For every ray incident on the surface of an object, ASAP creates a scattered ray that essentially propagates on top of the original ray. Incident rays of this type are presumed to come from point sources. They are simulated with Gaussian beams that model diffraction phenomena. (For more information on physical optics simulations in ASAP see the Procedural Note “Physical Optics in ASAP,” BRO-1151.) The scattered ray has a Lorentzian beam shape that simulates the spreading of the scattered light. This scatter simulation technique is the least-used of all the scatter techniques in ASAP, and is not used for scattering that follows the Harvey scatter model described below.

5. **MEDIA…; SCATTER (volume scatter)**
   Volume scattering is simulated through the ASAP MEDIA command, which normally defines refractive indices. The inhomogeneous Monte-Carlo scattering model perturbs the incident ray according to a volume scatter model, which depends on the 3D position of the ray within the volume. The angular distribution of the scattered rays may be specified as isotropic (as predicted by MIE theory, Henyey-Greenstein distributions) or a user-defined function.

Three of these scatter techniques require the definition of a specific scatter model. ASAP has the most comprehensive set of scatter models available in any commercial code. A primary way of communicating surface scatter data to ASAP is through a standard, radiometrically defined scattering function. A definition and interpretation of this scatter function will help you understand the data necessary to simulate scatter in ASAP.

Scatter Models: Bi-directional Scattering Distribution Function (BSDF)

ASAP has a number of models available for simulating scattered light from surfaces. The primary way of describing scattering from surfaces in these models is with a special type of function called the bi-directional scattering distribution function (BSDF). Scattering from reflective surfaces is called the BRDF or bi-directional reflection distribution function and scattering from transmissive surfaces is called the BTDF or the bi-directional transmission distribution function. Many people are intimidated by this function because of its mathematical complexity. In reality it is an angular resolved reflection or transmission function. It is the reflectivity or transmissivity of a surface per unit solid angle of collected scatter. Furthermore, the reflectivity or transmissivity is also a function of the incident angle and scatter angle from the specular. We need to discuss BSDFs in greater detail, as this is essentially the method of communicating scatter data to ASAP and understanding its powerful modeling features. Furthermore, BSDF measurements are an industry standard for describing scattering from surfaces.

Scatter is a process of reflection and transmission at a surface. Reflection is a process during which part of the incident flux or power on a surface propagates back into the general direction of the hemisphere formed by incident flux, and the base of the differential area of incidence. The direction and amount of power reflected in a particular direction is a function of the incident beam and surface properties. In particular, we speak of specular, diffuse, and angle resolved reflections. We think of scatter as a sub-process of reflection or transmission, even though the macroscopic laws of specular reflection and refraction at a surface can be considered special cases of the statistical averages of scattering phenomena.

The general process of scatter is not normally defined in the way we usually think of specular or diffuse reflection and transmission at a surface. A generalized scatter description requires a more complex mathematical definition and description than specular or diffuse reflection and transmission. Specular or diffuse reflection and transmission, along with the types of surfaces they are normally used to describe, are two specific types of characterizations of reflection and transmission. They describe the reflection and transmission behavior of purely specular (perfectly polished optical surfaces) and diffuse (Lambertian) surfaces. We can think of these material types as bounding the general class of scattering materials. In reality, no surface behaves in a purely specular or diffuse manner and the scatter behavior of most surfaces actually falls in between these two classes. A more comprehensive scatter description is needed to quantify their behavior. The generalized reflection or scatter off a surface is a function of a number of parameters including the incident angle and the scatter angle.

For simplicity we will restrict our present discussions to reflection; similar arguments follow for transmission. In this case the most general geometric characterization of reflection is the bi-directional reflectance distribution function (BRDF). There are nine different geometrical definitions of reflection, which are all derived from the BRDF. The BRDF is an angle-resolved reflection function. This means that you are quantifying the surface reflection as a function of incident and output angles. Operationally, the non-spectrally dependent BRDF is defined as

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s) = BRDF(\theta_i,\phi_i;\theta_s,\phi_s) = \frac{L(\theta_i,\phi_i;\theta_s,\phi_s)}{E}$$

“E” is the incident irradiance or power per unit projected area and “L” is the scattered radiance. The units of BRDF are inverse solid angles or steradians. It is like a directional reflectivity per unit solid angle of collected scatter. Because of this definition, the BRDF can assume values greater than 1 close to the specular direction. This will be demonstrated shortly. This does not violate conservation laws because it is used in an appropriately normalized power transfer equation.

BRDFs depend on wavelength, but the wavelength dependency is dropped for notational convenience. In general, BSDF measurements are usually taken at one wavelength with scaling laws applied to obtain the BSDF at other wavelengths. This is done because most scatterometers may not have a source at your desired wavelength. For convenience, some of the ASAP scatter models have this scaling built in. But not all types of scattering surfaces have wavelength scaling laws.

The BRDF is a function of the incident (input) and scatter (output) angles. Hence the name “bi-directional”. The polar angle, θ, is measured from the normal to the surface and the azimuth angle, ϕ, is measured from a reference plane, most often the plane formed from the plane of incidence. In ASAP terminology, this plane is usually represented by that formed from the z-axis and the y-axis. For sake of definition and discussion, the y-z plane is assumed to be the plane of incidence. If the surface is isotropic, the BRDF becomes a function of only three variables, the polar and azimuth angles of incidence and the difference in the polar angle of reflection and the polar angle of scatter. In other words, reflection from an isotropic surface is symmetric with respect to the plane of incidence and surface normal—the reflectivity does not change when the surface is rotated about its normal. This is a particular statement of isotropism that also applies to isotropic transmissivity and scatter in general. ASAP can simulate a wide variety of isotropic and anisotropic surface scattering models. Scattering from anisotropic surfaces, such as brushed or diamond turned objects, is not rotationally symmetric about the plane of incidence and surface normal.

The mathematical definition of the BSDF is a clever means of describing the bi-directional reflectance at a particular surface. But how did it come about? To gain an appreciation for this function we can use heuristic argument to describe its definition.

