Modeling Light Pipes in ASAP

This technical publication describes the general process for simulating light pipes in the Advanced Systems Analysis Program (ASAP®) from Breault Research Organization (BRO). ASAP offers a variety of options for simulating complicated light pipe geometries and sophisticated optical properties. A brief discussion on some of the important issues in modeling light pipes is included here. A variety of light pipes and sources are used to illustrate how light pipes are modeled in ASAP.

Figure 1 An ASAP light pipe computer model mixes the output from three multi-colored LEDs. Illuminance is not uniform at the target plane.

LIGHT PIPES IN THE DESIGN PROCESS

Light pipes, sometimes called waveguides, are optical elements that transfer, “pipe” or “guide” light from a source to a lighting task, primarily by the process of total internal reflection (TIR). They are found in all types of devices, in just about every industry. While production is simple, designing a light pipe is a complex task.

Although light pipes appear to have simple performance requirements, a false assumption is that they are simple devices to design. Consequently, light pipes are often neglected until late in the engineering process, when it is too late to produce a usable, cost-effective, manufacturable design.

Quite often, even though the device is optical in nature, the optical design is not started until all the other engineering disciplines, such as mechanical and electrical, have already staked their claims to the valuable real estate of the device. This situation usually leaves insufficient room for the optical design. Also, mechanical requirements frequently conflict with the optical requirements. The laws of optics cannot be broken to force a light pipe...
to guide light where it physically cannot. It is like trying to stick an oversized square peg into an undersized round hole.

**Business and manufacturing requirements**

Light pipes must meet business and manufacturing requirements. While light pipes are made in mass quantity (keeping their costs low), they are expensive to develop and design. Although the plastic part itself might cost only pennies, its injection mold may be on the order of thousands, if not tens of thousands, of dollars to tool. Tool development costs alone make the cost of repetitive hardware prototyping prohibitive. Complicated single or multi-element shaped light pipes are more expensive and more difficult, if not impossible, to injection mold. The shape of the light pipe must not prevent it from being separated from its mold.

General optical system performance requirements (software capabilities) dictate the optical configuration and the performance metrics, regardless of the available light pipe real estate.

**The primary process for moving photons in a light pipe**

Light pipes guide light from the source to the object or surface that is to be illuminated by totally internally reflecting the light off the surfaces of the light pipe. TIR works for light traveling from a medium of a higher index of refraction to a medium of lower index of refraction. If a ray of light inside the material intersects the interface beyond the critical angle of the material, as referenced to the normal at the point of incidence, it is totally internally reflected at the interface. Mathematically, the critical angle between a material of index n_{material} and air is defined as follows:

$$\theta_c = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{material}}} \sin(90^\circ)\right) = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{material}}}\right)$$

*Equation 1*

For a material of n=1.5, the critical angle is approximately 42 degrees. If a ray of light inside the material hits the side of the light pipe at an angle less than the critical angle, part of the light is reflected and transmitted according to Snell’s law and the Fresnel reflection and transmission relationships.

In classical optical systems, light transfer is accomplished with optical elements like relay lenses and fold mirrors. However, these optical elements are too expensive and impractical to use in many low cost devices requiring illumination systems. Among other processes such as refraction, reflection, and scattering, TIR is the primary process for moving photons from one place to another in the light pipe. Unfortunately, this tool is often underutilized or neglected. A misconception is that the available space can be filled with plastic and somehow the light can get to the lighting task. This is analogous to optical software, which, if given the opportunity, fills the universe with glass to improve the optical design. It cannot, and most likely the light ends where you least want or expect it.

**Measurements as critical input for the light pipe design process**

Measurements are crucial input for the light pipe design process, including decisions about when they are, and are not, necessary. Measurements quantify the physical properties. The accuracy of the simulation is directly influenced by the quality of the measured data. Original equipment manufacturer (OEM) suppliers are sometimes
unwilling, or unable, to supply the data you need for the simulation. Be prepared to measure or have measured the physical property yourself. This might include material measurements as well as source measurements. This is especially true in the case of light pipe design where material information is practically non-existent.

