Ghost and Stray Light Analysis using TracePro®

February 2012 Webinar

Lambda Research Corporation

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Format

- *A 25-30 minute presentation followed by a 10-15 minute question and answer session*

- *Please submit your questions anytime using Question box in the GoToWebinar control panel*

Ghost and Stray Light Analysis using TracePro®

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In this webinar you will:

- *Learn how to use TracePro to analyze ghost paths*
- *Learn how to understand and use importance sampling for scatter analysis*
- *Learn how to understand and use tools to analyze stray light issues*

Current TracePro Release

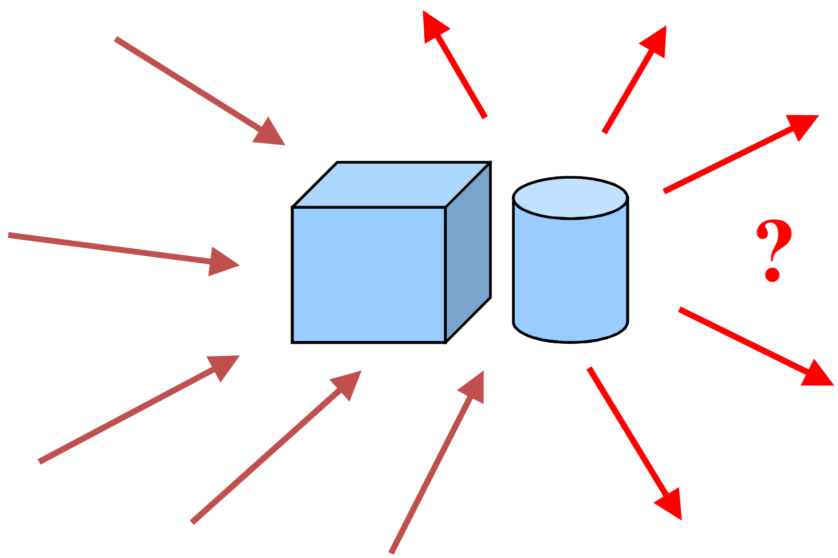
- *TracePro 7.1.2*

- *Can be downloaded by anyone with a current Maintenance and Support Agreement*

- *www.lambdares.com*

Raytracing for Optical Simulation: The Approach

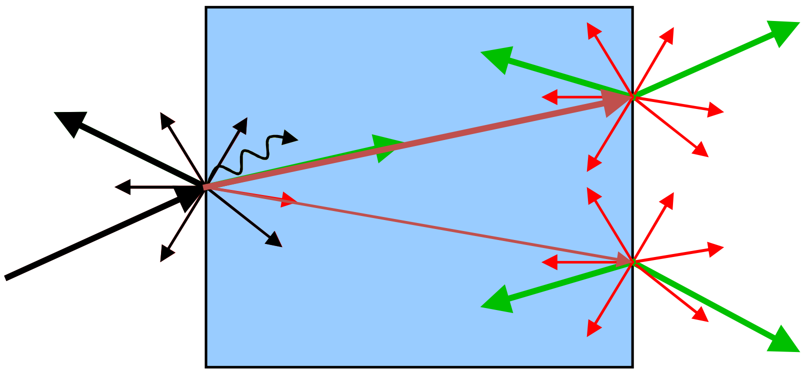
- Ignore all optical constructs
  - Make no assumptions
- Create a "realistic" virtual 3D model



- Apply surface and material properties to the model
- Launch light into the model
- Let the model determine where the light goes (calculate surface order)

Optical Simulation (cont.)

5 things can happen to light when it hits a surface…

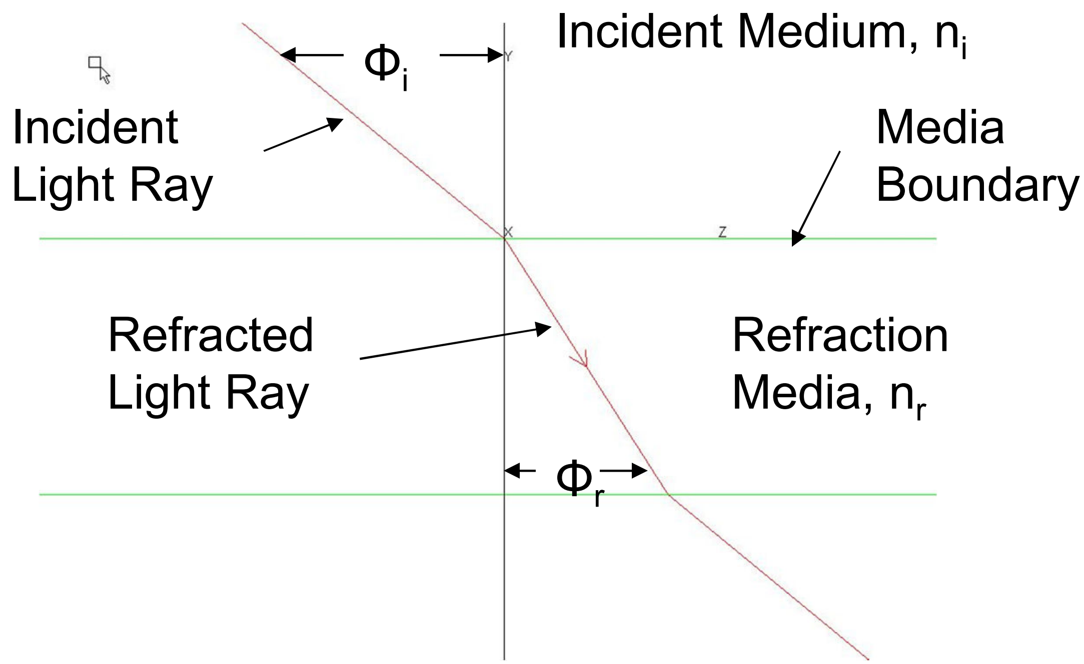


- Refract
- Reflect
- Absorb
- Forward Scatter
- Backward Scatter

And it happens at each surface… (not to mention volume effects)

TracePro keeps track of where all this flux is going and reports it!

Material Property Definitions



Snell's Law: The formula used to define when light rays are incident to a boundary between two mediums, i.e. plastic or glass and air. The light rays are refracted at this boundary and this shows this interaction. For an angle of incidence θ_i in a material with an index of refraction n_i, the angle of refraction θ_r in a material n_r can be defined as $n_i \sin\theta_i = n_r \sin\theta_r$. TracePro automatically used Snell's law when this is a material present on any object that a ray intersects.

Surface Properties Info

Fresnel Loss: Occurs when light rays cross from one refractive boundary to another. There is a loss associated with this transition and it is defined as:

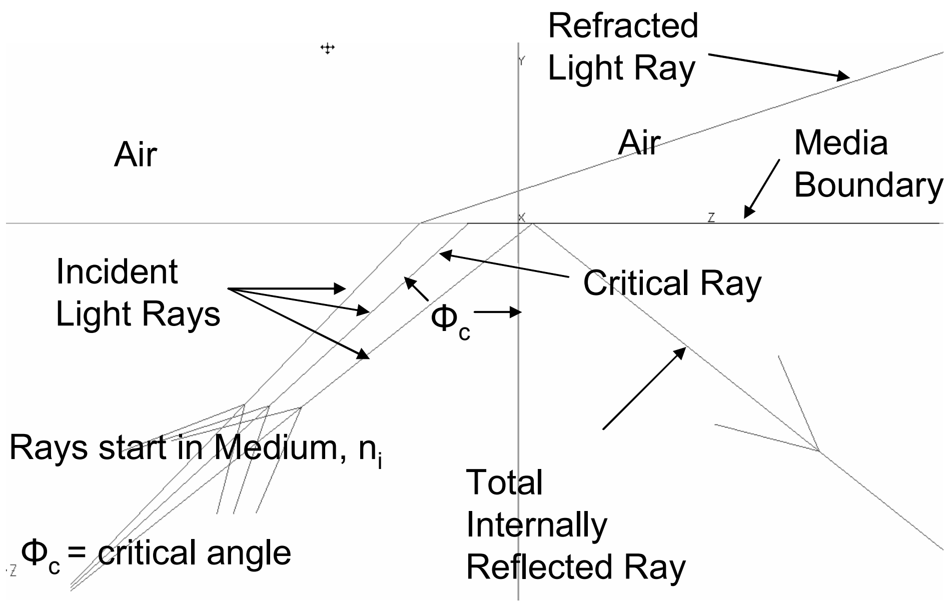
$$\left[\frac{n_i - n_f}{n_i + n_f}\right]^2$$

Where n_i and n_f are as shown in the Snell's law Powerpoint slide. For plastic to air and glass to air, the Fresnel loss at visible wavelengths is about 4 percent. The Fresnel loss is much greater in the infrared wavelengths!

In TracePro, Fresnel loss is automatically calculated at a surface when the object has a material property but no surface property (surface property is shown as none in the system tree)

Surface Properties

Total Internal Reflection (TIR): TIR occurs when light passes from a medium of high refractive index into a material of lower refractive indices. If the angle of incidence is greater than the critical angle then the light will be reflected.



The critical angle is defined where the sin θ_f (90°) = 1. This then reduces Snell's law to: Sin $\theta_c = n_f/n_i$ where $n_f = 1$ (air). The critical angle is usually 42 degrees for plastics and glass in the visible wavelengths.

Generalized Monte-Carlo Ray Tracing

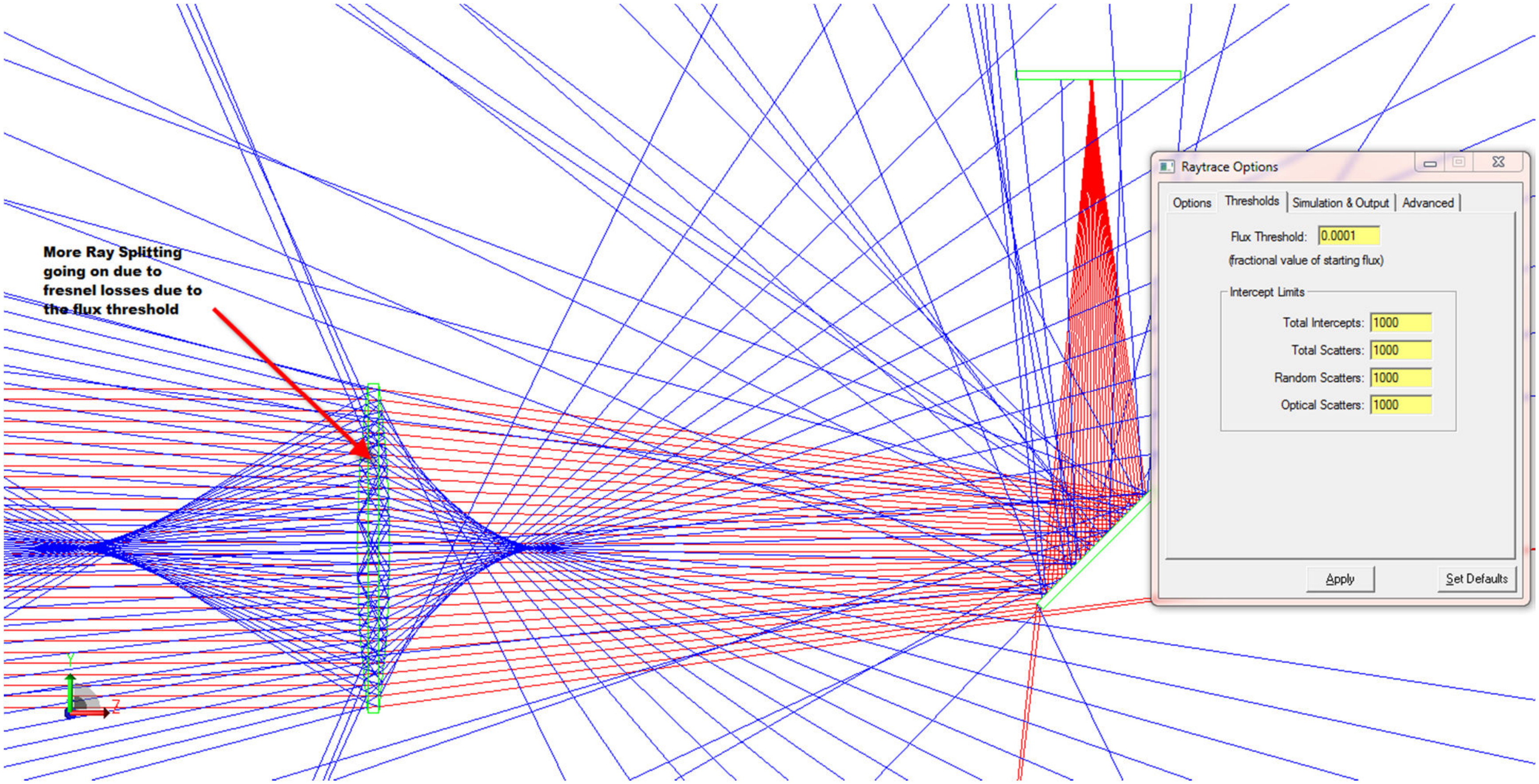
- Non-deterministic computational algorithm
  - The ray trace has multiple choice points
    - Each choice is determined by pseudo-random sampling of probability
    - A good sampling requires many rays
    - Rays can be split at choice points (determined by user)
      - Splitting (or not) does not affect accuracy of results but does affect ray-trace time, i.e. convergence to accurate result
- Low probability paths my be under-sampled with traditional Monte Carlo methods
  - Importance Sampling methods increase sampling in low-probability paths