Scattered power is dependent on the measurement geometry, but what we really want is a measurement of scatter that is dependent only on the surface properties. Consider measuring the power reflected off of an isotropic surface into a detector that is scanned in scatter angle from the surface normal. The ratio of this power to the incident power, as a function of incident and scatter angles, might serve as a suitable metric. Unfortunately, the detector size determines the amount of measured power and hence the amount of scatter. Therefore, it is reasonable to normalize the detector power by the detector area. Our reflectivity at a surface might look like this

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\frac{P_{\det}(\theta_s)/A_{\det}}{P_i(\theta_i,\phi_i)}$$

Dividing the detector power by the detector area normalizes the detector output. Furthermore, we should include the source to detector distance in the measurement because the power on the detector is also a function of its distance from the source by way of the inverse square law. We should also include a cosine factor for the projected area of the detector because it is not necessarily perpendicular to the sample surface. These corrections result in the following relationship

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\frac{P_{\det}(\theta_s)/A_{\det}}{P_i(\theta_i,\phi_i)\cos(\theta_i)}R^2$$

We can now multiply the above equation by 1 in the form of the ratio of the spot size on the sample. This results in

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\frac{P_{\det}(\theta_s)/A_{\det}}{P_i(\theta_i,\phi_i)\cos(\theta_i)}R^2\left(\frac{A_{spot}}{A_{spot}}\right)$$

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\left(\frac{P_{\det}(\theta_s)}{A_{\det}/R^2\,A_{spot}\cos(\theta_i)}\right)\left(\frac{1}{P_i(\theta_i,\phi_i)/A_{spot}}\right)$$

But the quantity in the denominator of the first parenthesis is the solid angle the detector makes with the center of the spot on the surface. That quantity divided into the power on the detector is the surface radiance. The incident power divided by the area of the spot is the incident surface irradiance. We therefore can write

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\left(\frac{P_{\det}(\theta_s)}{\left(A_{\det}/R^2\right)A_{spot}\cos(\theta_i)}\right)\left(\frac{1}{\phi_i(\theta_i,\phi_i)/A_{spot}}\right)$$

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\left(\frac{P_{\det}(\theta_s)}{d\omega A_{spot}\cos(\theta_i)}\right)\left(\frac{1}{P_i(\theta_i,\phi_i)/A_{spot}}\right)$$

$$\rho_{BRDF}(\theta_i,\phi_i;\theta_s)=\frac{L(\theta_s)}{E_i}=BRDF(\theta_i,\phi_i;\theta_s)$$

This leads us to conclude that the BRDF is the surface radiance divided by the surface irradiance.

The BRDF is the fundamental geometrical characterization of reflection. It is fundamental in the same sense that radiance is fundamental. The other radiometric parameters, irradiance and intensity, can be obtained from appropriate integrals of the radiance function. Similarly, Nicodemus defined the nine reflection geometries, mentioned above, by various integrals of the BRDF. All nine are just different geometrical characterizations of reflectance. Further information regarding these nine reflection geometries can be found in the *Handbook of Optics*. As an example, we can examine the relationship between BRDF and directional hemispherical or diffuse reflectivity. The collection solid angle in this definition is a hemisphere. Therefore, we can integrate the BRDF over a hemisphere to obtain the diffuse reflectivity. Operationally, we have

$$\rho_{\mathrm{dh}}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\pi/2}\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)\cos(\theta_s)\sin(\theta_s)\,d\theta_s\,d\phi_s$$

$$\rho_{\mathrm{dh}}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\pi/2}\frac{dL(\theta_i,\phi_i;\theta_s,\phi_s)}{dE}\cos(\theta_s)\sin(\theta_s)\,d\theta_s\,d\phi_s$$

This is also the definition of the total integrated scatter or TIS. The TIS is also defined as the ratio of power scattered into a hemisphere from a surface divided by the power incident on the surface. The TIS is obviously a function of the incident polar and azimuth angles. For isotropic surfaces, the TIS is only a function of the polar angle. The TIS is the integral of the BRDF over all angles.

If the surface is a Lambertian surface, the radiance L is a constant. Operationally, we obtain

$$\rho_{\mathrm{dh}}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\pi/2}\frac{L}{E}\cos(\theta_s)\sin(\theta_s)\,d\theta_s\,d\phi_s=\frac{\pi L}{E}$$

$$\frac{L}{E}=\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)=\mathrm{cons}\tan\mathrm{t}=\frac{\rho_{\mathrm{dh}}}{\pi}$$

The BRDF of a Lambertian reflector is then the diffuse reflectivity divided by π. We also could have derived this relationship directly from the diffuse reflectivity definition by noting that the exitance of a Lambertian surface is just πL.

If the surface is what we normally call a "specular" surface, it likely follows the Harvey scattering law. The Harvey law is a scatter model that describes scatter from smoothly polished surfaces with a minimum of two parameters. Harvey found an invariant relationship in scatter behavior as a function of incident angle when the BSDF is plotted in a special coordinate system. The Harvey BSDF model is peaked in the specular direction and is independent of the angle of incidence when the logarithm of the BSDF is plotted against the logarithm of the difference in the sine of the angles of scatter and reflection or transmission. A scattering surface that obeys the Harvey BSDF model is a straight line when plotted in this log-log space. Graphically, the Harvey curves for different angles of incidence are all on top of each other. One of its parameters describes the slope of this line and the other parameter an intercept. Specifying a scattering function with only two parameters greatly reduces the dimensionality of the model and subsequently its complexity. Many polished surfaces exhibit a Harvey behavior. Many diffuse surfaces also follow the Harvey model if the BSDF is allowed to approach a finite constant at small angle of incidence.

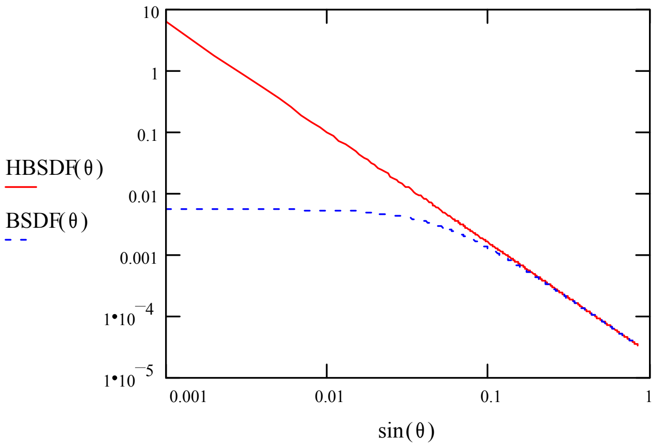


Figure 3 Harvey scatter model with and without shoulder parameter

The basic Harvey model for isotropic surfaces without the shoulder parameter is

$$BSDF(\theta_s) = b\left(100\sin(\theta_s)\right)^S$$

Here "b" is the BSDF at 0.01 radians. The exponent "S" is slope of the BSDF curve when the logarithm of the BSDF is plotted, versus the logarithm of the difference in the sine values of the scatter and reflected or transmitted angle. The integral of this function over the hemisphere is the total integrated scatter. We now have

$$\mathrm{TIS} = \rho_{dh}(\theta_i,\phi_i;\theta_s,\phi_s) = \int_0^{2\pi}\int_{0.01}^{\pi/2} \mathrm{BSDF}(\theta_i,\phi_i;\theta_s,\phi_s)\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

$$\mathrm{TIS} = \int_0^{2\pi}\int_{0.01}^{\pi/2} b\left(100\sin(\theta_s)\right)^S\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

$$\mathrm{TIS} = \int_0^{2\pi}\int_{0.01}^{\pi/2} b100^S\sin(\theta_s)^{S+1}\cos(\theta_s)d\theta_s d\phi_s$$

$$\mathrm{TIS} = \frac{2\pi b100^S}{s+2}\ \text{for } s > -2$$

Note that the integral is performed from 0.01 radians to π/2 radians, not quite the full hemisphere. This is primarily done for a historical, physical reason. The parameter "b" is the BSDF at 0.01 radians. It is like the y-intercept of a straight line. In an empirical sense, the BSDF curve is anchored at this position because inside this angle the point spread function of the diffracting incident beam can drastically affect the measurement resulting in instrument signature recorded in the scatter data. In a theoretical sense, there really are no accurate models that describe the behavior of the BSDF within 0.01 radians of the reflected or transmitted beam. Moreover, the Harvey model can yield infinite BSDF values at normal incidence.