Measurements are still the best course of action even though many optical software programs include material databases for simulating some physical properties. As a minimum, check the information from supplied databases used in your simulations against measured data for accuracy. If you do not, you could end up with a bad design. For example, if you use incorrect refractive indices, the critical angles for TIR you expected will be wrong, and subsequently so will the radiant output from your simulation. Or, if you are using a source with the wrong emission properties, the radiometric output from your light pipe will be incorrect.

**Quantitatively measuring optical performance**

Many different performance requirements exist for systems using light pipes, and many are qualitative and not quantitative. Every light pipe designer will, at least once, design a light pipe to the requirement, “the output just has to look uniform”. This requirement, aside from not being measurable, is subjective. It is probable that what is called “uniform” cannot be uniform enough for your customer, thereby necessitating a redesign.

Fortunately, we can conveniently categorize light-pipe optical performance requirements according to their radiometric and photometric properties:

- Radiometry is the measurement and geometric characterization of power.
- Power is geometrically characterized by projected areas and solid angles.
- Power per unit solid angle is called intensity.
- Power per unit projected area is called irradiance.
- Power per unit projected area per unit solid angle is called radiance.
- Intensity and irradiance can be obtained by appropriate integration of the radiance.
- Photometry is a normalized form of radiometry.
- Normalization is a process in which a measurement or calculation is made to conform to a standard or established norm. The established norm, in the case of photometry, is the response of the human eye.

In the context of ASAP, radiometry is simply the calculation of the quantities outlined in this section. ASAP can compute these radiometric quantities, as well as their photometric counterparts, including color coordinates.


Common threads bind the calculation of the radiometric quantities together. These threads are coherence, polarization, amplitude, and phase. The interaction of light with light pipes is physically and mathematically distinguished and defined primarily by these qualities. Given these four characteristics and the optical system behavior, we can compute the system’s intensity, irradiance (exitance), and radiance. ASAP can simulate and calculate all of them.
Software simulation as virtual prototyping

Optical performance requirements, as well as business and manufacturing requirements, make the case for software simulation or virtual prototyping. Even with sophisticated software simulation tools, light pipe design is often more difficult and time consuming than anticipated, and sometimes more so than classical optical design.

ASAP supports your creation of sophisticated, extended source models according to their physical properties. ASAP automatically changes the polarization, amplitude, and phase of light as it interacts with optical components. For example, ASAP changes the polarization and amplitude of light incident on an interface according to Fresnel’s equations including TIR. ASAP also adjusts the phase of the light according to the indices of refraction, optical path length, and aberration of the optical components. ASAP uses this information to compute power, intensity, irradiance (exitance), and radiance.

The source of electromagnetic (EM) radiation, and how it interacts with your light pipe, determine the relationships between the optical performance requirements and important physical properties. The physical properties you need to simulate light pipes and their sources are derived from the optical performance requirements, and are used as input into the software programs.

Table 1 illustrates how radiometric properties are related to the source and system's physical properties, and the required optical software capabilities. The important point is that these inputs dictate the type of optical software needed for simulation, and not vice versa. The software must have the capabilities to accurately simulate the physical properties that affect performance.

<table>
<thead>
<tr>
<th>Optical Performance Requirements</th>
<th>Physical Property and Software Capability (feature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Coherence (temporal/spatial)</td>
</tr>
<tr>
<td>Intensity</td>
<td>Polarization (Fresnel relationships)</td>
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<tr>
<td>Irradiance/exitance</td>
<td>Amplitude (Fresnel relationships)</td>
</tr>
<tr>
<td>Radiance</td>
<td>Phase (aberrations)</td>
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<tr>
<td>Color coordinates</td>
<td></td>
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LIGHT PIPE DESIGN AND ANALYSIS

The optical design process means different things to different people. Lens designers create classical lens systems such as cameras, telescopes, or microscopes, and primarily use commercially available “optical design” software, which are really lens design programs. Like light pipe designers, lens designers start the design process by defining the first-order optical properties of the optical system from the requirements. However, their first-order optical properties are usually different from that of the light pipe designer.