Ghost Analysis

Definition of Ghosts

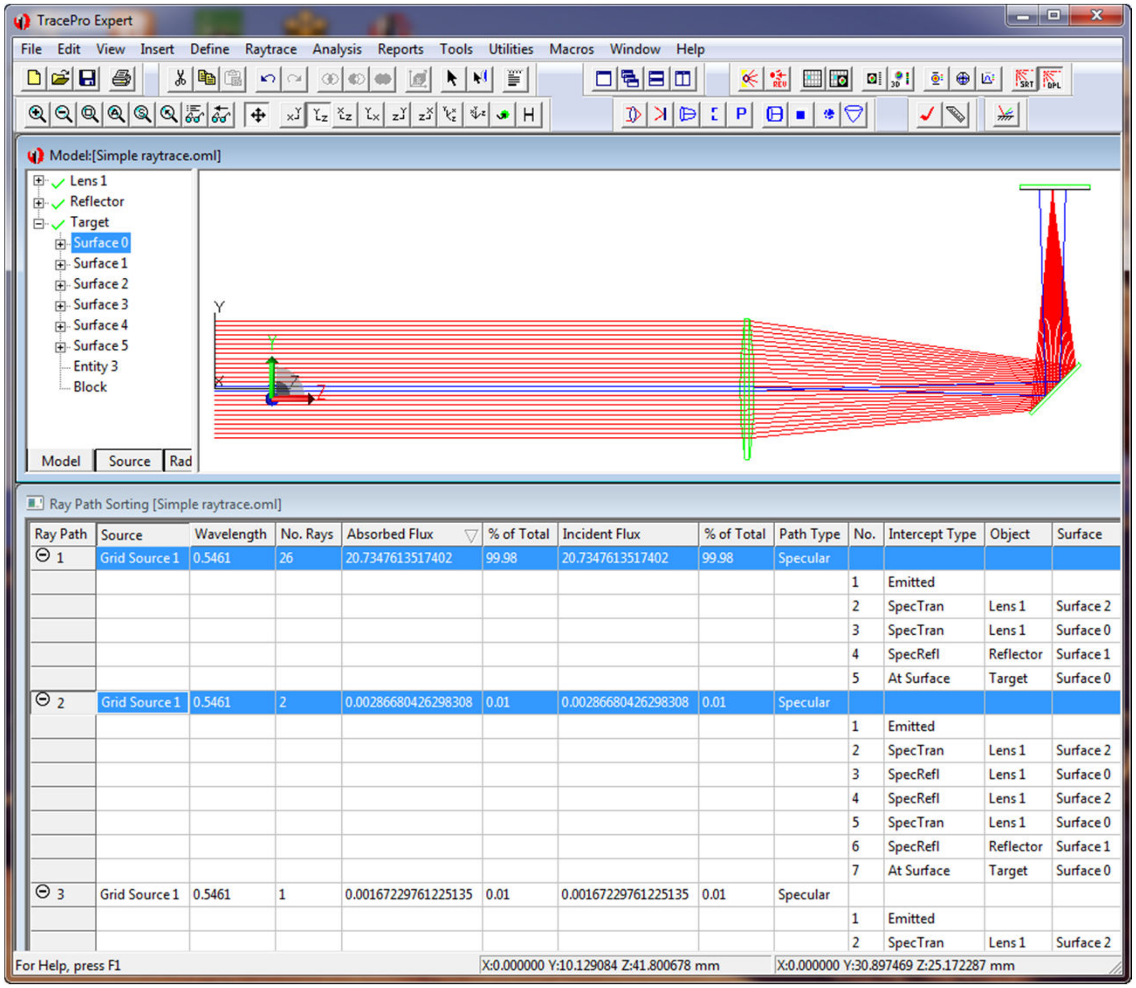
Ghost images are out-of-focus images of bright sources. Light must reflect an even number of times from lens surfaces. If the source is small each ghost looks like the aperture stop. If the ghost is focused on the image plane, the ghost looks like the source

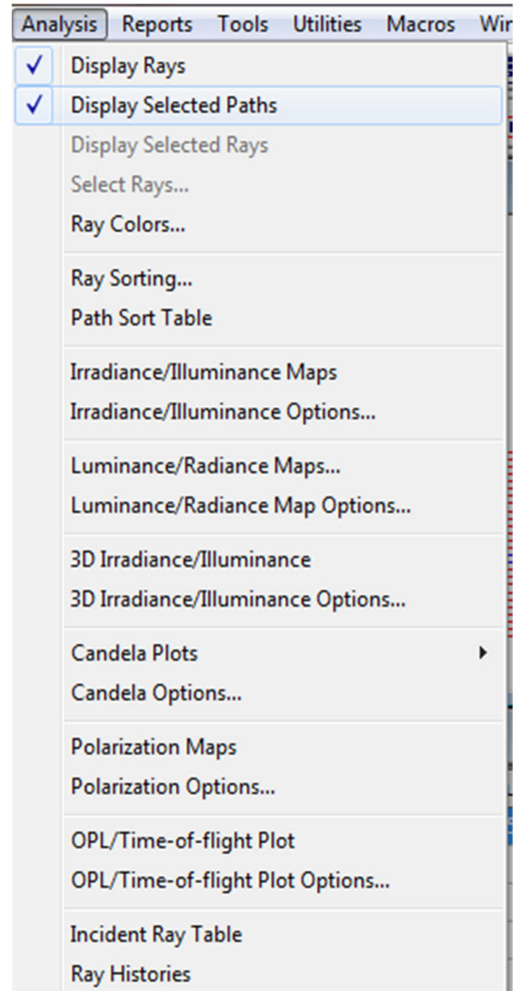
A Complex Ray Trace Example with threshold reset



Decreasing the Flux Threshold in Raytrace Options increases the number of ghosts due to fresnel losses. For this re-evaluation of the system, the flux threshold was set to .0001.

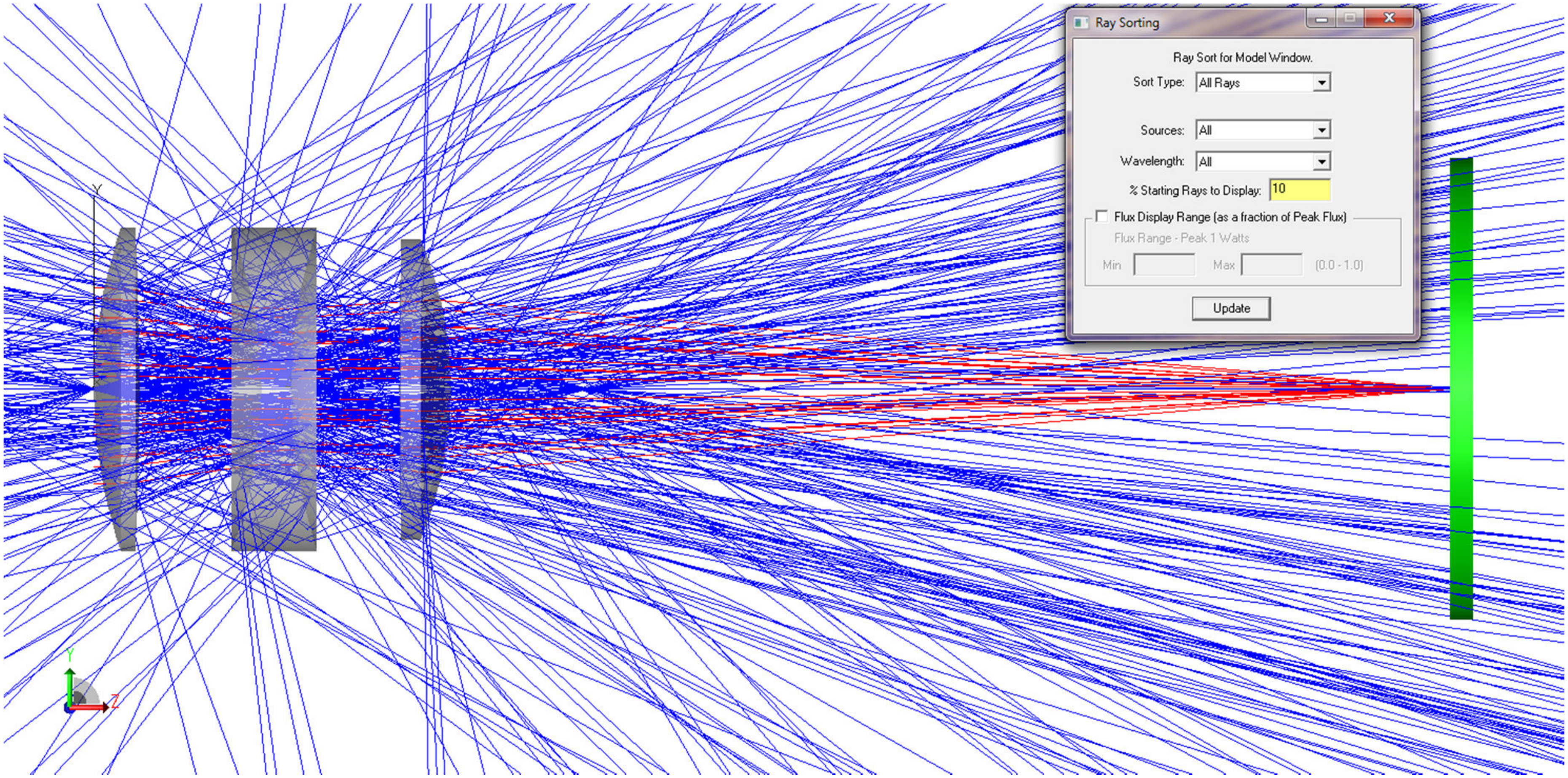
A Complex Ray Trace with ray paths shown