Our general, BSDF relationship can be used to further demonstrate that the BRDF can have maximum reflectivity values greater than 1 close to the specular direction. Reflectivities greater than one are confusing when we think of a specular reflectivity but are a natural consequence of the BSDF definition. BSDF with values greater than one can be demonstrated using the directional conical reflectivity, another one of the nine ways to describe reflectivity. The directional conical reflectivity is similar to the directional hemispherical reflectivity, with the exception that the integral is done over a conical solid angle and not the hemisphere. The directional conical reflectivity is

$$\rho_{dc}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\omega}\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

$$\rho_{dc}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\omega}\frac{dL(\theta_i,\phi_i;\theta_s,\phi_s)}{dE}\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

The differential directional conical reflectivity is then

$$\rho_{dc}(\theta_i,\phi_i)=\int_0^{2\pi}\int_0^{\omega}\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

$$d\rho_{dc}(\theta_i,\phi_i)=\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)\cos(\theta_s)\sin(\theta_s)d\theta_s d\phi_s$$

$$\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)=\frac{d\rho_{dc}(\theta_i,\phi_i)}{d\Omega}$$

Now, consider a quasi-collimated beam of light incident on a planar, specular surface. The projected solid angle in the denominator goes to zero because the beam remains quasi-collimated on reflection, and in this limit the BRDF becomes infinite.

$$\mathrm{BRDF}(\theta_i,\phi_i;\theta_s,\phi_s)=\lim_{d\Omega\to 0}\frac{d\rho_{dc}(\theta_i,\phi_i)}{d\Omega}=\infty$$

In reality the BRDF does not go to infinity, but can obtain extremely large values on specular surfaces close to the specular beam. As shown above, theoretically this can occur on specular surfaces and we will need a way to control this phenomena on scatter models. For example, to prevent the BSDF from becoming infinite in the specular direction, a shoulder roll-off parameter is used in the ASAP Harvey BSDF model. The Harvey BSDF model with the shoulder parameter is operationally defined as

$$BSDF(\theta_s)=b_0\left(1+\left(\frac{\sin(\theta_s)}{\ell}\right)^2\right)^{\frac{S}{2}}$$

$$b_0=b(100\ell)^S$$

Here b is the BSDF at 0.01 radians and b_0 is the BSDF at θ_s=0. "ℓ" is the shoulder point, in radians, at which the BSDF begins to roll over to a constant value.

We can integrate this form of the BSDF function over the hemisphere to determine the TIS just as with the first Harvey BSDF model. At normal incidence, integration yields

$$TIS=2\pi b\frac{100^S}{S+2}\left[\left(1+\ell^2\right)^{\frac{S+2}{2}}-\left(\ell^2\right)^{\frac{S+2}{2}}\right]\quad for\ S\neq 2$$

$$TIS=2\pi b\frac{(100\ell)^S}{2}\ell^2\ln\left(1+\frac{1}{\ell^2}\right)\qquad for\ S=-2$$

Model Library

Developing good, realistic, scatter models anchored against measured data is an essential part of stray light analysis, and one that is usually underestimated. Although ASAP has the ability to simulate general BSDF data or scatter data that follows very special scattering laws using simple or complex models, it is up to the user to determine the correct scatter model for a particular application. ASAP offers everything from a simple Lambertian (perfectly diffuse) model, where the only input is the hemispherical reflectivity, to models using measured data including angles of incidence, scatter, and BSDF measurements to fit or interpolate BSDF information for scatter calculations.

Unlike many other commercially available programs, ASAP scatter models make every effort to obey reciprocity laws, unless you force them to do otherwise. Reciprocity is like a reversibility law. Reciprocity means that the BSDF is the same when the incident and scatter directions are reversed. Therefore, the BSDF of an isotropic surface is symmetric in the specular and scatter directions. Reciprocity is a law of nature that many commercially available stray light analysis programs are unaware of or ignore in their model implementations, a practice that can lead to erroneous results.

Isotropic Surface Scatter Models in ASAP

1. LAMBERTIAN—a one-parameter model simulating purely diffuse scatter, specified by the hemispherical reflectivity/transmissivity.
2. HARVEY—a six parameter shoulder or non-shoulder model for near specular, diffuse, and mixed scatter behavior using standard variables including an anchored BSDF point and slope from the Harvey smooth surface scatter model with wavelength scaling.
3. POLYNOMIAL/TRINOMIAL/BINOMIAL —an extremely powerful and general isotropic surface scattering model that is

linear in free parameters and useful for simulating painted surfaces by either entering the model coefficients directly or by computing the model coefficients using fitted data.

4. NONLINEAR—a generalized combination of the Harvey (sharp peaked) and Phong (wide peaked) models applicable to both smooth and rough surfaces where the coefficient are directly entered or computed by fitting BSDF.
5. USERBSDF—a user definable model (function) whose scatter behavior is a function of the three isotropic surface symmetry variables accessed through the extrinsic ASAP macro language function capability.
6. RMS—a physical optics model of a surface with random height variations, primarily for smooth surfaces.
7. PHYSICAL—a comprehensive physical reflection model that is useful even for rough surfaces at grazing incidence.
8. VCAVITY—a rough surface model geometrically simulated as a random collection of v-cavities, which includes the effects of shadowing and multiple reflections within the cavities.
9. PARTICLES—a scattering model that simulates scatter from a uniform distribution of surface particles based upon the Henyey-Greenstein, and exact and approximate Mie models.
10. BSDFDATA—a scatter model that indirectly interpolates from a series of BSDF data entered as a function of incident and scatter angles.

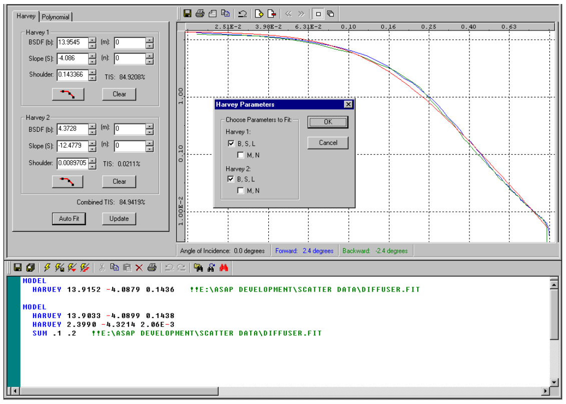
The isotropic scatter models in ASAP can be combined with the SUM command. Being fully recursive, one SUM model can reference another.