Lens designers are interested in first-order optical properties such as image location, magnification, effective focal length, and radiometric or photometric properties. They then use the mathematical tools of first-order optics, such as the y-ybar diagram, Gaussian reduction, paraxial imaging, and the power transfer equation, to translate the first-order properties into a preliminary system layout, which serves as a starting point for the actual lens design. Some designers also use patent applications and experience to generate design starting points. In any case, the first-order design layout is entered into a lens design code.

Lens design codes vs. optical analysis programs

Lens design codes are essentially geometrical ray trace simulation programs that apply a mathematical optimization algorithm to determine an optimal lens design for a given set of conditions. While performing and evaluating geometrical ray traces, the lens design code changes element radii of curvature, thickness, spacing, and refractive indices, forcing the optical system to conform to a certain merit function. Think of the automated lens design process as a feedback loop. Lens design codes are efficient at finding solutions to this type of problem. Unfortunately, the specific simulation and optimization features of lens design codes are usually impractical to use in illumination systems, especially light pipes, because of their peculiar geometries. It is also difficult or impossible for lens design codes to model some of the unusual illumination system extended sources and non-sequential ray trace behavior. An extremely large number of rays must be traced to simulate, in a Monte Carlo statistical sense, the extended sources commonly found in light pipes. These ray traces typically take a significant amount of time, especially in light pipes. Large, Monte-Carlo ray traces that are used with lens design optimization routines—involving an algorithm trying to solve a non-linear problem, while also requiring a minimum of hundreds of iterations to reach a local minimum—render this process intractable.

Illumination engineers design light pipes primarily by using computer-aided design software (CAD) and optical analysis software.


Optical analysis programs are used to analyze processes and phenomena that cannot be easily simulated in lens design programs, such as the extended sources of the light pipe. Some optical analysis programs contain a CAD interface or CAD translators to facilitate the light pipe design procedure. Their user interfaces (UI) are basically a CAD interface wrapped around ray tracing engines. The UIs allow you to input geometry and drag it. These programs may allow you to draw a light pipe and trace rays to determine the radiometric output, but their processes are not automated. However, you must still supply the design algorithm for achieving the desired performance. For example, you must change the optical prescription of the light pipe yourself to achieve a different performance, and trace rays to see the result. There is no graphical interaction between the input geometry and the radiometric output.

This paradigm ignores the fact that optical engineering, and particularly optical design, are inherently not graphical disciplines. You cannot design an optical system by simply “drawing” optical component shapes. And you
certainly cannot design a light pipe by filling the available real estate with plastic. You must take into account the spatial interaction between light and optical materials and shapes that change the behavior of the light after it interacts with the various parts of the light pipe. This is an important point because the required illumination pattern is typically known, and what you want is to have the optical software create a light pipe that produces that pattern. Unless there is a specialized program for illumination system design, such as ReflectorCAD®, it is usually easier to design illumination systems in general, and light pipes in particular, directly in the macro language of the software simulation program. This way you have complete mathematical control over the system geometries and, therefore, how light interacts with those geometries.


**SOLVING LIGHT PIPE PROBLEMS**

It is usually best to start a problem at the beginning. First-order calculations are invaluable for determining if potential designs come anywhere near meeting the performance requirements. If your design cannot satisfy the performance requirements of first order, there is little hope that the derived design can work. It is true that some light pipe designs are too complicated for these calculations. A first-order layout for the light pipe may not exist at this stage. Typically, the layout is driven primarily by mechanical constraints. Even if this is the case, you should estimate how much power can be guided to the lighting task, taking into consideration such factors as total source output and TIR conditions. Such a power budget, along with some simple conservation of radiance calculations, can prevent you from wasting time on unrealizable design concepts.

Before we can compute output of the light pipe, we must model its source or sources. This is due to illumination engineering's golden rule: there is never enough light. The light pipe cannot produce a brighter image than that of the source supplying light to it. This conservation of radiance is the thermodynamic limit of light concentration. The radiance is conserved and, in the event of transmission losses, the etendue. Many optical engineers refer to the etendue as “throughput” or the “A-Omega” product, because it is the product of the cross-sectional area of a beam, at a location in the optical path, and its projected solid angle. The power loss in the optical system is due to component transmission losses, which are managed through the power budget.

