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ARP6833™

Issued

2022-06

Optical Simulation and Analysis for Aircraft Lighting

RATIONALE

Nearly every aircraft light now developed is first simulated using optical software. This document will provide guidance on how to create useful, accurate optical simulations. Guidance on how to present and interpret the results of such simulations will also be provided.

1. SCOPE

This document contains guidance for designers, specifiers, regulatory personnel, purchasers, managers, and others who specify or use optical simulations of aircraft lights. All aircraft lighting will be considered—interior, flight deck, and exterior lighting. Guidance on standard methods of analysis and presentation of data will be provided. Although this document concentrates on lighting, many of the principles covered will be helpful in other types of optical simulation, such as for displays, non-visible radiation, etc.

1.1 Purpose

The purpose of this document is to inform lighting designers and others about typical practices in optical simulation of aircraft lights. No specific simulation software package is recommended, but the document will provide general guidance on properly using a range of optical simulation tools. Guidance will also be provided about the limitations of optical simulations and the expected accuracy of their predictions.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP693 Landing and Taxiing Lights – Design Criteria for Installation

ARP6253 LEDs and Aircraft Applications

ARP6621 Predicting Photometric Degradation of Exterior Aircraft Lights

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SAE WEB ADDRESS:

Full document details: SAE ARP6833

For more information on this standard, visit
<https://www.sae.org/standards/content/ARP6833/>

Documents
Document Sharing Hub

AS8037 Minimum Performance Standard for Aircraft Position Lights

SAE J1330 Photometry Laboratory Accuracy Guidelines

2.1.2 IES Publications

Available from Illuminating Engineering Society, 120 Wall Street, Floor 17, New York, NY 10005-4001, Tel: 212-248-5000, www.ies.org.

The Lighting Handbook, Tenth Edition

IES TM-25-20 Ray File Format for the Description of the Emission Property of Light Sources

IES LM-63-19 Approved Method: IES Standard File Format for the Electronic Transfer of Photometric Data and Related Information

2.1.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

Code of Federal Regulations (CFR), Title 14 Part 25.1309 and Part 25.1385 – 25.1395

2.2 Definitions

2.2.1 ILLUMINANCE

Illuminance is the incident luminous flux per unit area. The unit's name depends on the unit of measure used for the area. It is footcandles (fc) if square feet are used for the area, and lux (lx) if square meters are used. (1 fc = 10.76 lx) In many specifications it is measured normal to the incident light.

2.2.2 INTENSITY

Luminous intensity specifies the amount of photopic light leaving a light source in a particular direction. It is the ratio of luminous flux per steradian and has the unit candela (cd). It is also sometimes called candlepower.

2.2.3 LUMINANCE

Luminance is the density of photopic light leaving a particular surface in a particular direction. The unit's name depends on the unit of measure used for the area. Candelas per square foot are called footlamberts (fL), and candelas per square meter are called nits (nt). (1 fL = 3.426 nt)

2.2.4 LUMINOUS FLUX

The amount of photopic light being emitted from a light source. Measured in lumens (lm) or sometimes Mean Spherical Candlepower (MSCP).

2.2.5 PHOTOPIC

Electromagnetic radiation that has been filtered or scaled to match the wavelength sensitivity of the human eye in well-lit conditions. Intensity, illuminance, luminance, and luminous flux are photopic units.

2.2.6 RADIANCE

Radiance is the amount of electromagnetic radiation leaving a particular surface in a particular direction. The units are Watts per square meter (W/m²).

2.2.7 STERADIAN

The unit of solid angle, which is the area on a sphere divided by the radius squared (sr).

2.2.8 LAMBERTIAN

Lambertian refers to a surface that reflects or emits light according to Lambert's cosine law. The intensity emitted or reflected is proportional to the cosine of the angle from the normal.

2.2.9 FAR FIELD

Far field measurements are made at a large enough distance from the light source so that it can be considered a point source. A rule of thumb is that the distance should be at least 10X the largest dimension of the light source.

2.2.10 NEAR FIELD

Near field measurements are made close to the light source, such that the geometry of the light source can have an impact on the measurement.

3. GENERAL CONSIDERATIONS

The discussion in this document concentrates on visible light. However, many of the principles mentioned apply to electromagnetic radiation in other wavelength ranges as well. For example, some lights are designed to emit radiation in the near infrared region so that they can be viewed with night vision equipment. The principles discussed below would apply to these lights, with the exception that the material properties of the objects in the simulation would need to account for the longer wavelengths of light involved, and the response of the night vision equipment would need to be considered.

3.1 Training and Experience

Although optical simulation software is a powerful and useful tool, it is not a substitute for trained and experienced optical engineers. Without a thorough understanding of the underlying physical and optical principles, it is easy for an inexperienced engineer to make improper choices when setting up a simulation, resulting in incorrect results that may lead to costly redesigns. It is recommended that those who perform optical simulations have a degree in optics or physics, or that they have several years' experience in optical design and simulation.

3.2 Limitations of Optical Simulations

Some optical simulation packages are integrated within CAD programs, and others allow the user to create geometry which can later be exported to CAD software. However, the main purpose of optical simulation software is to simulate how light travels through a set of optical elements and to determine the distribution of that light in space or on a particular surface. It is usually left to the optical engineer to create the shapes of the reflectors, lenses, and other optical elements to generate the desired light distribution. This document will concentrate on the optical simulation of lights, not their optical design.

Optical simulation always involves some simplification and idealization—such as modeling reflector and lens surfaces that are perfectly smooth, light sources that emit evenly in all directions, etc. While many software packages have ways of modeling non-ideal situations, there are often trade-offs involved. For example, it is possible to measure the wavelength-dependent bi-directional scattering distribution function (BSDF) for a surface, and to incorporate the result into a simulation, but doing so for every different surface within a flight deck could become extremely expensive and time-consuming. Thus, an important part of optical simulation is knowing where simplification will not significantly impact the results.