ASAP also has a powerful BSDF fitting utility integrated into its user interface. This fitting utility allows you to fit data to the HARVEY and POLYNOMIAL models, illustrated in *Figure 4*.

The input data format can be of several forms including

- ASTM, American Society for Testing and Materials as outlined in “Standard Practice for Angle Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces”
- ASCII-formatted output, generated by some Schmitt Industries’ BSDF scatterometers
- HARVEY fit files that were originally saved under ASAP version 6.6 or higher
- User definable ASCII file

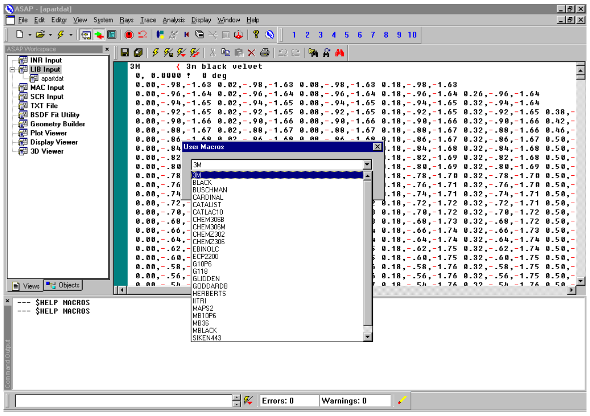
You can specify the HARVEY parameters by pointing and clicking on the graph or by using the automatic fitting feature. The HARVEY fit option allows you to SUM two HARVEY models together. The POLYNOMIAL option allows you to fit data to the POLYNOMIAL model by specifying the desired coefficient of the fit. In either case ASAP prints out model data that you can integrate directly into your ASAP model. ASAP also has a library of isotropic scatter models. These models are measured data fitted with the TRINOMIAL model, which attempts to force potentially non-reciprocal BSDF data to be reciprocal. Some of the models are illustrated in *Figure 5*.



```
MODEL
  HARVEY 13.9152 -4.0879 0.1436   !!E:\ASAP DEVELOPMENT\SCATTER DATA\DIFFUSER.FIT

MODEL
  HARVEY 13.9033 -4.0899 0.1438
  HARVEY 2.3990 -4.3214 2.06E-3
  SUM .1 .2   !!E:\ASAP DEVELOPMENT\SCATTER DATA\DIFFUSER.FIT
```

Figure 4 ASAP BSDF fitting utility and the ASAP file it created



```
3M        { 3m black velvet
 0, 0.0000 !  0 deg
 0.00,-.98,-1.63 0.02,-.98,-1.63 0.08,-.98,-1.63 0.18,-.98,-1.63
 0.00,-.96,-1.64 0.02,-.96,-1.64 0.08,-.96,-1.64 0.18,-.96,-1.64 0.26,-.96,-1.64
 0.00,-.94,-1.65 0.02,-.94,-1.65 0.08,-.94,-1.65 0.18,-.94,-1.65 0.32,-.94,-1.64
 0.00,-.92,-1.65 0.02,-.92,-1.65 0.08,-.92,-1.65 0.18,-.92,-1.65 0.32,-.92,-1.65 0.38,-
 0.00,-.90,-1.66 0.02,-.90,-1.66 0.08,-.90,-1.66 0.18,-.90,-1.66 0.32,-.90,-1.66 0.42,-
 0.00,-.88,-1.67 0.02,-.88,-1.67 0.08,-.88,-1.67 0.18,-.88,-1.67 0.32,-.88,-1.66 0.46,-
```

```
--- $HELP MACROS
--- $HELP MACROS
```

Figure 5 ASAP library scatter models

Anisotropic Surface Scattering Models

As mentioned previously, scattering from anisotropic surfaces such as brushed or diamond turned is not rotationally symmetric about the plane of incidence and surface normal. Therefore, the orientation of the model on the surface is important and is generically specified by an additional axis parameter. With the exception of one model, all these models are the anisotropic equivalents of certain isotropic surface scattering models.

- VANES - a surface scatter model that simulates a locus of vane tips parallel to a particular orientation
- HARVEY - the elliptical equivalent of the isotropic HARVEY model
- NONLINEAR - the anisotropic equivalent of the isotropic NONLINEAR model
- USERBSDF - the anisotropic equivalent of the isotropic USERBSDF model
- BSDFDATA - the anisotropic equivalent of the isotropic BSDFDATA model

Figure 6 illustrates Lambertian, anisotropic Harvey, and isotropic Harvey BSDF at 30 degrees incident angle. ASAP has a special plot feature on the model definitions for creating data sets of scattering functions, and a wide variety of features for visualizing them.

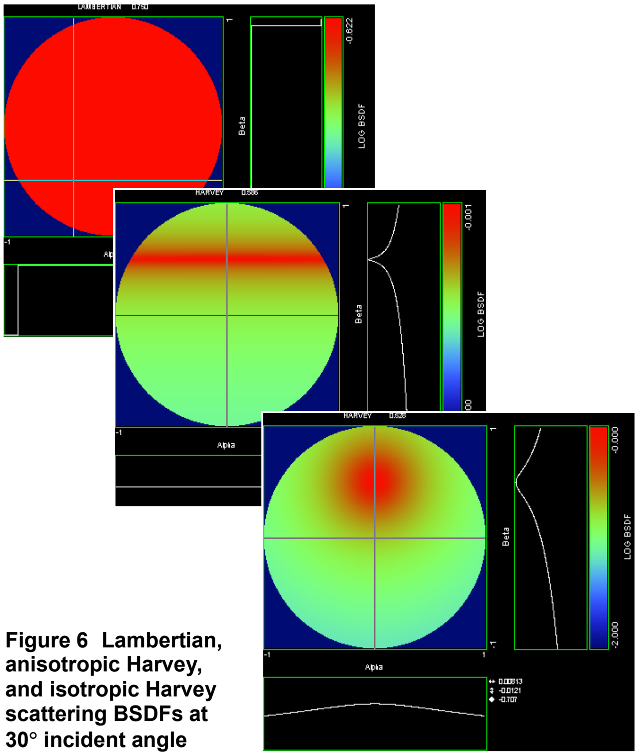


Figure 6 Lambertian, anisotropic Harvey, and isotropic Harvey scattering BSDFs at 30° incident angle

Figure 7 illustrates scattering off LAMBERTIAN, anisotropic HARVEY, and isotropic HARVEY models assigned to three different sections of a tube illuminated by a source above the tube. The picture was created with the ASAP RENDER command, which renders scenes including any scatter models assigned to objects for a realistic visualization of scatter behavior. *Figure 8* illustrates scatter off a tire (Lambertian) and a machined wheel hub (anisotropic) further demonstrating the powerful scatter simulation capability in ASAP.