The etendue relationship is derived from the definition of radiance. Radiance is the power per unit projected area per unit solid angle. Operationally, the radiance is defined as,

\[
\mathcal{L} = \frac{d^2 \phi}{dA \cos(\theta)d\Omega}
\]

*Equation 2*

The radiance is conserved if light propagates between two differential areas without loss, as illustrated in Figure 2. The amount of power transferred out of differential area one and its solid angle, assuming a constant radiance, is
The cosine term is traditionally grouped with the solid angle in this equation, yielding a mathematically convenient projected solid angle, \( \Omega \).

\[
\Omega = \pi \sin^2 \left( \frac{\theta_1}{2} \right)
\]

Equation 4

Alternatively, the cosine term can also be grouped with the area, resulting in a projected area, which has a more meaningful physical interpretation than a projected solid angle. The two-dimensional angle is then the solid angle of a right circular cone,

\[
\varpi = 2\pi \left( 1 - \cos \left( \frac{\theta_1}{2} \right) \right)
\]

Equation 5

In both cases \( \theta_{1/2} \) is the half-angle of the cone. The throughput \( T \) is defined as the A-Omega product. The geometric extent, or throughput, from differential area one to two is then

\[
T_{1 \rightarrow 2} = dA_1 \cos \left( \theta_1 \right) \, d\varpi_1
\]

Equation 6
However, the solid angle viewed from area one to two is,

\[ d\Omega_1 = \frac{dA_2 \cos(\theta_2)}{r^2} \]

*Equation 7*

Substituting this into the first etendue equation results in,

\[
T_{1\rightarrow2} = dA_1 \cos(\theta_1) \frac{dA_2 \cos(\theta_2)}{r^2}
\]

\[
= dA_2 \cos(\theta_2) \frac{dA_1 \cos(\theta_1)}{r^2}
\]

\[
= dA_2 \cos(\theta_2) d\Omega_2
\]

\[
= T_{2\rightarrow1}
\]

\[
T_{1\rightarrow2} = dA_1 d\Omega_1 = dA_2 d\Omega_2 = T_{2\rightarrow1}
\]

\[
A_1 \Omega_1 = A_2 \Omega_2
\]

*Equation 8*

The last equation is the conservation of etendue. If the conservation takes place across a loss less boundary of index of refraction “n”, the conservation of radiance or etendue, becomes \( L/n^2 \) or \( T/n^2 \). The diameter of the beam changes by “n” and its area by \( n^2 \), in accordance with Snell's law.

The solid angle from the first differential area can be substituted in the original radiance equation to yield the power transfer equation,

\[
\phi = L \frac{dA_1 \cos(\theta_1) dA_2 \cos(\theta_2)}{r^2}
\]

*Equation 9*
Figure 3 illustrates a simple etendue calculation in ASAP for a tapered light pipe, just after refraction through the first surface, and then through the light pipe. The input source is a rectangular, isotropic emitter that emits into a cone with an angle of 60 degrees. All these calculations can be done in ASAP.

The consequence of these interactions is that the radiance or luminance (lumens/projected area/solid angle) at the lighting task is the luminance of the source, with light pipe transmission losses. A calculation of the throughput at the beginning of the design process, or even just an understanding of the physical and optical implications of the relationship, can help determine if the light pipe will meet any system-level luminance requirements.

For example, light squeezed by a light pipe into a smaller area generally has a larger emission output angle than the input emission angle. Moreover, it is important that your simulation software properly simulates sources and any optical element coatings that affect power loss. ASAP is able to simulate the near and far-field properties of sources and the prescription, or measured behavior, of optical coatings.

ASAP can compute not only the irradiance but also the radiance from a light pipe, a quantity that your eye “sees”. The radiance is a four-dimensional quantity, which generally changes with viewing angle. Only the fictional Lambertian source, or diffuser, has a constant radiance. Its radiance is constant at all viewing angles, whereas its irradiance changes as a cosine function. Irradiance is an insufficient radiometric requirement, describing light...
pipeline outputs viewed at multiple angles. Radiance is necessary, so your optical software should be able to compute it. Figure 4 illustrates an ASAP radiance and irradiance calculation from a “Lambertian” emitter.