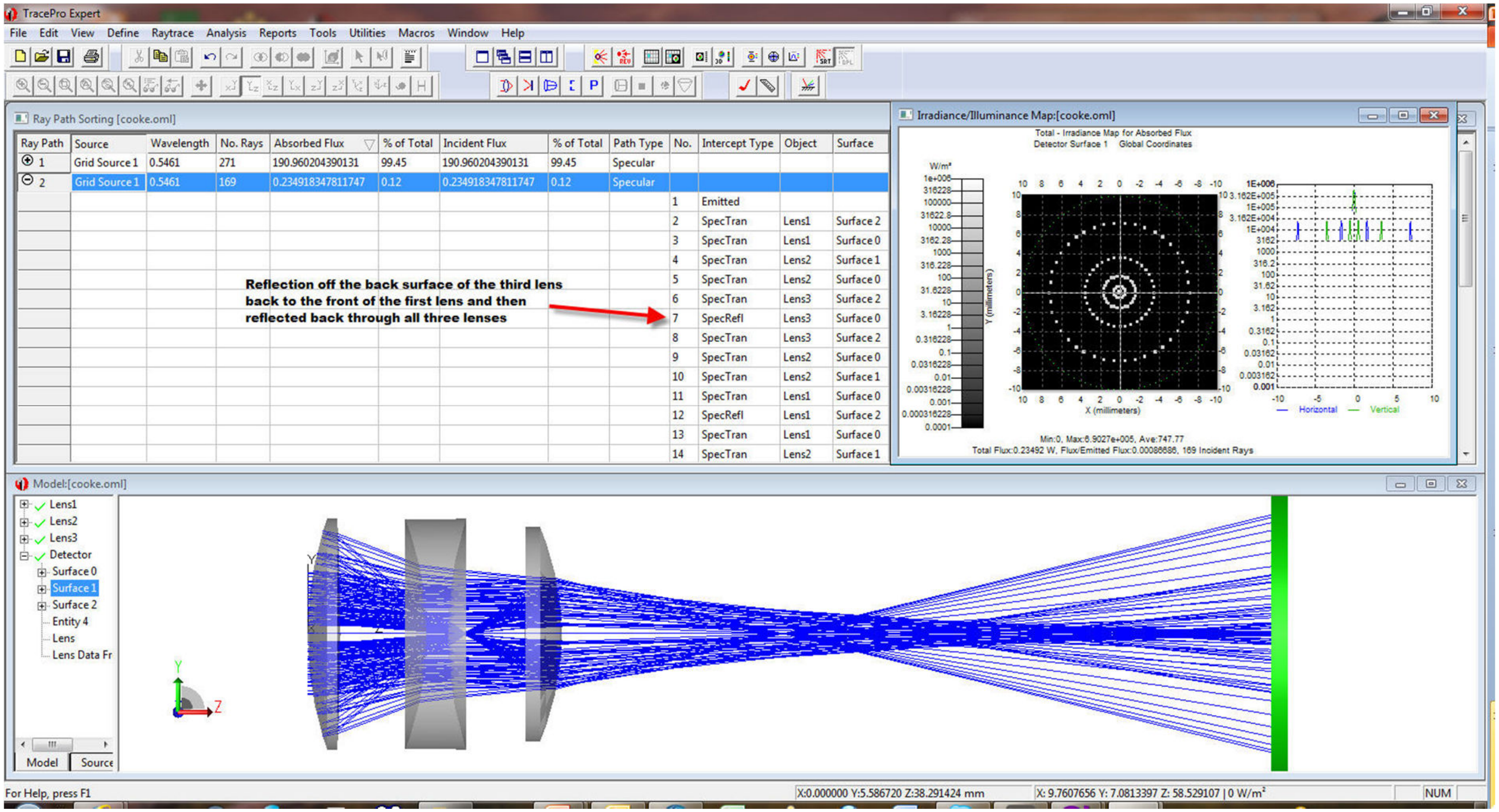
TracePro 7.1 has the ability to display a path sort table. In this table we can select paths that we want display in the system view using the Analysis| Display Selected Paths options as shown. For this example we have selected the first and second ray paths which are shown by the high intensity red rays for the first path and blue rays for the second.

Cooke Triplet Example



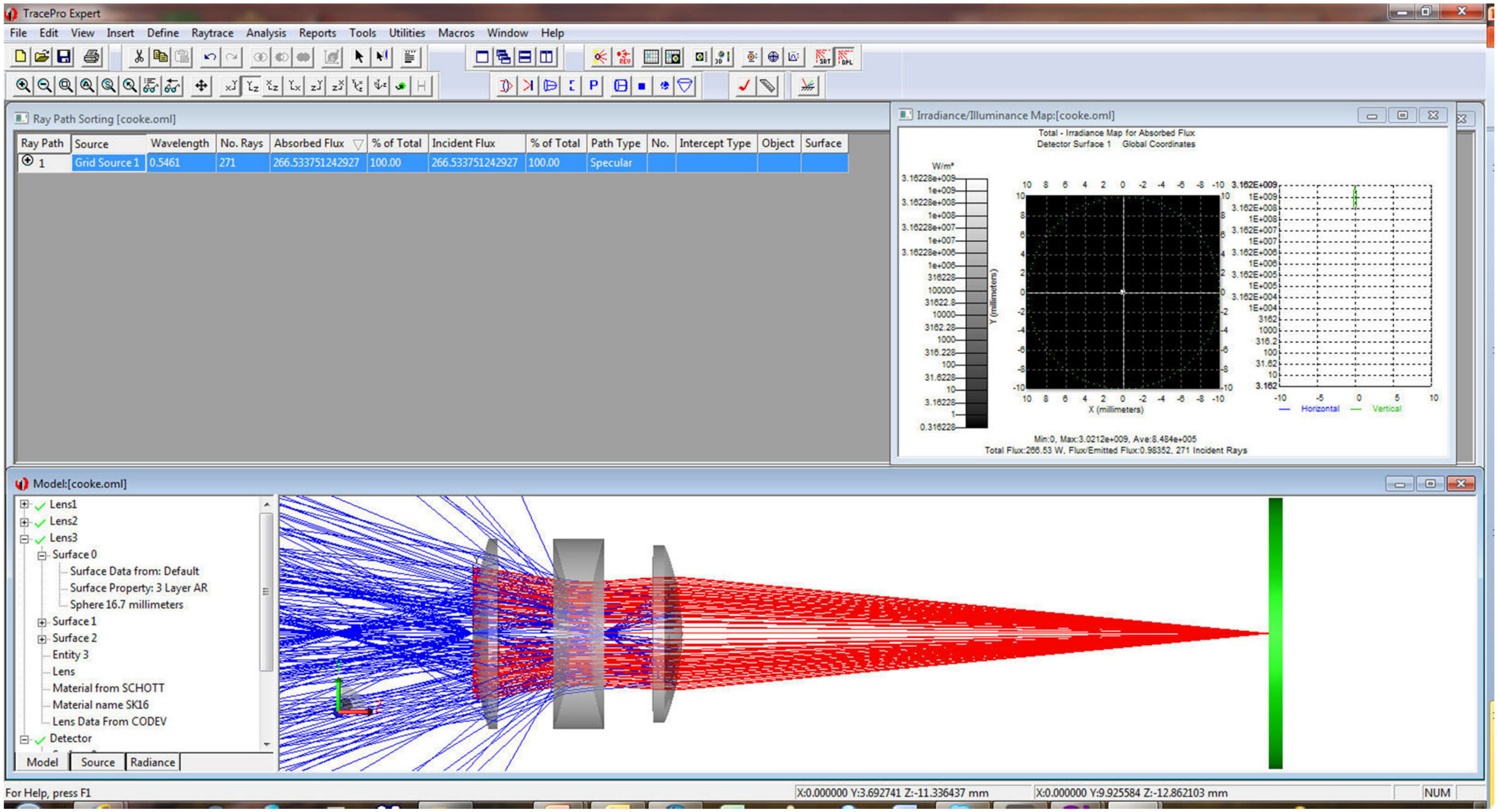
Analyzing a cooke triple with the flux threshold set to .001 we can create quite a few ghost paths. The Ray Sorting capability is quite helpful when trying to see these ghosts.

Cooke Triplet Example



Using the Analysis|Display Selected Paths option allows the user to see this 2nd largest contributing path. This is important to determine if the paths is right on top of the signal or diffused out over the entire detector. The irradiance map works in conjunction with the ray path sorting and shows only the contribution from this second path.

Cooke Triplet Example



If we coat the lenses with a 3 layer AR coating, you can see that all the ghosts no longer have paths to the detector. There is only one ray path and the signal is perfectly focused on the detector.

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The Monte Carlo Method, Ray Splitting and Importance Sampling

Monte Carlo Ray-tracing and Sampling

- A crude Monte Carlo calculation is the simplest form of a probability experiment
  - Perform an experiment N times, count the number of times n that the event occurs
  - An estimate of the probability is: $p_e = n / N$
  - We can never get an exact value of p_e, but we can make the uncertainty in p_e arbitrarily small by increasing N.
    - The absolute uncertainty in p_e is: $\sigma_{ab} = \sqrt{\frac{p(1-p)}{N}}$
    - The relative uncertainty in p_e is: $\sigma_{rel} = \sqrt{\frac{(1-p)}{pN}}$ (where p denotes the true probability)
  - Hence, the accuracy of the result is inversely proportional to the square root of the number of trials (enough trials will always lead to the correct answer)
- On a higher level, Monte Carlo is a technique of numerical integration for complicated multiple integrals that cannot be done by more conventional numerical methods
  - An integral such as $\int \ldots \int g(x_1, x_2, \ldots, x_L) dx_1 dx_2 \ldots dx_L$ can be estimated by sampling the variables x_i, computing g for this set of samples, and repeating this process N times, summing the terms to obtain the estimate (histogram method, trapezoidal rule, Simpson's rule, …etc.)

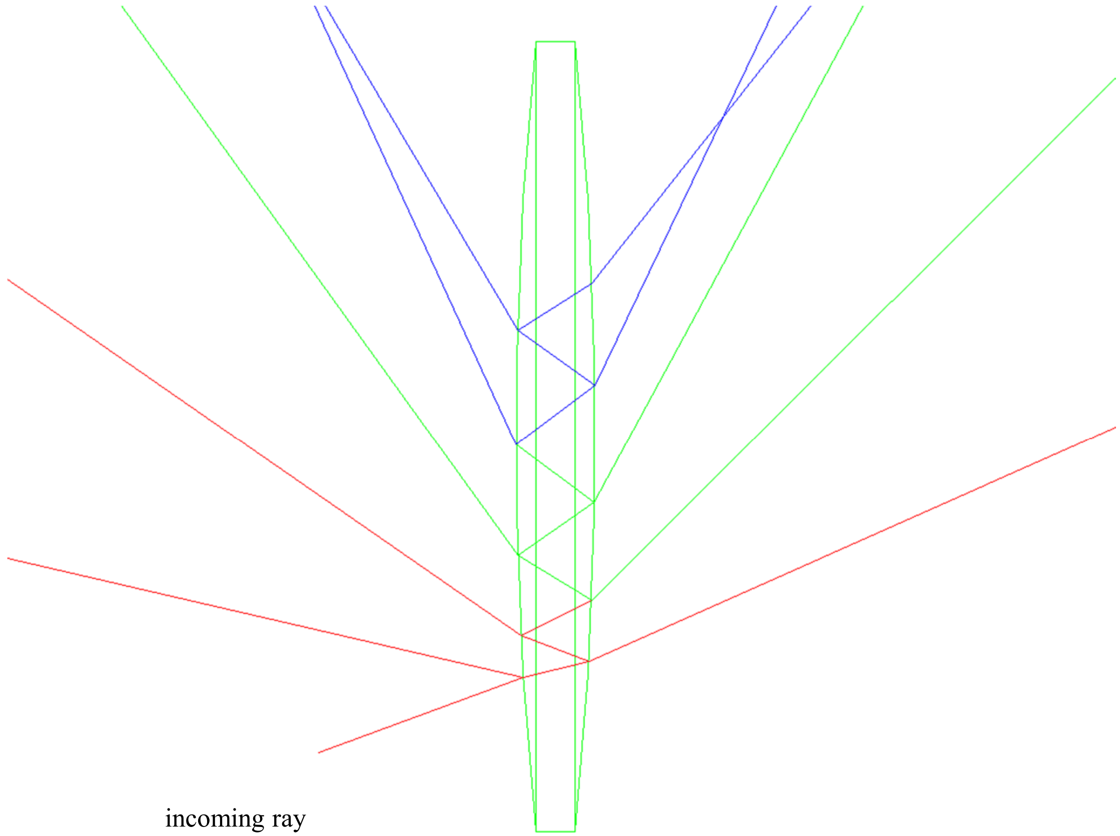
Variance reduction

- Variance reduction techniques are used to reduce the variance or uncertainty in the result of a Monte Carlo calculation after a given number of trials. Conversely, the number of trials needed to obtain a given uncertainty can be reduced.
- Splitting is a variance reduction technique used in Monte Carlo simulation. Ray splitting is used in TracePro.
- Importance sampling is a second commonly used method for variance reduction.