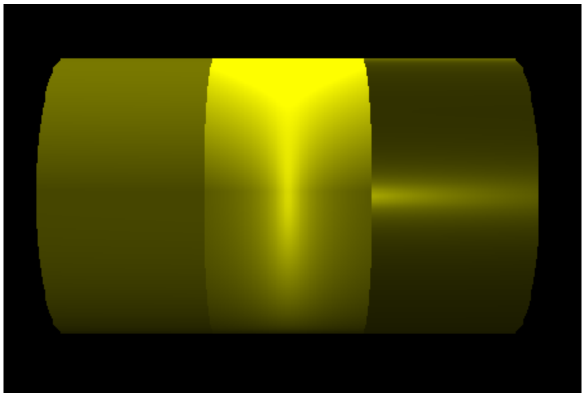


Figure 7 Lambertian, anisotropic Harvey, and isotropic Harvey scattering from a tube

Figure 8 Realistic scatter scene rendering in ASAP

Any of the anisotropic scatter models in ASAP can also can be combined with the SUM command. This command is fully recursive so that one SUM model can reference another. However, only one anisotropy orientation can be used for all the models.

Volume Scatter Models

The volume scattering calculation in ASAP is different from the most common type of surface scattering in that the ray path in volume scatter is changed according to the scattering function, as opposed to the volume generating scattered rays. It is an inhomogeneous Monte-Carlo scattering model, which perturbs the incident ray according to a volume scatter model that depends on the 3D position of the ray within the volume. *Figure 9* illustrates this Monte-Carlo technique along with the ability in ASAP to calculate the fluence in a volume with its VOXEL (volume picture or pixel elements) command.

The following volume scatter models are available in ASAP:

- VOLUME - a volume scattering model that simulates scattering within a uniform distribution of volume particles, based upon the Henyey-Greenstein and exact and approximate Mie models
- USERBSDF - a user-defined volume scatter function

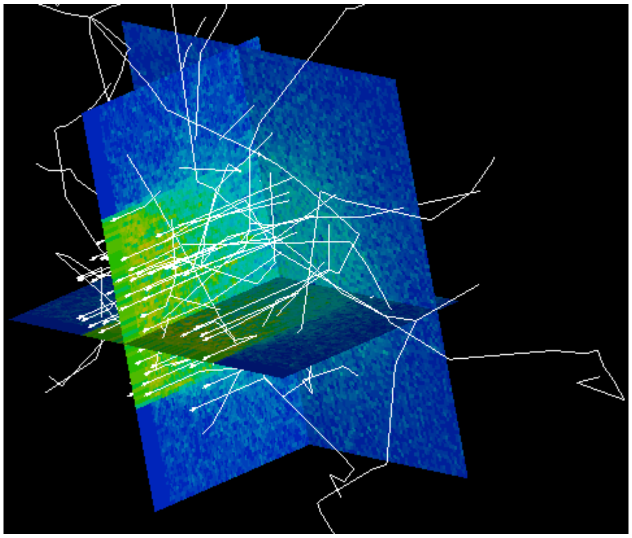


Figure 9 Volume scattering and volumetric energy tracking (fluence) calculations in ASAP

Importance Area Sampling for Surface Scatter Simulations

Scattering rays into a hemisphere is an inefficient way to simulate scattered light, especially if you are trying to propagate rays towards a small area or into a small solid angle. Consider an example from BRO's Stray Light Analysis tutorial. How many rays must be generated to sample a hemisphere with a density of 1 square degree in a telescope, assuming an initial sampling of the entrance pupil of an optical system of 1,000 by 1,000 rays? 1 million initial rays x (20,600 square degrees in a hemisphere)^2 = 4x10^{14} rays (400 million million rays).

Now consider that the typical ray trace through complex geometry is done at about 1 million rays per hour and you end up with a whopping 46,000 years to finish the ray trace. And this is only for one field angle and one wavelength. Clearly scattered light analyses cannot be solved with a purely brute force method.

Fortunately, ASAP has a useful and necessary feature for targeting scattered rays towards a particular area or into a solid angle. The TOWARDS command allows you to specify an area or solid angle into which scattered rays are generated. This technique saves considerable time by targeting scattered rays only towards areas of interest, such as pupil locations, making the ray trace extremely efficient. *Figure 10* illustrates the technique. Rays may be scattered towards or away from important areas. Importance area sampling is an essential feature of any serious stray light analysis program.

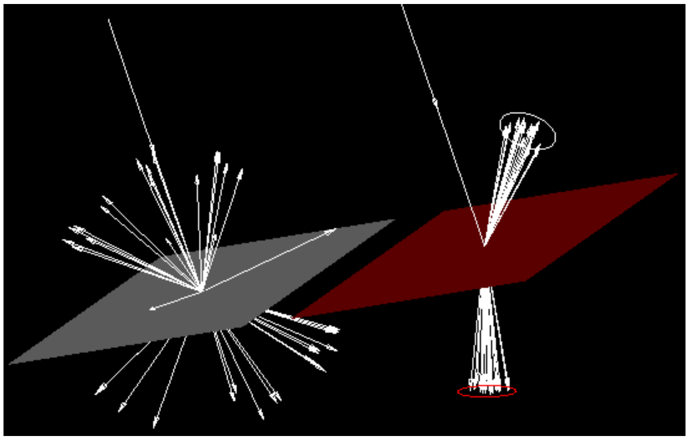


Figure 10 SCATTER RANDOM without and with TOWARDS command

Powerful scatter simulation capabilities and the macro language in ASAP allow you to compute the amount of stray light getting to your detector, as well as other radiometric quantities like irradiance, intensity, radiance, and even the point source transmission (PST).

The PST is also known as the normalized detector irradiance (NDI) and the point source normalized irradiance transmission (PSNIT). The PST is basically a signal to noise ratio of the entrance pupil irradiance of a point source to the scattered light detector irradiance as a function of field angle. It is also a function of position on the detector, which can be analyzed with the SPOTS POSITION command, which computes irradiance. The PST is a common measure of scattered light performance in classical satellite imaging optical systems.

Calculations such as the PST are possible in ASAP because the program tracks how each ray is created and traced though the optical system. Even though both scattered and signal rays might coexist at the detector, you can isolate scattered rays from the signal rays with the SELECT command to perform numerical and graphical radiometric calculations on these rays only. Moreover, ASAP has the PATHS command, which sorts different stray light paths so that you can see numerically and graphically where the stray light is coming from. Both of these powerful and useful commands will be demonstrated in the following section.

Ghost Image Analysis

Ghost images are another manifestation of stray light. Ghost images are produced by the inter-reflections of light from optical element surfaces that have non-zero reflection and transmission coefficients as illustrated in *Figure 11*.