![Graphs of radiance and irradiance from a Lambertian source.](image)

Figure 4 Radiance and irradiance from a Lambertian source (note that the peak radiance, not the peak irradiance, is constant at different viewing angles)

### Extended sources for light pipes

A light pipe's source is usually an extended source. Extended sources are physically and mathematically different than point sources commonly used in lens design. Point sources are important and necessary constructs in lens design codes. Although point sources are rarely used in light pipe design, they can sometimes be useful enough that modern optical design and analysis software used to simulate light pipes must have the capability to simulate point sources as well as extended sources.

Extended sources are collections of point sources. A point source is a mathematical construct. It is a point singularity of emission on a source. Physically, the smallest point source is an atomic-level emitter, which is small. Point sources emit spherical waves of radiation. The surface of constant phase of the light from the point source is called a wavefront. In other words, a wavefront is a surface of constant spatial phase.

Classical optical design primarily uses the concept of a point source, with point sources spread out at different but regulated field points covering the extent of the object, scene, or source. The purpose of the classical optical system is to image a point on the object, scene, or extended source to a corresponding point in its image. However, this concept is less useful in illumination system design, specifically in light pipe design. This is because in illumination systems such as light pipes you are trying to spread the light from a point source over an area or into a solid angle to produce uniform illumination.

The emission of light from a point source can also be represented by a set of rays. A ray is a purely geometrical concept—it does not exist physically. It is basically a vector that simulates radiative transfer. The spatial point of the ray vector is its location in space or the optical system. The direction of the ray vector is the propagation direction of the radiation. The power of the ray, whether the optical path length or another parameter, can be considered the magnitude of the vector. Rays are normal to the wavefront. In fact, they are the wavefront normals. Wavefronts are surfaces over which the optical path lengths of rays (refractive index of the material the ray is in, multiplied by the distance the ray travels in the material), from a point source, have the same length. Figure 5 illustrates the wavefront concept.


![Wavefront of a point source](image)

Figure 5 Wavefront of a point source

Having established the fact that extended sources are made of point sources, and point source are described as a collection of phase-related rays, we would assume that extended sources are ensembles of point sources whose rays are related in phase. However, extended sources in ASAP are not simulated in this manner. Instead, a Monte-Carlo technique is used where a single ray represents each point source of the extended source. Hundreds of
thousands, if not millions, of such rays comprise the extended source. This is done for physical and mathematical reasons.

Physically, many different types of extended sources are used in light pipes where we are not concerned about the phase relationship between point emitters of the extended source. We are typically interested in the incoherent addition of the point source's flux or power with other point sources and their subsequent geometric characterization into intensity, irradiance, and radiance. The phase information is not needed for this calculation. Mathematically, we save time by tracing a single ray from a point source instead of many rays from the point source.

ASAP can simulate incoherent filament, fluorescent, LED, and discharge sources, which are commonly found in light pipes. ASAP offers many ways to set up and use extended sources. ASAP has a number of “basic” sources that can be used as sources themselves or as building blocks for more complicated sources. These are typically emitting entities, objects, and volumes. They are useful as simple sources to get started in your design when you do not yet have a complete source model. You define the basic source by defining its spatial size or volume.

ASAP automatically and randomly creates ray positions and propagation directions on the surface or within the volume of the emitter. The source used as the input to the light pipe in Figure 3 is an example of an emitting rectangle. Most geometrical entities used to model system geometries in ASAP can be turned into an emitter. And these emitters can even be polarized. By default, the extended sources in ASAP are randomly linearly polarized.

**TIP** The BRO Light Source Library features many common automotive bulbs and LEDs. Several Lumiled LEDs are part of this catalog. Lumiled supplies these models directly to BRO.

The source models contain filaments simulated as emitting objects, as well as the source's opto-mechanical structure. The LED models contain the exterior LED geometry and a ray set starting on the exterior LED geometry. Figure 6 illustrates an LED source created in ASAP and an Epitech catalog source. The ASAP source library
models contain the actual optical and mechanical geometry from the source, which is necessary for accurate and thorough analysis.