Ray Splitting

- Ray splitting is a technique in which a ray that strikes a surface can be split into several component rays, namely absorbed, specularly reflected, reflectively scattered, specularly transmitted, and transmissively scattered.
- The flux of the incident ray will also be split, with a fraction of the incident flux assigned to each component ray according to the properties of the surface.
- The process of splitting is repeated at each surface intercept, so that a tree-like structure of rays results.
- This process tremendously improves sampling in most cases, with a tolerable slowing of the raytrace.

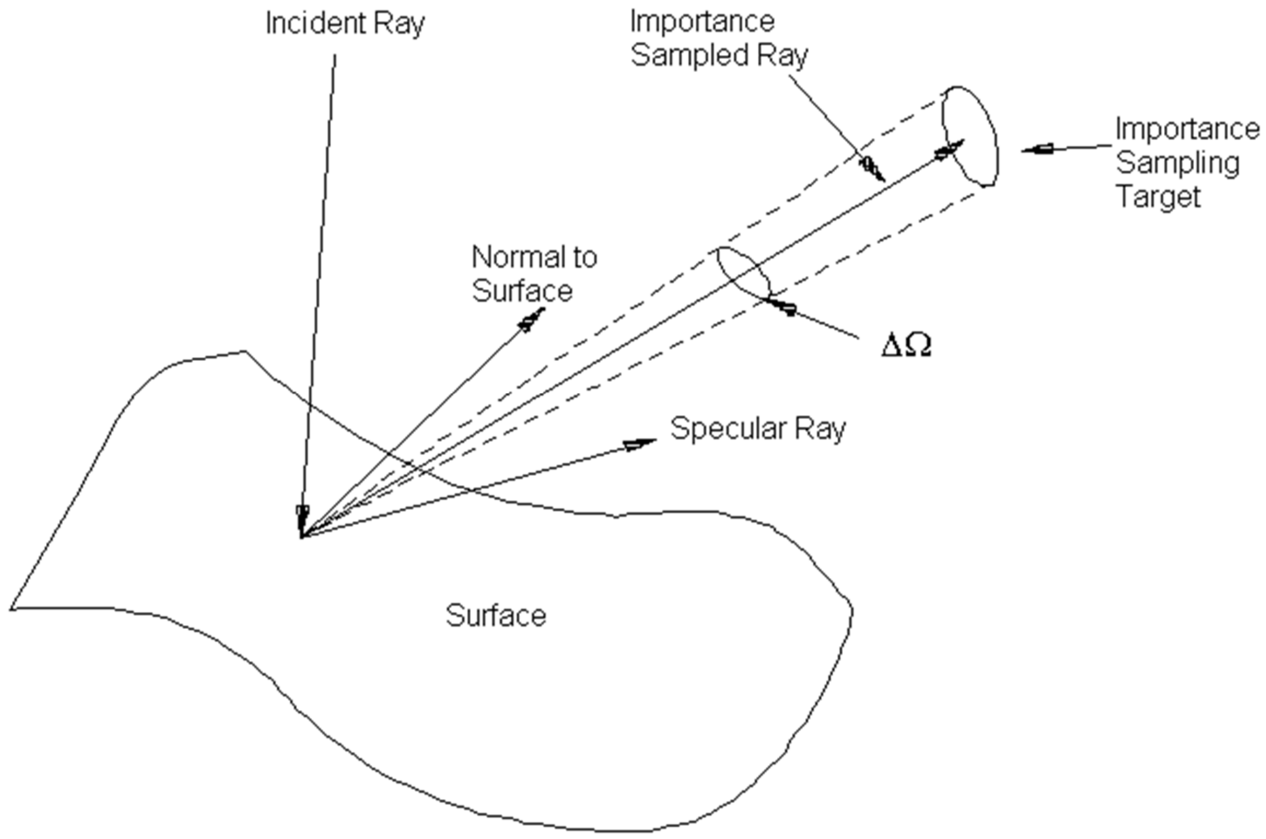
Ray Splitting



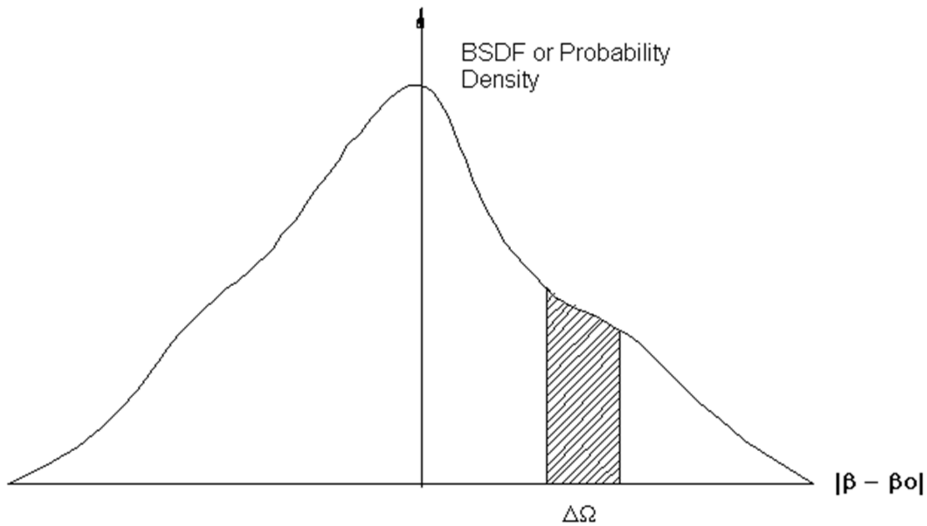
Importance Sampling

- Importance Sampling is used to improve the sampling of random events without dramatically increasing the number of rays started.
- Uses the scattering distribution function as a probability density to apportion a fraction of the scattered ray flux into a desired direction.
- May be used for emitted, scattered and diffracted rays only, on surface sources, scattering surfaces, diffracting surfaces and bulk scattering objects.
- Apply to object(s) for Bulk Scatter.
- Apply to surface(s) for all others.

Importance Sampling



Importance Sampled Flux

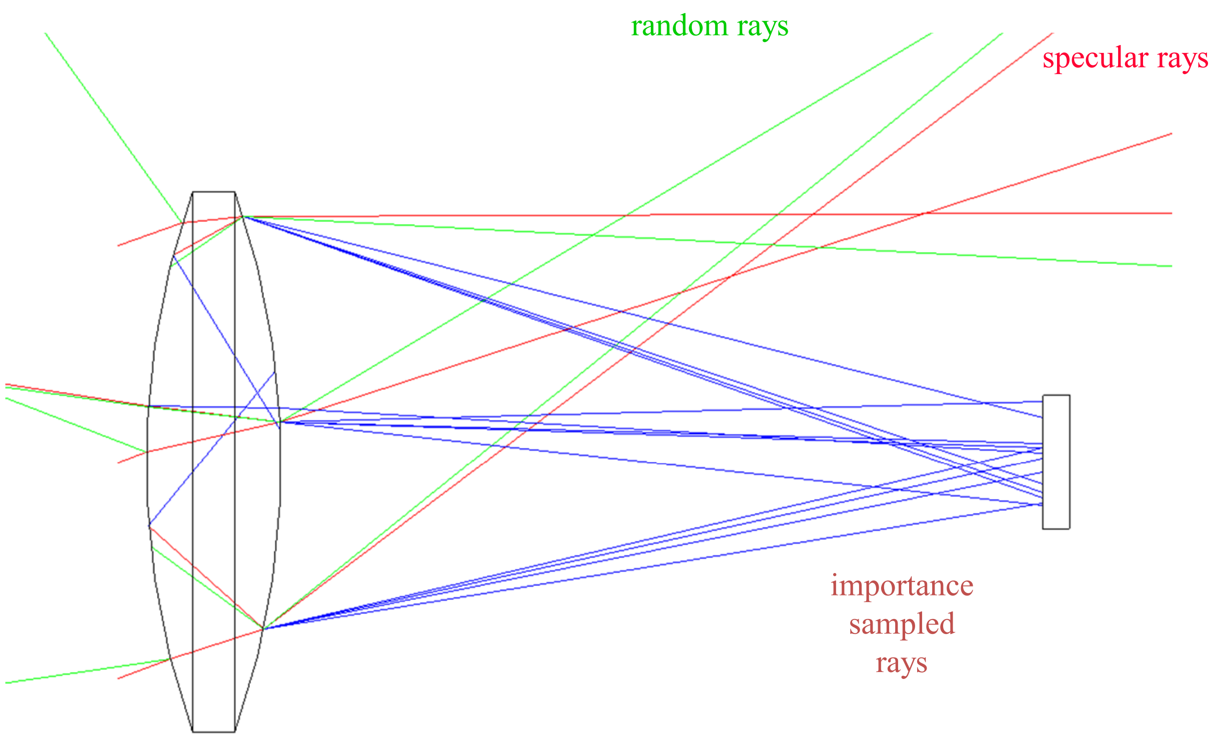


$$\Phi_{imp.samp.} = \Phi_{inc.} \int_{\Delta\Omega} BSDF \cos\theta \, d\Omega$$

$$\Phi_{random} = \Phi_{inc.} \cdot TS - \Phi_{imp.samp.}$$

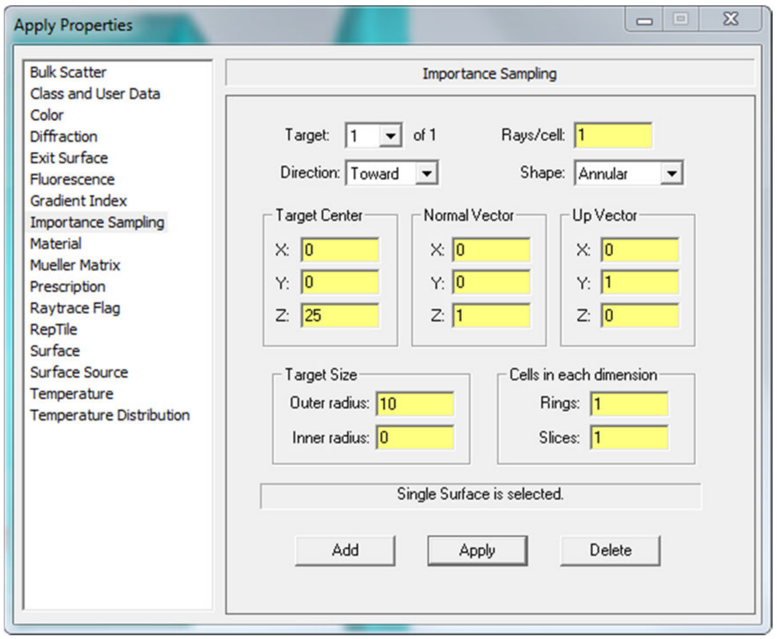
$$TS = \int_{hemisphere} BSDF \cos\theta \, d\Omega$$