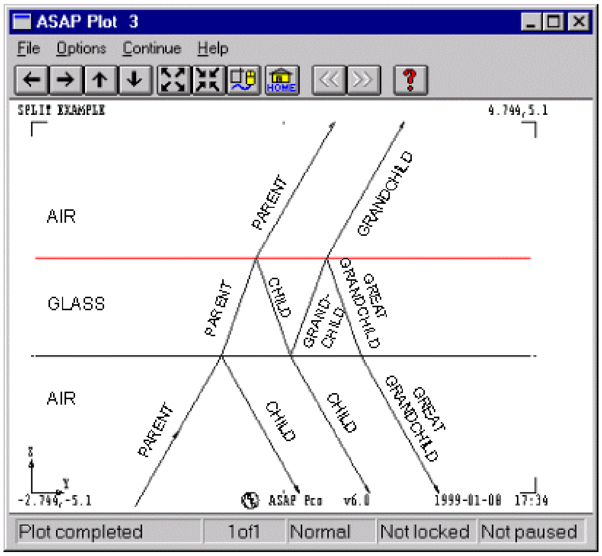


Figure 11 Inter-reflections of light from planar surfaces

The non-zero reflection and transmission is due to the difference in the refractive index on either side of the interface. Some of the incident light is transmitted at the surface of the element while some is reflected at the same time. The reflected light propagates back to another element surface, is reflected there, and eventually propagates to the image plane. The culmination of these reflections at the image plane results in a ghost image. ASAP has a suite of tools for computing ghost images such as these in optical systems, including the ability to simulate ghost rays deterministically or with a Monte-Carlo technique.

The magnitude of ghost reflections depends upon the surface reflectivity and transmissivity. The simplest form of the definition of the reflectivity of a surface is the ratio of the incident power to that of the reflected power, operationally defined as

$$\rho(\lambda) = \frac{P_r(\lambda)}{P_i(\lambda)}$$

Unfortunately this is not a real world model. Specular reflectivity is the reflected power divided by the incident power as a function of wavelength, angle of incidence, and polarization.

$$\rho(\theta_i, \phi_i, \lambda) = \frac{P_r(\theta_r, \phi_r, \lambda)}{P_i(\theta_i, \phi_i, \lambda)}$$

Here λ indicates that the radiant power, ϕ, can be spectrally dependent on wavelength. The angles of incidence and reflection are related through Snell's law. Note that the incident and reflected powers are the powers in the specular incident and reflected beams. The specular reflectivity is a function of the incident angle and wavelength. Usually this angle is defined in the plane of incidence formed by the surface normal, the incident ray, reflected, and transmitted rays.

The theoretical reflectivity, when defined as above, explicitly includes dispersion by way of the spectral distribution and implicitly includes polarization by way of Fresnel's amplitude coefficients. Any program claiming to simulate ghost images must have this simulation capability. Not only does ASAP fully account for Fresnel reflection and transmission coefficients it also accounts for the phase. Both important parameters are computed as a function of wavelength, polarization, and angle of incidence for simple substrates, complex multi-layer coatings, and even measured data. The FRESNEL command can be set globally or for each object individually. And just as the LEVEL command controls the number of scattered rays, the SPLIT command controls the number of split rays at an interface—giving you complete control over the creation of ghosted rays.

ASAP can generate ghost rays in the traditional sense by creating a reflected and transmitted ray at each interface having a non-zero reflection and transmission coefficient, or it can launch either a reflected or transmitted ray based upon the probability of reflection and transmissions at that interface. The probability of reflection or transmission is in fact the reflection and transmission coefficients and generating ghost rays in this manner allows you to simulate a Monte-Carlo process. The SPLIT command, along with the interface command, allows you to fully control these features. *Figure 12* illustrates a Fresnel calculation in ASAP.

Ghost image analysis, like scattered light analysis, requires forward and backward ray tracing. Forward ray tracing is understandable. In a forward ray trace you can determine the amount of ghost radiation getting to the detector as a function of field angle. This type of calculation is usually done with point sources. You can, for example, calculate the detector irradiance or other radiometric parameters. Tracing rays backward to the front of the optical system and computing the intensity pattern there will allow you to determine hot spot directions where the ghost irradiance is largest at the detector.

Calculating the overall ghost contribution to an image, even from the detector as in the case of narcissus in the infrared, is important in determining system performance. Furthermore, evaluating the contributions of individual components of the ghost images is crucial to identifying the major ghost image contributors for later corrective action. ASAP has a powerful command for such an evaluation called PATHS. The PATHS command sorts ghosted and scattered rays at a particular object into common categories