![Light Sources Manager](image)

```plaintext
Category:
- Search
- Favorites
- Arc
- CCFL
- Filament
- LED
  - Avago
  - Bridgelux
  - CITIZEN ELECTRONICS
  - Cree
  - Epitech
  - Kingbright
  - Lumileds
  - Nichia
  - OSLAM
  - Seoul Semiconductor
  - SunLED
  - Weldon Technologies
```

**Items:**
- L1200.03
- L1450.03
- L1550.03

**Notes:**
- The reference plane of the LED is located at the intersection of the primary and secondary axes.
- Emission angle = +/-10 degrees
- Peak wavelength = 1200 nm
- Please refer to the manufacturer data sheet for part epitech L1200-03 for more detailed information.

![LED modeled in ASAP](image)

**Figure 6** Epitech source from the BRO Light Source Library (upper) and LED modeled in ASAP (lower)
Emitting sources have predefined spatial and angular flux-weighed apodizations or predefined ray density apodizations. Apodization is a term used to describe how the flux or power of a ray from a source varies as a function of position on the source and propagation direction from the source. A flux-weighted apodized source is a source whose rays' fluxes or powers vary as a function of position or propagation direction (or both) from the source. A ray density apodized source is a source whose emission properties are determined by spatially placing more rays in one area or volume of the source, or propagating more rays per unit solid angle in a particular direction from the source. The flux of the rays in a ray density apodization are typically the same. ASAP can simulate both types of apodizations.

The basic sources in ASAP can be combined with opto-mechanical structures. This is illustrated in the LEDs in Figure 6 and the incandescent bulb in Figure 7.

In many applications, the basic source is created as a ray density apodized source whose properties simulate the near-field emission properties of the source. These source models are then combined with the opto-mechanical structure, which in large part determines the far-field emission properties of the source. “Near-field” describes the emission properties close to a source. These properties are a function of both the spatial location and angular propagation direction of the ray from the source. The far-field properties are primarily a function of the angular propagation direction of the ray from the source.

Physically, the far-field emission pattern is obtained when we observe the source from a very large distance. Analogous measurements under this circumstance are made with the detector at a very large distance from the source. Such is the case in goniophotometer measurements of the luminous intensity from automotive lights. The spatial variations of the source cannot be observed at such a large distance.
Mathematically, it is as if we integrated out the spatial component of the source's radiance pattern. Extended sources then sometimes behave and, therefore, can be treated like point sources, even though they are not point sources. Under these conditions, we commonly model an extended source as a point source with a flux-weighted apodization. Figure 8 illustrates the concept of a point or far-field source, an intermediate and an extended or near-field source.

![Figure 8 Sources: far (point) (lower left), intermediate (upper left), and near (extended) (upper right)](image)

What constitutes a “large distance” that distinguishes the near from the far fields? The near- and far-fields for coherent point sources can be computed from scalar diffraction theory, and are usually represented by the terms Fresnel (near field) and Fraunhofer (far field). For incoherent extended sources, we turn to a rule developed by Yamuti and Fock. They outlined a general rule for Lambertian emitters to determine whether or not a source may be considered a point source with far-field emission properties. Their rule, originally called the “Rule of 5”, states that if the distance from the source to the next optical element or detector is greater than 5 times the maximum dimension of the source, for all practical purposes, the source may be considered a point source with respect to that optical element or detector. Many optical and illumination engineers use the rule of 10 where a factor of 10 replaces the factor of 5. However, depending upon your source and optical systems, this rule may not apply.

You must decide how you will simulate your source. Your decision will most likely be based upon the source's emission properties and the information you have about the source. ASAP has a comprehensive and sophisticated ray-based source simulation capability.

**Modeling optical or mechanical systems**

Complicated source geometries are not all that ASAP can simulate. ASAP can accurately model virtually any optical or mechanical system and its optical properties. ASAP is similar to 3D solids modeling programs in that it utilizes a powerful geometrical modeling approach. This permits a nearly limitless variety of light pipes to be constructed in a straightforward manner in the Builder, through a translated CAD Initial Graphics Exchange Standard (IGES) file, or in the command language as illustrated in Figure 9.