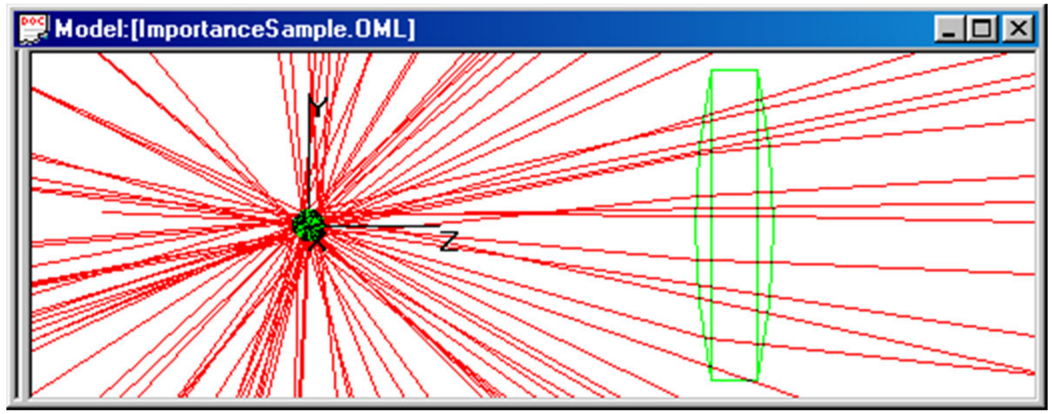
Importance Sampling Example

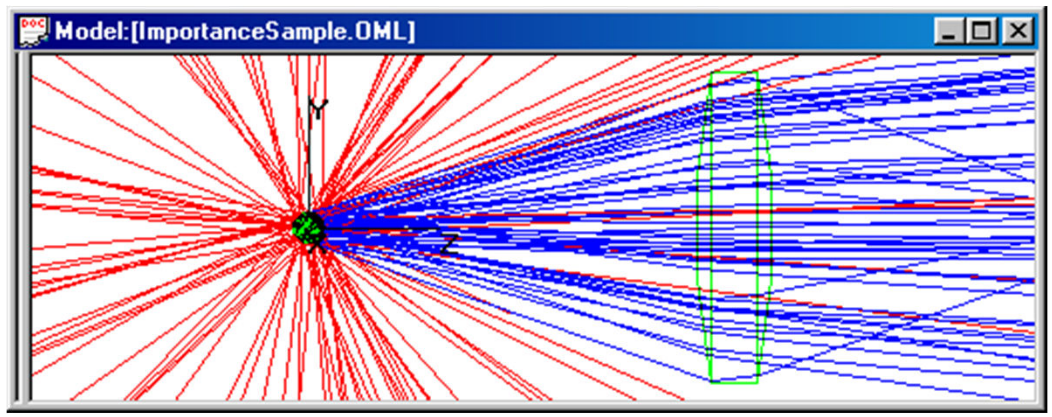


Importance Sampling Sources

Source Example



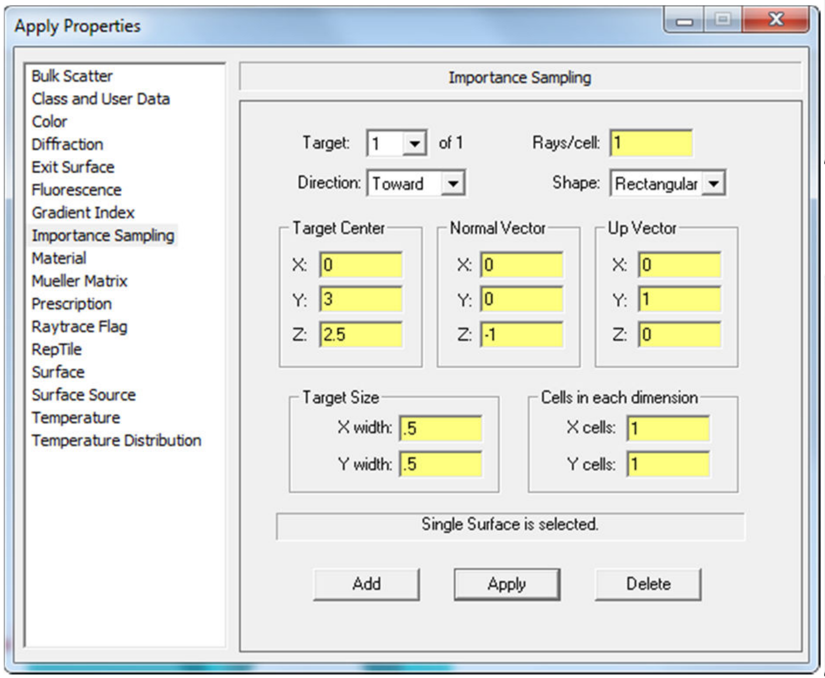


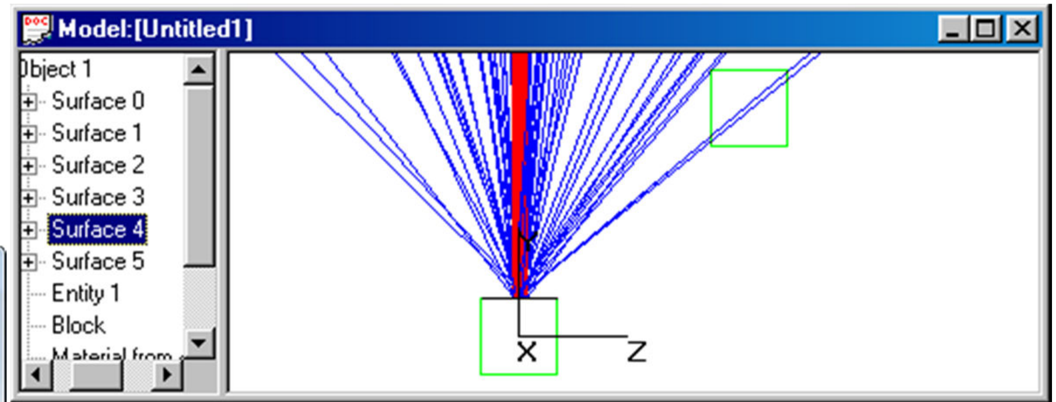


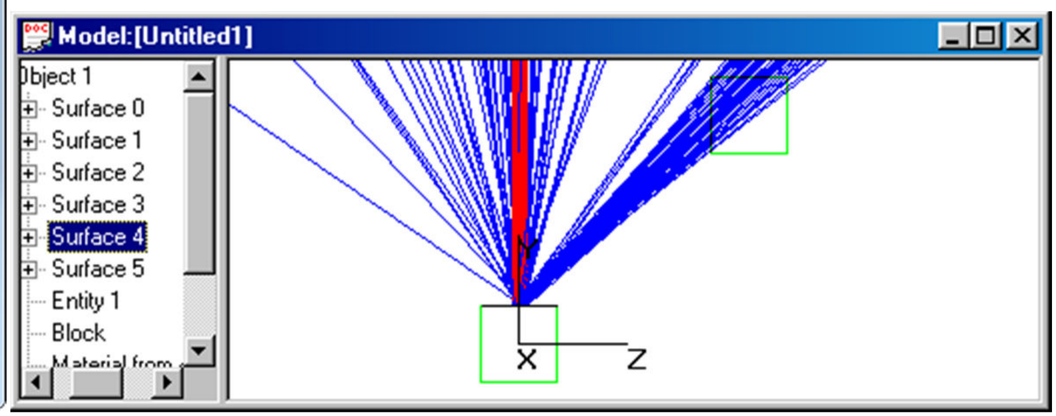
Importance Sampling Scatter

Surface Example

- Flux threshold typically set very low

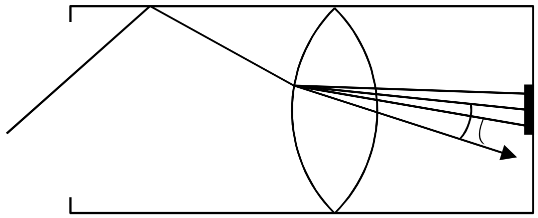






A World without Importance Sampling

- Suppose lens BTDF is
  A = 2e-5, B = 1e-6, g = 2.
- Lens scatters at angle of ~30º to get to detector, so



$$p_2 = f_s \cos\theta \, \Delta\Omega$$

θ ≈ 30º ⟶ $\cos\theta = 0.87$

$|\beta-\beta_0| \approx 0.5$ ⟶ $f_s = 8 \times 10^{-5}$

$\Delta\Omega = (0.002 \text{ radian})^2$ ⟶ $\Delta\Omega = 4 \times 10^{-6}$

$p_2 = 2.77 \times 10^{-10}$

A World without Importance Sampling

- Total probability is $p_{total} = p_1p_2 = 3.46 \times 10^{-11}$
- You must start 3×10^{10} rays to get 50% chance of one ray hitting the detector!
- Solution: define importance sampling target for lens surface. Probability p_2 increases to 1.0, total probability is 1/8.
- You can also define a target for sampling from the baffle to the lens, but this is not always necessary.

Stray Light and BSDF

Used Definitions:

NAME	SYMBOL	UNITS
Irradiance	E	w/m^2
Radiance	L	w/m^2-sr
BSDF	f	1/sr

Forms of Stray Light

Straight Shots

Where light from a bright source can bypass the intended path and finds a straight specular path to the focal plane.

Ghost Images

Ghost images are out-of-focus images of bright sources. Light must reflect an even number of times from lens surfaces. If the source is small each ghost looks like the aperture stop. If the ghost is focused on the image plane, the ghost looks like the source

Singly-Scattered light

Occurs when a stray light source illuminates the optics or some hardware that the focal plane sees. Some portion of the light will scatter into the field of view and become stray light. Once in the field of view, there is no way to eliminate it.

Multi-Scattered Light

Even when stray light sources do not illuminate the optics directly, they can still scatter from structure or baffles and then illuminate the optics. While this is always smaller than direct scatter it may be large enough to be of concern.

Edge Diffraction

When the ratio of aperture diameter to wavelength is relatively small (10^4 or smaller), edge diffraction from the aperture stop from out-of-field sources can be a significant source of stray light.

Self-Emission of Infrared Systems

Thermal imaging systems can have stray light caused by emission from the instrument itself. The peak of the blackbody emission curve for room temperature is at about 10μm. Thermal imagers typically subtract the background to enhance contrast, but this is best performed when the background is uniform.

Combinations Of The Above

Four Methods to Reduce Stray Light

Move It

Moving the stray light by tilting a lens, moving the detector, or angling the offending stray light surface is the best way of getting stray light out of a system. You may need to add a beam dump to completely get rid of the problem.

Block it

Even when stray light sources do not illuminate the optics directly, they can still scatter from structure or baffles and then illuminate the optics. Using baffles is a great way to stop out of field sources from sending light directly to the detection device.