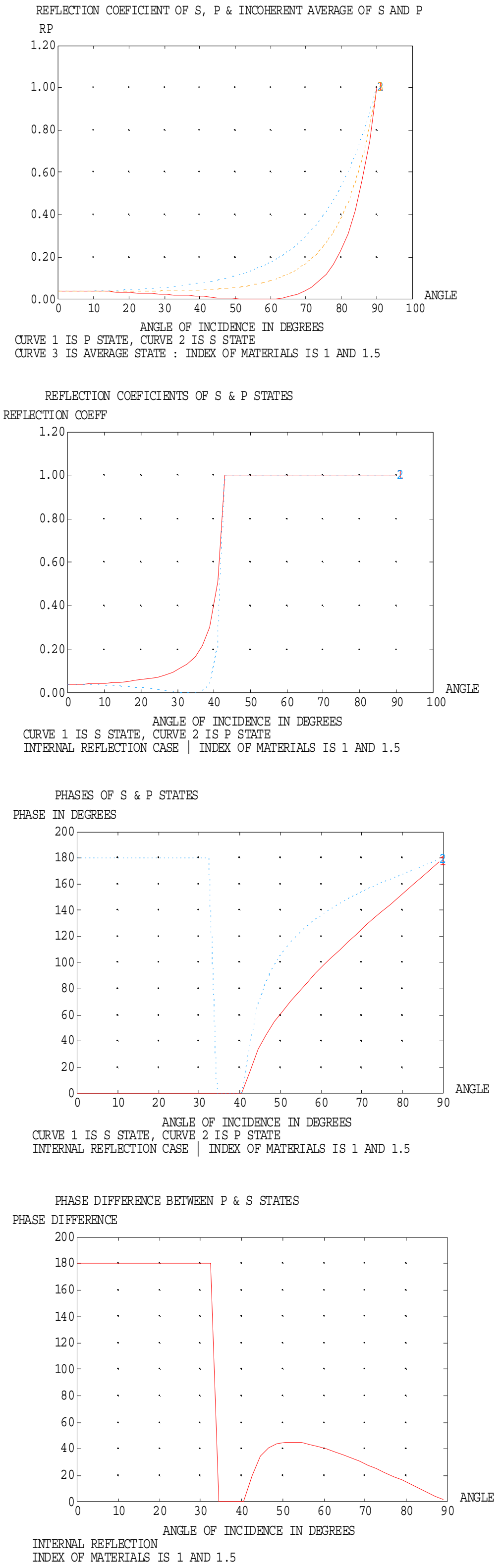


Figure 12 Fresnel external and internal reflection with internal phase plots

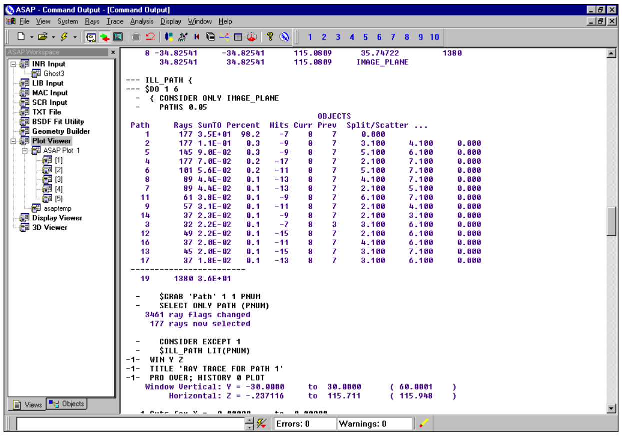
based upon their stray light origin. Rays in a particular category form a stray light path which can be evaluated numerically in the path table, or the SELECT PATH command can isolate

individual paths for further calculations such as total power, irradiances, intensities, and radiances. Each stray light path can even be individually visualized when used with the SAVE and HISTORY…PLOT commands as illustrated in *Figure 13*. The SAVE command saves every ray intersection, direction, and flux during the ray trace which can be plotted to illustrate a particular stray light path.

Once you determine that you have a ghost problem, ASAP can help you eliminate it or reduce its magnitude. Ghost images are treated by applying anti-reflection coatings, adding baffles and apertures, and tilting or wedging optical components. Sometimes the optical system must be redesigned to change the optical prescription to reduce the effects of ghost images. ASAP has the ability to model multi-layer coatings by entering the coating prescription on a layer-by-layer basis with complex indices of refraction. ASAP also has the ability to simulate coatings with measured data. Reflection and transmission coefficients can be entered as a function of wavelength and polarization. Sometimes it is actually better to use such measured data because it more accurately models the coating behavior due to variability in coating manufacture from the actual prescription. Also, coating manufacturers will not often disclose their coating designs, but will share reflection and transmission data.

Baffles and apertures are easily modeled in ASAP. The $ITER command can be used to automatically and parametrically change surface wedges and element tilts while recalculating ghost effects to find conditions of maximum performance. Although ASAP has an optimization feature implemented through $ITER and its lens entities, it is perhaps not the best way to design actual coatings or redesign the optical system. The optimization feature implemented through the lens entities is restricted to on-axis, symmetric systems.

The ghost image calculations discussed above are necessary for quantitative optical engineering



```
    8 -34.82541     -34.82541     115.0809     35.74722          1380
       34.82541      34.82541     115.0809    IMAGE_PLANE

--- ILL_PATH {
--- $DO 1 6
  -  { CONSIDER ONLY IMAGE_PLANE
  -    PATHS 0.05
                                           OBJECTS
 Path      Rays SumTO Percent  Hits Curr Prev  Split/Scatter ...
    1       177 3.5E+01  98.2    -7    8    7     0.000
    2       177 1.1E-01   0.3    -9    8    7     3.100      4.100      0.000
    5       145 9.0E-02   0.3    -9    8    7     5.100      6.100      0.000
    4       177 7.0E-02   0.2   -17    8    7     2.100      7.100      0.000
    6       101 5.6E-02   0.2   -11    8    7     5.100      7.100      0.000
    8        89 4.4E-02   0.1   -13    8    7     4.100      7.100      0.000
    7        89 4.4E-02   0.1   -13    8    7     2.100      5.100      0.000
   11        61 3.8E-02   0.1    -9    8    7     6.100      7.100      0.000
    9        57 3.1E-02   0.1   -11    8    7     2.100      4.100      0.000
   14        37 2.3E-02   0.1    -9    8    7     2.100      3.100      0.000
    3        32 2.2E-02   0.1    -7    8    3     3.100      6.100      0.000
   12        49 2.2E-02   0.1   -15    8    7     2.100      6.100      0.000
   16        37 2.0E-02   0.1   -11    8    7     4.100      6.100      0.000
   13        45 2.0E-02   0.1   -15    8    7     3.100      7.100      0.000
   17        37 1.8E-02   0.1   -13    8    7     3.100      6.100      0.000
 -------------------------
   19      1380 3.6E+01

  -    $GRAB 'Path' 1 1 PNUM
  -    SELECT ONLY PATH (PNUM)
   3461 ray flags changed
    177 rays now selected

  -    CONSIDER EXCEPT 1
  -    $ILL_PATH LIT(PNUM)
-1-  WIN Y Z
-1-  TITLE 'RAY TRACE FOR PATH 1'
-1-  PRO OVER; HISTORY 0 PLOT
   Window Vertical: Y = -30.0000     to  30.0000      ( 60.0001    )
          Horizontal: Z = -.237116    to  115.711      ( 115.948    )
```