Figure 9 Light pipe modeled in the ASAP command language

All surfaces and ray data in ASAP are referenced by default to a single global coordinate system, as opposed to other ray tracing algorithms found in lens design codes. Smooth, continuous object surfaces can be represented in ASAP by a sequence of simple conicoids or a general 286-term polynomial. Anything from a simple plane to an arbitrarily oriented elliptical toroid can be modeled precisely. ASAP can simulate parametric mesh surfaces (NURBS). In fact, polynomial and parametric entities can be used to trim each other, a common technique for creating peened and brightness-enhancing film (BEF) geometries. Polynomial and parametric surfaces can even be made into emitters in ASAP.

The most common approach to constructing light pipe geometry is within a CAD program. There are two primary reasons for this:

1. CAD programs are an easy graphical way to construct sophisticated light pipe geometries that must fit into complicated mechanical envelopes. This is the case even though construction of the light pipe geometry in the ASAP macro language can sometimes be faster and give you greater mathematical (as opposed to graphical) control over the light pipe's surfaces.
The CAD database typically serves as the general engineering database containing the project mechanical and electrical information as well. Information is shared between different databases through translators.

The ASAP translation standard is a common CAD industry-accepted practice. Individual CAD programs maintain their own databases for storing geometrical data, which may not be in the exact form as in another CAD program. Several industry data exchange standards have been created to facilitate data transfer between different CAD programs. The most commonly used exchange standard is IGES, which provides ASCII-neutral file formats, so that different CAD databases can exchange data.¹

BRO’s approach to CAD combines the best of CAD and optical design and analysis software. At the heart of the CAD capabilities in ASAP is its abilities to translate CAD entities into ASAP entities.


By providing dual ways to handle translation, ASAP users are not forced to learn another CAD program to design and analyze light pipes. They can simply translate their existing CAD information, as acceptable CAD entities, directly into ASAP through its CAD to ASAP translator.

The CAD to ASAP translator translates your CAD entities, while allowing you to turn on or off various components of your light pipe geometrical model. You can add a variety of optical properties to the light pipe, including refractive induces, reflection/transmission coefficients, and scattering properties for ray tracing. Figure 1 illustrates a light pipe for mixing the output from three multicolored LEDs translated from an IGES file. Figure 10

¹ Although called an “initial” standard, it has undergone continual development since 1980, and was approved as an ANSI standard in 1981.
shows the light pipe in the ASAP translator.

![Figure 10 Light pipe in the CAD to ASAP translator](image)

The powerful geometrical modeling capability in ASAP is complemented by its equally powerful ability to simulate a variety of optical transformation processes such as reflection (TIR), refraction, diffraction, polarization and scattering. ASAP allows you to create optical properties databases that describe real and complex homogeneous and gradient refractive indices with absorption or gain, complex multilayered coatings, diffractive optical elements (gratings, binary optics, and so on), uniaxial crystals, polarizers, and a variety of scattering surface types. The Fresnel equations are used not only to calculate—as a function of incident angle and polarization—transmission losses at interfaces between two dielectric media, but also reflection losses and any dielectric/conductor interfaces. Moreover, ASAP is capable of splitting any ray into transmitted, reflected, total internally reflected (TIR), diffracted, near specular, diffuse, and backscatter components.

ASAP has the most powerful scatter simulation capability in the industry, allowing you to create roughened or diffuse scattering surfaces. The modeling capability in ASAP allows you to simulate surfaces with predefined scatter models, actual measured scattering data, or models fitted to measured scattering data. Models such as Lambertian diffusers are available to simulate the simple effects of paints, especially those used in diffuse illumination. Diffuse illumination illuminates objects by a diffusing screen or diffusing cavity. If a diffusing screen is not used, fluorescent tubes are commonly used as sources, with a redirecting light pipe and scattering, painted
dots. A diffusing cavity and simple fluorescent tube are illustrated in Figure 11.