Paint It

Usually occurs when a shiny object is illuminated by a stray light source. Coating the offending shiny object with black paint usually reduces this stray light quite substantially but not completely to 0. For instance, black anodized aluminum can be 35% reflective but there are better black paints available several are in the 3 percent range but there can be problems with out gassing and degradation over time with these coatings. Some portion of the light will always scatter into the field of view and become stray light even with the best of coatings. Set a tolerable specification

Coat It

Especially important to get rid of ghost images - Ghost images are out-of-focus images of bright sources. Light must reflect an even number of times from lens surfaces. If the source is small each ghost looks like the aperture stop. If the ghost is focused on the image plane, the ghost looks like the source. To get rid of ghost images we coat the lenses with anti-reflective coatings to reduce ghosts

Importance Sampling for Stray Light

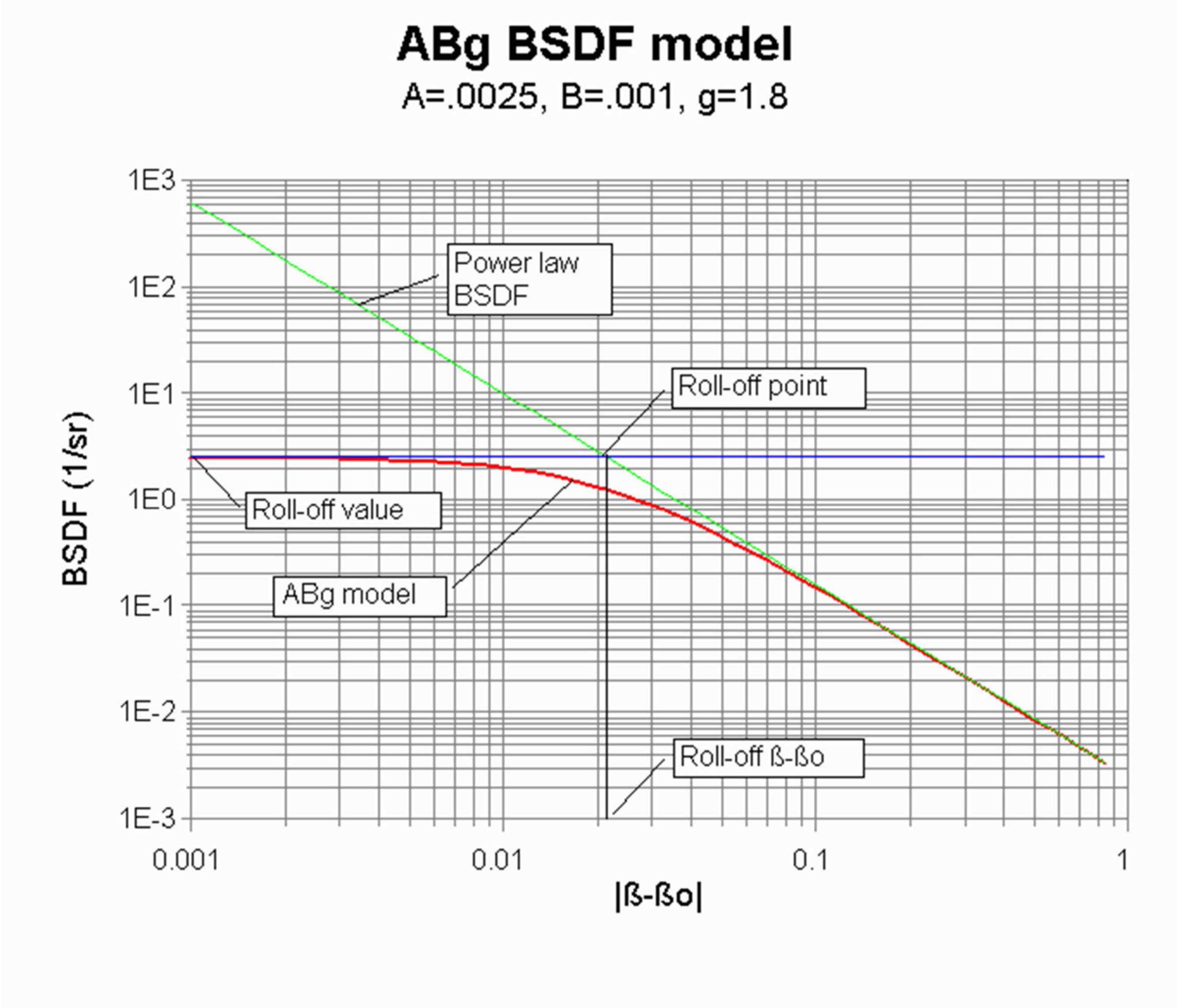
- Importance Sampling targets should be defined for each optical surface. The target should coincide with the real or virtual image as seen from that surface.
- The Auto Importance Sampling Setup feature will define targets for all optical surfaces.
- Importance sampling targets can always be added manually. Each surface can have an unlimited number of importance sampling targets.
- You may or may not need importance sampling on non-optical surfaces (lens barrels, baffle vanes, etc.).
- If you do define importance sampling targets for non-optical surfaces, surfaces that can "see" an image should have a target at that image. Surfaces that cannot see an image should have an importance sampling target at the next optical surface in the optical train.
- You should define importance sampling targets for diffracting surfaces, just like an optical surface.
- If only a few randomly scattered (non-importance-sampled) rays hit the image with high flux, causing hot spots, this usually means more importance sampling is needed.
- It is possible to overdo importance sampling, slowing the raytrace. A goal is to get about one ray on the image surface for each starting ray. Getting within an order of magnitude of this goal (either way) is OK. Modeling of bulk scattering will make this goal hard to achieve.

BSDF vs. Scattered Intensity

- BSDF is a generic term for measured scattering of light. There are three specific varieties of BSDF
  - BRDF (Bidirectional Reflectance Distribution Function)
  - BTDF (Bidirectional Transmittance Distribution Function)
  - BDDF (Bidirectional Diffraction Distribution Function)
- Scattered Intensity or "Cosine Corrected BSDF"
  - In the old days, people measured the scattering properties of a surface by measuring the scattered intensity (w/sr) normalized to the incident power (w). This differs from the BSDF by a factor of $\cos\theta$.

Typical BSDFs

- Polished surfaces
  - BSDF from microroughness is proportional to Power Spectral Density (PSD) of roughness
  - Values of g from 1.5 to 3.5, but 2 to 3 is more common
  - B is small, 1e-6 to 1e-10, depending on surface statistics
  - Contamination BSDF: similar in form to microroughness BSDF
- Diffuse surfaces
  - If g = 0, BSDF is perfect Lambertian. Many baffle coatings come close to this.
  - If not Lambertian, typically B is large, 0.1 to 1, and g is large, 2, 3, 4, 5, 6…



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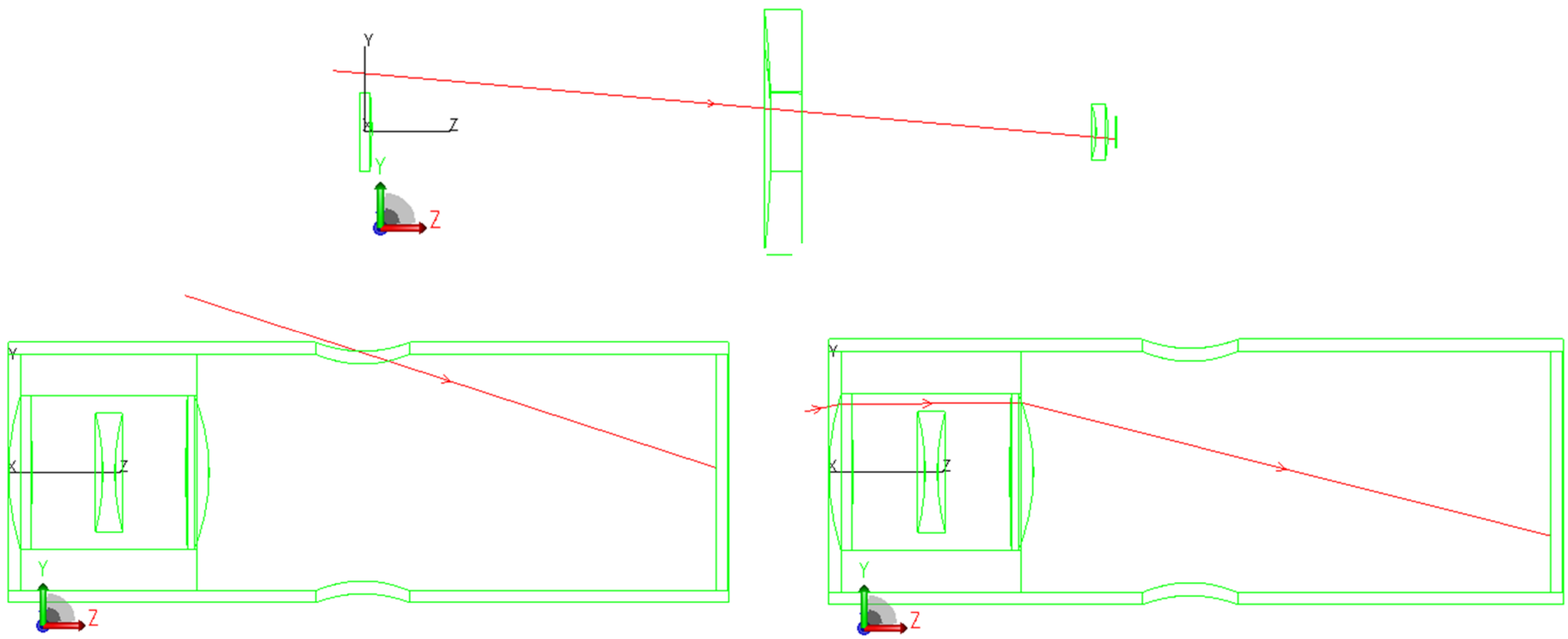
"ABg from RMS" spreadsheet

<u>**Input parameters:**</u>						
sigma (rms roughness)	**50**	**Angstroms**		min wave	0.25	um
autocorrelation length=	**100**	**um**				
wavelength =	**0.5**	**um**				
dn =	**2**		**dn = difference in index of refraction**			
R or T	**0.95**		**R or T is (total) reflectance or transmittance**			
			Note: for a mirror, dn=2			
Calculated ABC model coefficients:						
As =	1.570796327		Strictly valid only for C=2			
Bs =	628.3185307	um	Strictly valid only for C=2			
C =	2					
rms roughness/wave	0.01	Not valid if greater than 0.02				
S = power spectrum						
D =	2400.28779		Raw Integrated BSDF		0.015552516	
			BSDF(0) =		3770.363244	
<u>**ABg coefficients for TracePro**</u>			Bennett & Porteus TIS		0.01488397	
A =	**1.81832E-06**		Correction factor		0.95701366	
B =	**5.0393E-10**					
g =	**3**					Corrected