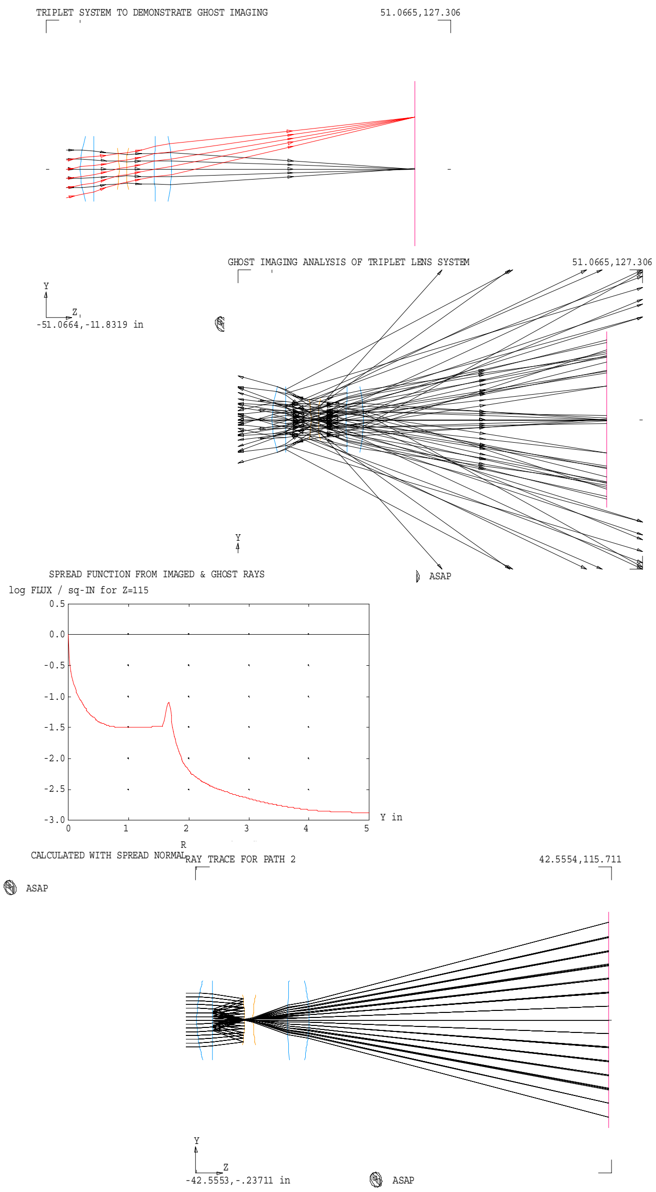


Figure 13 Ghost rays analysis using the PATH, SELECT, and SAVE commands

work. But it is sometimes difficult to convince a project manager that a change in design is needed based upon engineering data. In these cases the ability to demonstrate the effect with a scene simulation is an extremely valuable modeling technique that enables non-technical personnel to visualize the problem. ASAP allows you to simulate bitmap scenes as ray sets and then to propagate these rays sets through your optical system including the effects of stray light.

This powerful visualization technique is illustrated in *Figure 14* where a ghost image of the sun is manifested as the apodization of the aperture stop of the optical system.

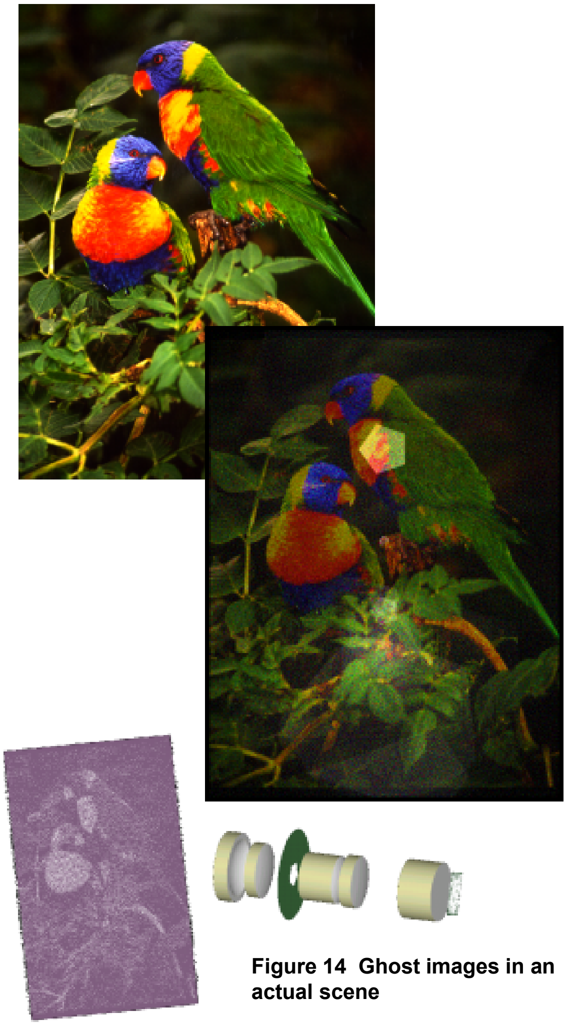


Figure 14 Ghost images in an actual scene

The picture with the aperture stop ghost has optical elements coated with a single layer anti-reflection coating. The picture without the aperture stop ghost has optical elements coated with a multi-layer anti-reflection coating. Which would you prefer? Sometimes performance is sacrificed for cost. ASAP will help you make these decisions by providing an extremely powerful engineering and visualization tool.

Edge Diffraction

Although ASAP can perform complicated diffraction (physical optics) calculations through its Gaussian beam superposition capability, it does not yet handle wide-angle diffraction calculations from edges. However, wide-angle diffraction calculations are possible in ASAP by implementing the method of stationary phase through the ASAP macro language. This method works at large diffraction angles where fields are small, which is exactly the area needed for stray light work. This technique and many others are taught in BRO's advanced ASAP Stray Light Analysis tutorial.

Script files (files containing ASAP syntax and macro commands) are an efficient and compact way to set up ASAP geometry, sources, and commands for analyses, and allow you to perform analyses that are not available as a standard feature. Software programs that lack a macro language cannot give you the full power and flexibility often necessary to solve your problem.

Other diffraction phenomena such as multiple grating orders are readily handled through the ray-splitting capability and the Gaussian beam superposition algorithm in ASAP. For more information, see the Procedural Note, "Physical Optics in ASAP," BRO-1151.

Thermal Emission

Warm bodies emit radiation in the infrared region of the electromagnetic spectrum. This radiation can make its way to your detector causing a stray light problem. ASAP allows you to simulate thermal emission by turning any relevant mechanical and optical components into ray emitting sources. The fractional blackbody irradiance and hence the power of each source can be set using the fractional blackbody irradiance FBI function in ASAP. The ability to turn any object into a ray emitter, coupled with importance area sampling, allows you to efficiently propagate thermal radiation from objects to areas of interest to determine thermal problems.

Summary

ASAP permits a nearly limitless variety of optical systems and the effects of stray light to be simulated in a straightforward manner. These capabilities, coupled with the ability to split rays into reflected, transmitted, diffracted, and scattered light, make it the most realistic commercially available simulation tool for optical analysis.

ASAP has been tested again and again against some of the world's most complex optical systems and difficult stray light problems, and continues to yield stray light analysis results consistent with measured data and performance. ASAP was designed by leaders in the field of stray light analysis and suppression. These experts also offer specialized, dedicated stray light analysis training through advanced tutorials—something no other company offers.

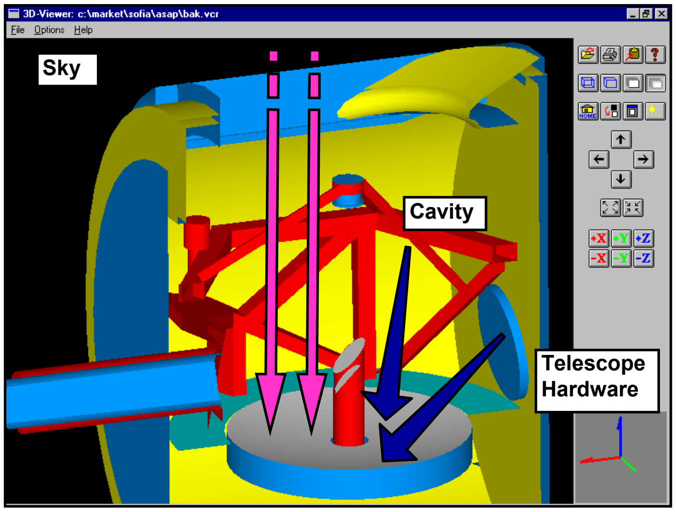


Figure 15 Thermal emission in a complex telescope