![Figure 11 Light pipe with scattering paint dots used in LCD illumination](image)

Lambertian diffusing screens and sources, such as white paints and fluorescent tubes, have a uniform brightness with a luminous intensity (lumens/solid angle) that falls off with the cosine of the angle from the surface normal. An interesting point about diffusers is that, in a sense, they destroy the conservation of etendue discussed previously. These devices drastically change the solid angle into which a given amount of power is redirected. Subsequent optical elements, or our eyes, see reduced luminance. Consequently, many back lit systems use peened surfaces in light pipes. Peened surfaces are small bumps or dimples in the light pipe that cause light to spread without scattering losses, as shown in Figure 12.

![Figure 12 Peened surface for redirecting light](image)

Diffuse illumination systems are most commonly found in back-lit display systems such as laptop computers and consumer electronics. They are photonically challenged and not light efficient enough to be used with projection display systems.
Light pipe sensitivity and tolerances: real-world simulations

The optical systems we design and manufacture are not perfect. We cannot tool a mold to exact dimensions, nor can we make all light sources emit exactly the same power. Mechanical dimensions have tolerances, and the sources used in light pipes typically have wide variations in output power performance—these factors must be considered for the design.

Variations in source radiometric performance, particularly power variations, are an important issue. In other words, the output power performance tolerance from one source to another can vary greatly. This can affect performance between different light pipes, as well as the performance between multiple sources used in the same light pipe. Look at the specification sheet for a common light pipe source, the LED. These LEDs are “binned” according to power, meaning that LEDs with similar, but not necessarily equal, outputs are placed in the same bin. The radiometric output within a bin can vary greatly, and even more so from bin to bin.

With the ASAP macro language, you can parameterize source and system models, allowing you to change variables and assess this variation on system performance. This flexibility allows you to perform sensitivity and tolerance analyses in order to create component specifications and evaluate cost performance trade-offs. For example, if an LED light pipe design requires a tight tolerance on LED power output, you will be forced to specify LEDs from a small number of bins. The basic laws of supply and demand apply, and you will pay more for those diodes than if you could use LEDs from a large number of bins. This is relatively easy to simulate in ASAP, since you can set up source power as a parameter in your source model. By changing a single variable, you can re-evaluate the performance, thereby helping you to specify an acceptable LED power variation.

The same parametric analyses can be performed on optical geometries and properties. How does source position and orientation affect the performance? Or how does the light pipe’s surface roughness affect performance? Set them up as parameters and evaluate the results. ASAP has a special macro language command called \$ITER that allows you to evaluate how a dependent variable, one of our performance requirements, changes as a function of an independent variable, another of our parameters. This information can be plotted on a graph to show the topographical system behavior. Script files, which contain ASAP system, source, and macro commands, are often the most efficient and compact way to set up ASAP geometry, sources, and commands for analyses.

SUMMARY

ASAP offers a powerful set of tools for designing and analyzing light pipes. Depending on your performance requirements, you can use ASAP to conceptually design and refine the light pipe design, or you can create a light pipe design in a CAD environment and translate it into ASAP for optical analysis. Either way, ASAP offers a variety of options for simulating complicated light pipe geometries and sophisticated optical properties.

You can then use the basic sources in ASAP with ray density and flux weighted apodization, or combine sources and apodization techniques to create more sophisticated sources. You can add the source's opto-mechanical geometry including its optical properties. You can use measured data, Radiant Imaging measurements, or sources from the BRO Light Source Library. Whatever you choose, ASAP—with its ability to simulate the coherence, polarization, amplitude, and phase of an optical field—is a flexible tool that supports your simulation of extended sources in a wide variety of light pipes. The change in the polarization, amplitude, and phase of an optical field is automatically computed as the rays propagate and TIR through the light pipe. At any surface in your light pipe you can compute the power, intensity, irradiance, or radiance.

Because of its ray trace approach and similarity to 3D solids modeling programs, ASAP permits a nearly limitless variety of light pipes and extended sources to be simulated in a straightforward manner. These capabilities—coupled with the ability in ASAP to split rays into reflected, transmitted, diffracted, and scattered light—make ASAP a highly realistic and commercially-available simulation tool for light pipe design and analysis.