Eliminate zero-order paths

- Examples of straight shot or zero-order paths



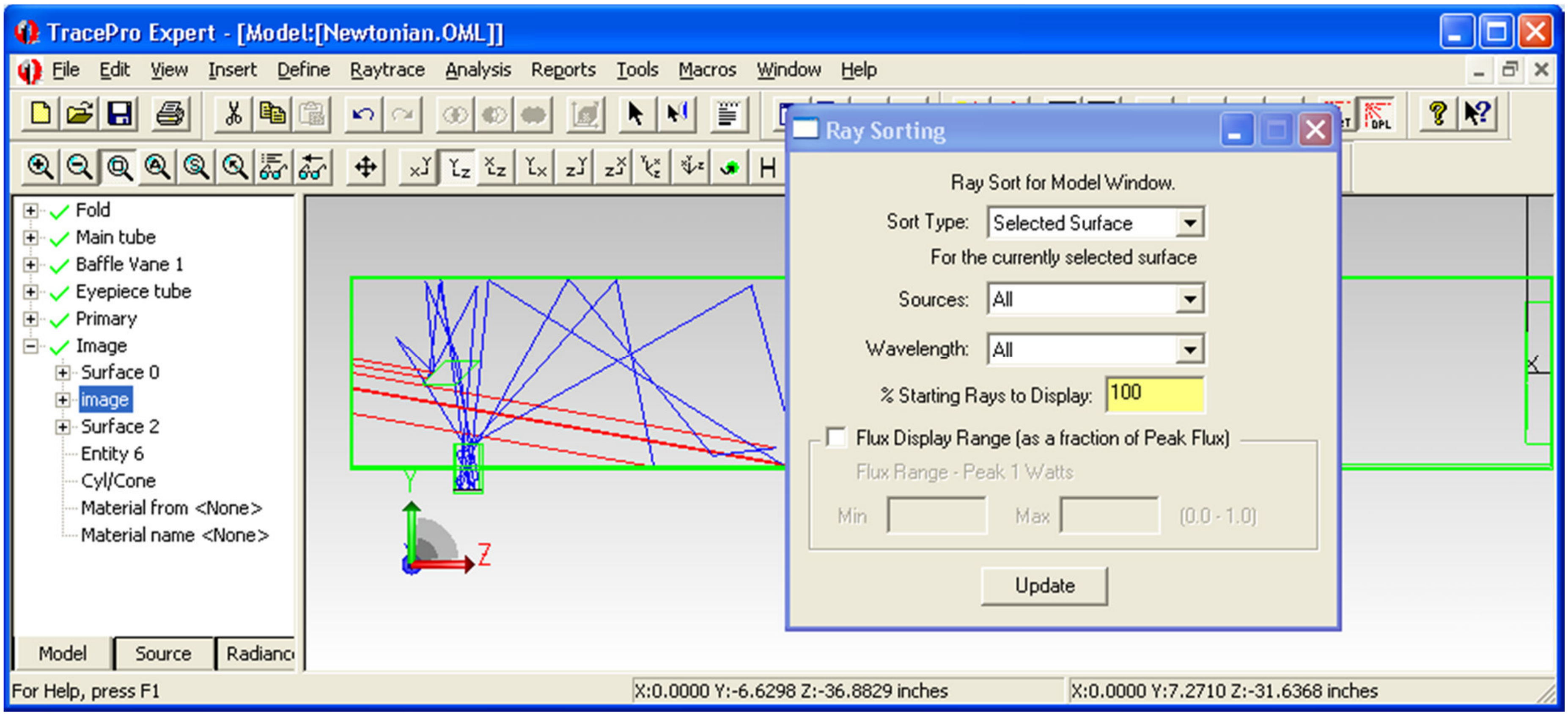
What can be “seen” by the detector?

- Trace rays backward from the image plane to help determine what surfaces can be “seen” by the detector
  - Make the detector surface into a surface source, or define a grid source immediately before the detector, pointing backward.
  - Display the Flux Report to determine which surfaces the detector can see.
  - Use Ray Sorting to see the paths of rays reaching those surfaces.
- In a similar way, trace rays forward to determine what surfaces can be illuminated by the source.
- Non-optical surfaces that can both be “seen” by the detector and illuminated by the source are “critical surfaces.” Either the illuminating or seeing path should be blocked by a baffle or otherwise mitigated.
- Consider different paths for cases of “before” and “after” the aperture stop.

Use Analysis Tools

- Analysis Mode
  - Ray sorting:
    - For ray display to see the paths of stray rays.
    - For irradiance maps to see irradiance distributions for specular vs. scattered rays.
    - For irradiance maps to see the paths where stray rays for hot spots.
  - Incident ray table
  - Ray history table
  - Path Sorting in TracePRO 7.1
    - Determine contributions of different stray light paths.
    - Determine under-sampled paths and improve importance sampling.
- Simulation mode
  - Ray Path Sorting
    - Determine contributions of different stray light paths.
    - Determine under-sampled paths and improve importance sampling.

Ray sorting for display



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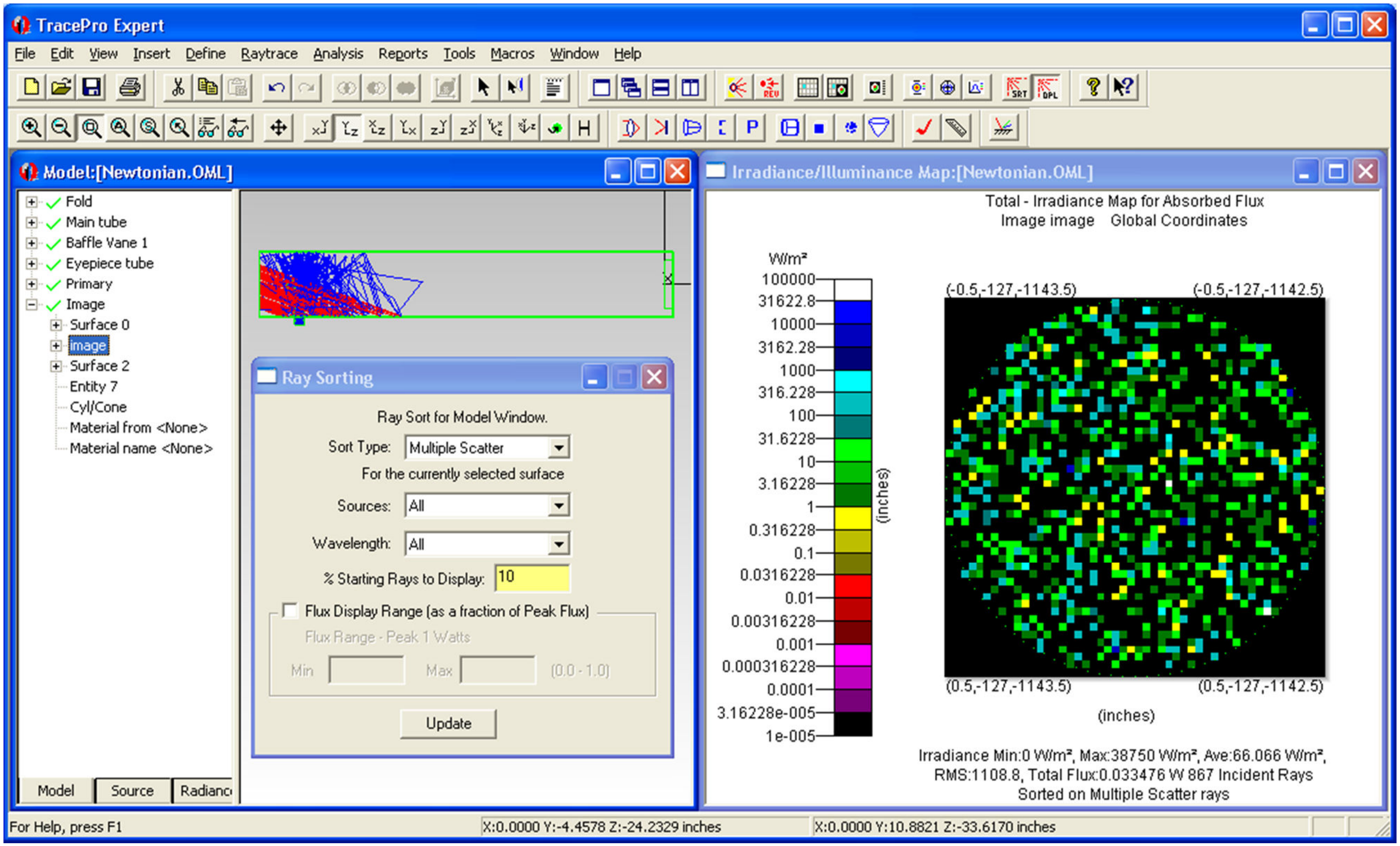
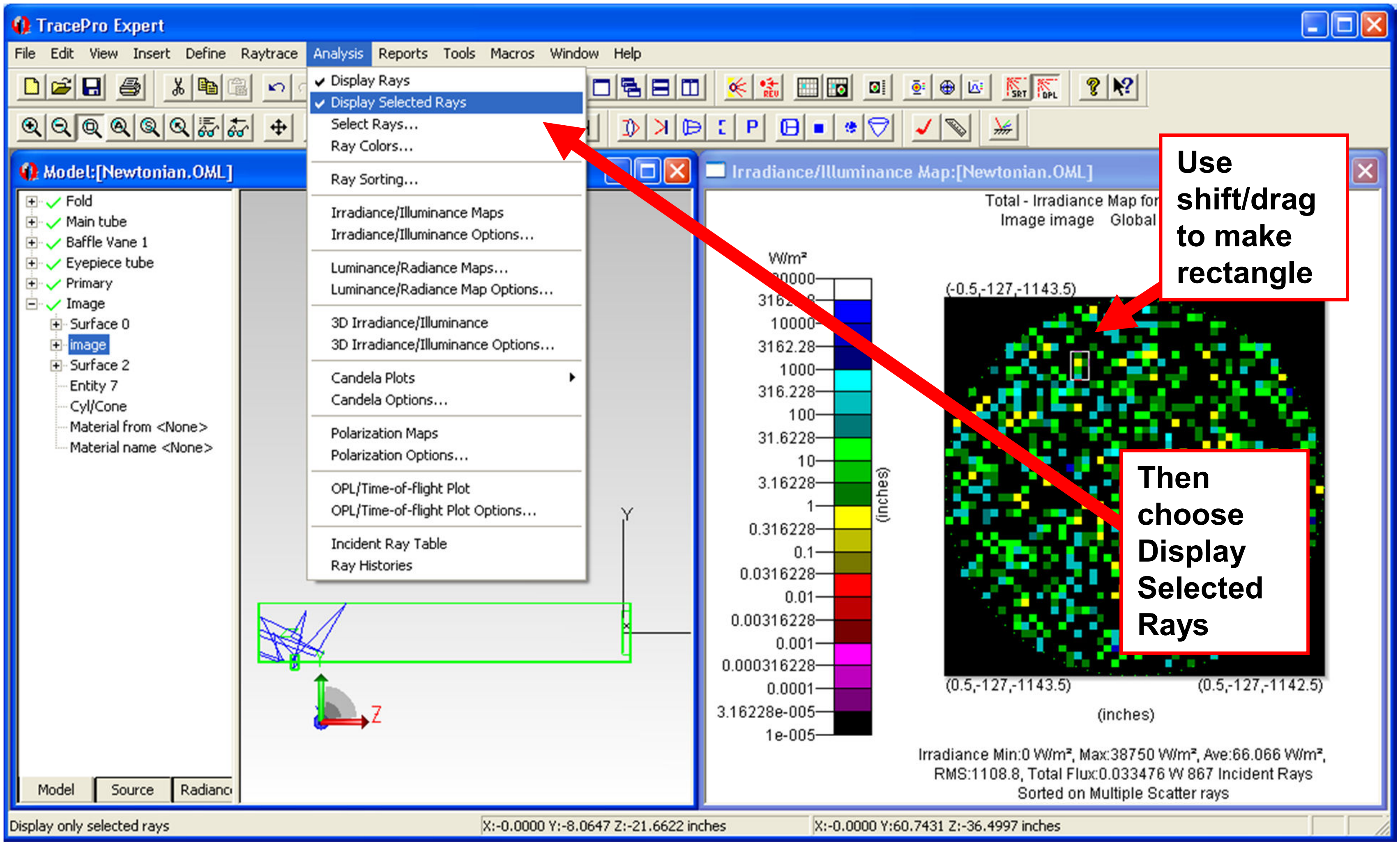
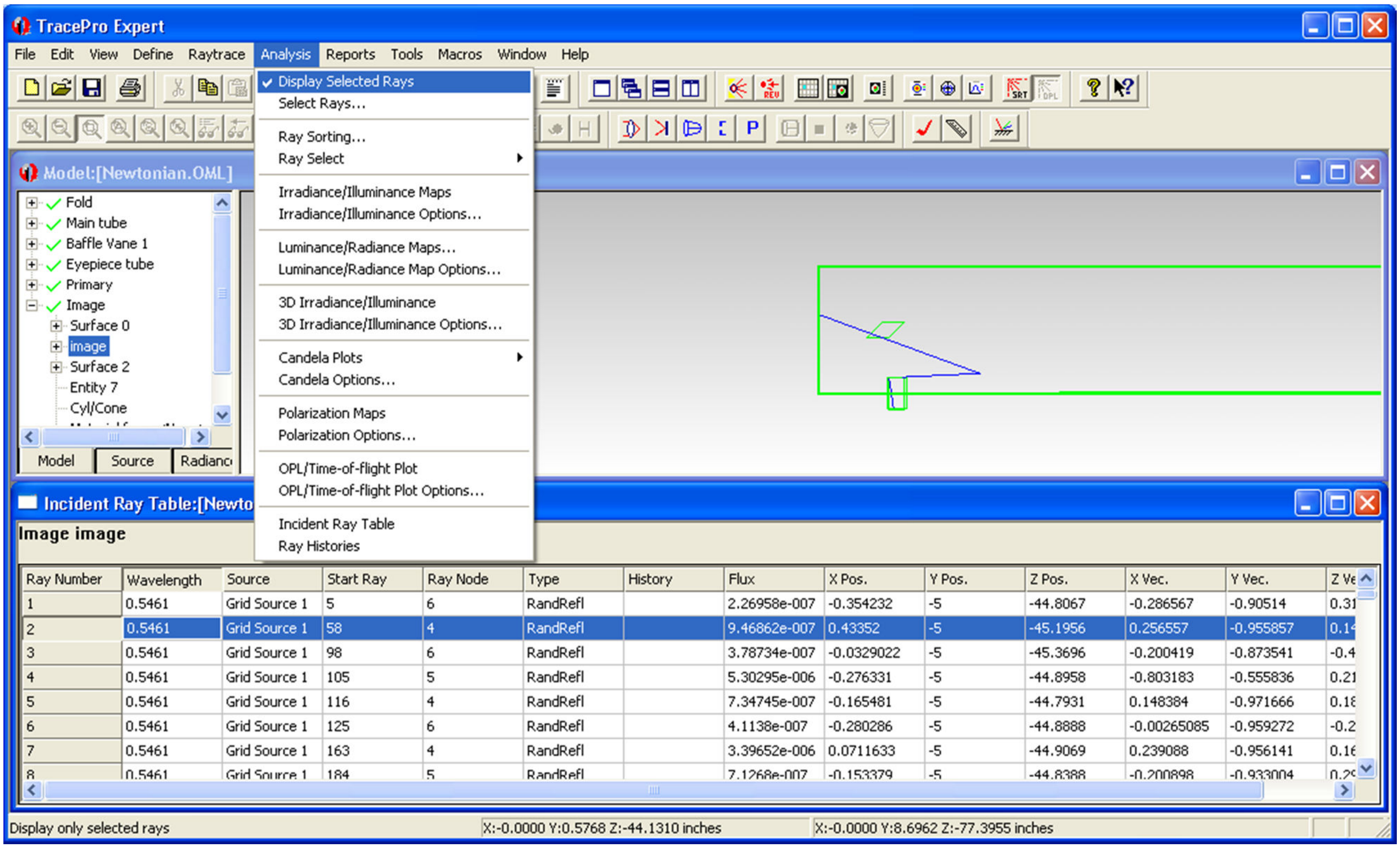
Ray sorting for ray type



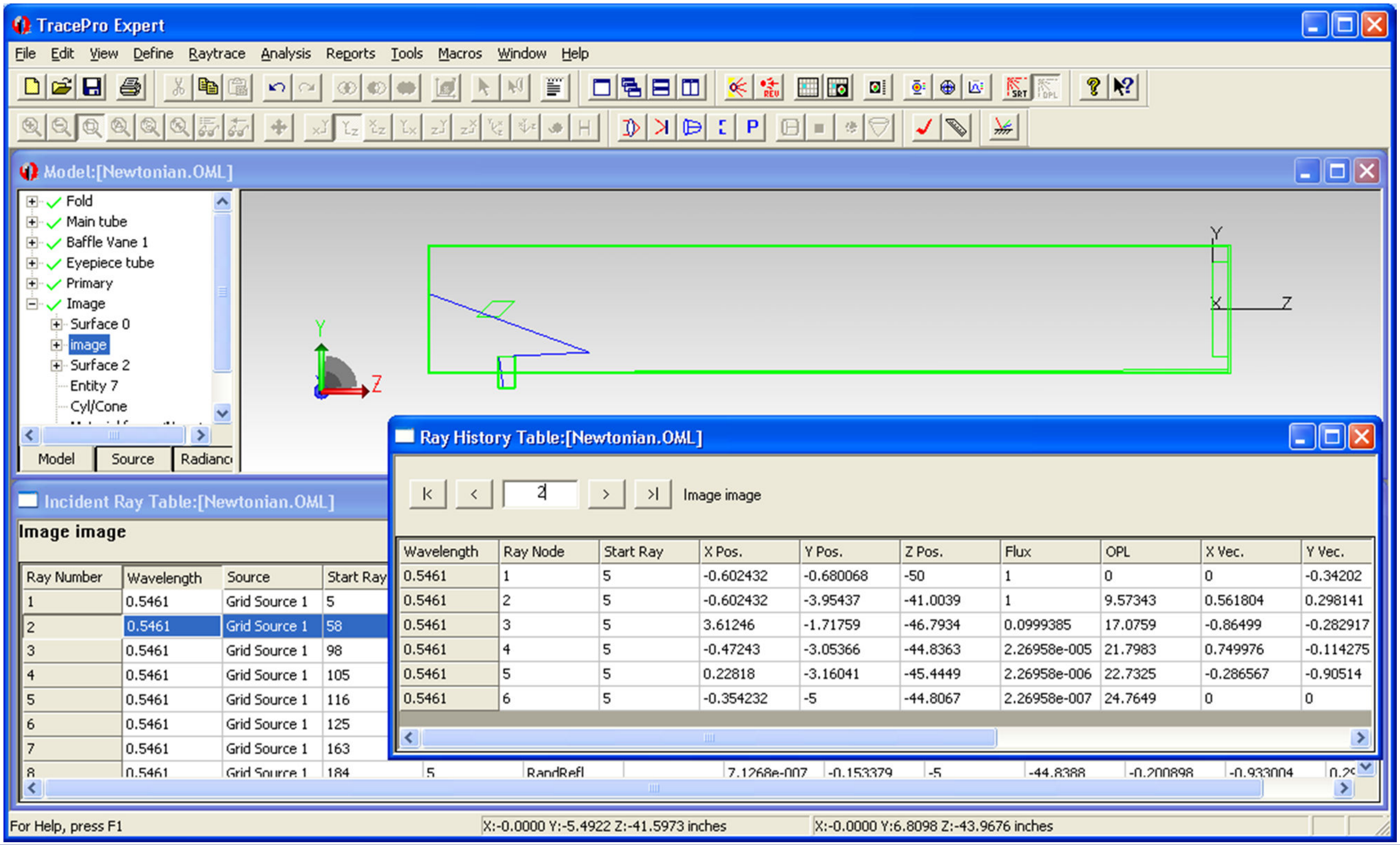
Ray sorting for hot spots



Incident Ray Table

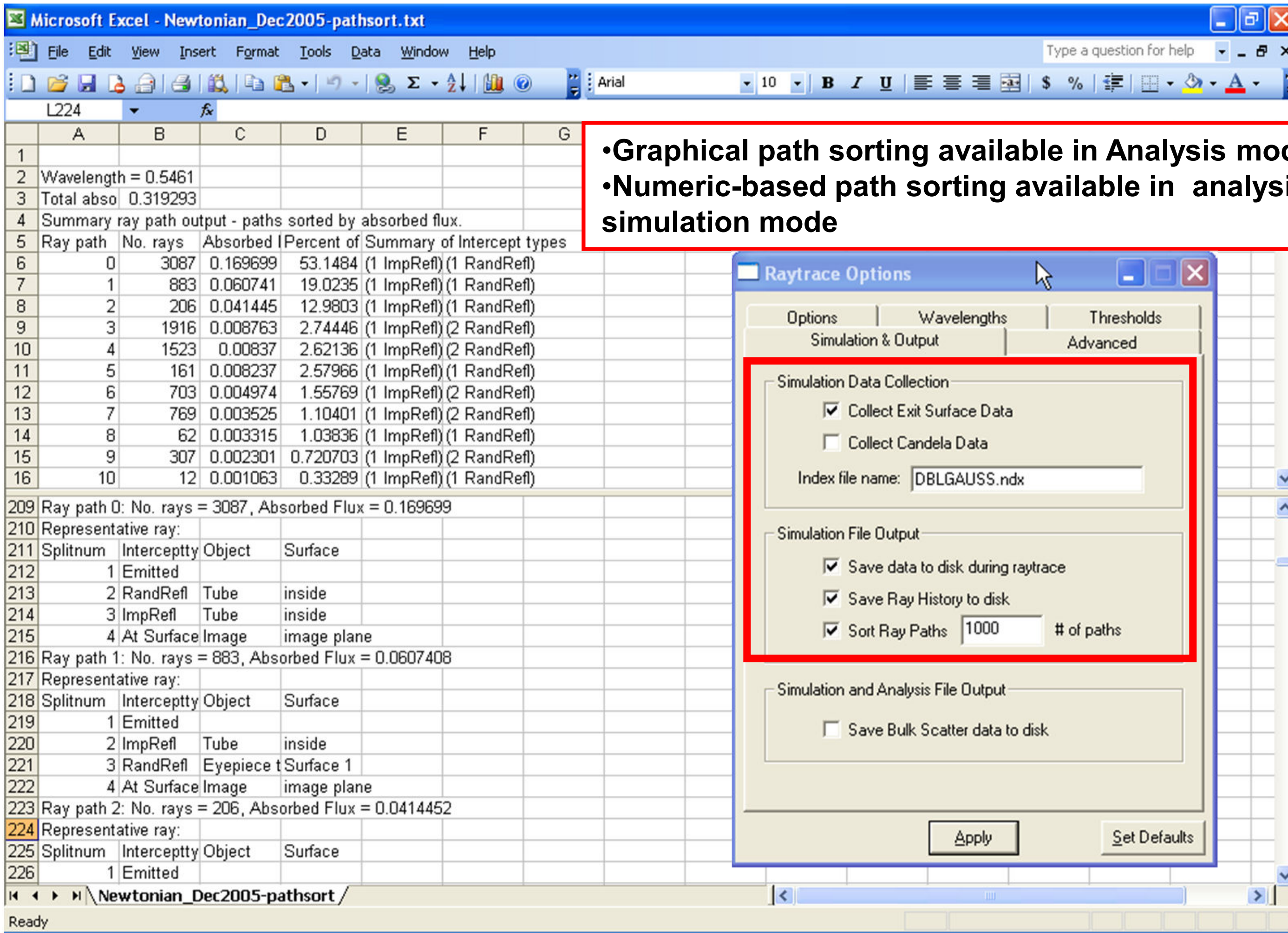


Ray History Table



Ray Path Sorting File

- Graphical path sorting available in Analysis mode
- Numeric-based path sorting available in analysis and simulation mode



Thank You

Questions and Answers

For Additional Information Please Contact:

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