3.3 Benefits of Optical Simulations

Optical simulation software has become a powerful tool for evaluating the optical performance of lights, displays, and other optical systems. In many cases, a well-crafted optical simulation can predict optical performance to a high degree of accuracy. When done properly, optical simulation can reduce tooling cycles, shorten design time, and reduce or eliminate the need for prototype parts. For these reasons, optical simulation has become an indispensable tool for aircraft lighting designers.

Optical simulation tools are intended to support complex optical design and reduce risk by validating performance. Typically, optical elements such as reflectors and optics require capital investment to manufacture. It can be faster and less expensive to verify the performance of the system via simulation. However, it is important to verify the accuracy of each input for a given simulation such as the light source, material reflectance/absorption, refraction index, etc. If the simulation inputs are not accurate the outputs will not be accurate.

Another key benefit of optical simulation is the ability to visualize and communicate the optical performance of a design.

4. SIMULATION SOFTWARE

Optical simulation software works by calculating the paths of light rays emitted from a source and passing through an optical system. Each time a ray intersects a surface, the software calculates what happens to the ray—whether it is absorbed, reflected, or transmitted. By tracing large numbers of such rays, the software can simulate the complete optical performance of a light.

4.1 Sequential Versus Non-Sequential Ray-Tracing

Calculating all the possible intersections between a light ray and the various components of an optical model can be difficult and may require a lot of computing power. One way to reduce the complexity is via sequential ray-tracing. For systems like cameras or telescopes, the light is intended to travel through the system in a pre-determined direction, intersecting each optical surface in order. Sequential ray-tracing software takes advantage of this fact to reduce the computation time by assuming that the optical surfaces will be encountered in a specific sequence. Non-sequential ray-tracing is more computationally intensive because it makes no assumptions about the order of intersection. Each ray can interact with any surface in the optical system, perhaps multiple times, and may split into multiple rays depending on the optical properties of the surface in question. Non-sequential ray-tracing is good for complicated optical systems where the light may follow multiple paths before intersecting the detector. As computers have increased in power, the need for sequential ray-tracing has been reduced, and many of the sequential ray-tracing software packages now include non-sequential ray-tracing components.

4.2 Optimization

Many optical simulation software packages include optimization routines. These tools allow the user to designate certain variables in the system, such as the radius of curvature of a lens, as optimizable, along with a merit function that specifies the desired results. The software will then run multiple simulations until it converges on the values of the variables which produce the best results.

4.3 Determining the Accuracy of Predictions

Optical simulations are only useful if they accurately predict the performance of the actual part being simulated. However, manufacturing variations and other factors can make it hard to determine the accuracy of a particular simulation. Following are some general methods to determine and improve the accuracy of simulations.

Since optical simulations are typically a statistical process, increasing the number of rays traced can increase the accuracy of a simulation. You can begin with a relatively small number of rays, then run multiple simulations with more rays each time, until the difference between the simulations approaches an asymptote.

Adding more detail to the simulations will help you determine the accuracy of a simulation. For example, you might start by simulating a perfectly smooth reflector and lens, then add scattering models to the reflector and lens surfaces. Or, you might start with a simple point source and then add a rayset source. By observing the effects of the added details, you can learn what parameters are important for an accurate simulation and what effect each parameter has on the final result.

You can compare the results of a test to the simulation, then make adjustments to the simulation until the results agree. While this may seem to be counter-productive, since the purpose of the simulation is generally to avoid testing, it can be a useful way to learn what variables are important to include in a simulation, and the adjustments can help you understand how to make the next simulation more accurate.

It can be helpful to keep records of simulation predictions and measured data from testing. These records can help you predict how accurate a future simulation might be.

5. COMPUTER HARDWARE

In order to perform an optical simulation, the simulation software traces millions of rays through the optical model, calculating where each ray intersects each optical surface and determining any changes in direction or intensity depending upon the surface properties. Some simulations spawn new rays at some intersections, increasing the number of rays to trace. Many millions of calculations are required to perform a complete simulation, so it is preferable to have a computer capable of performing those calculations quickly. Following are some general considerations to apply when selecting a computer for doing optical simulations.

5.1 Central Processing Unit (CPU)

The CPU of the computer should be capable of making many millions of calculations very quickly. 64-bit processors, multiple cores, and high clock speeds should all be considered.

5.2 Random Access Memory (RAM) and Disk Storage

During a trace, the computer must maintain data about each ray in the simulation. Larger amounts of RAM allow this data to be stored where it can be quickly accessed and used. If the data needs to be stored on a disk, the access time is much slower, and the simulation will likely take much longer. A solid state hard drive may improve access speed if drive access is required.

5.3 Multi-Threading

Most modern computers have more than one processor in their CPU. This allows them to work on multiple processes at once. Most optical simulation software is designed to take advantage of this ability. The user may need to adjust the usage of multi-threading depending upon their needs—for example, reserving one processor for other tasks that can be done while a simulation is running.

5.4 Graphics Processing Unit (GPU) Usage

Many computers have a separate video card designed to perform the calculations needed to present rapidly changing images on the screen. Some optical simulation software has been designed to take advantage of this fact and use the graphics processor to speed up the optical simulation calculations. If the user desires to have this capability, they may need to ensure that their graphics processor is compatible with their simulation software.

6. THE LIGHTING SIMULATION PROCESS

This section describes the general process for constructing a lighting simulation. While each application is unique and requires attention to how specific data is handled based on the goal of the simulation, the basic steps required are outlined in Figure 1.

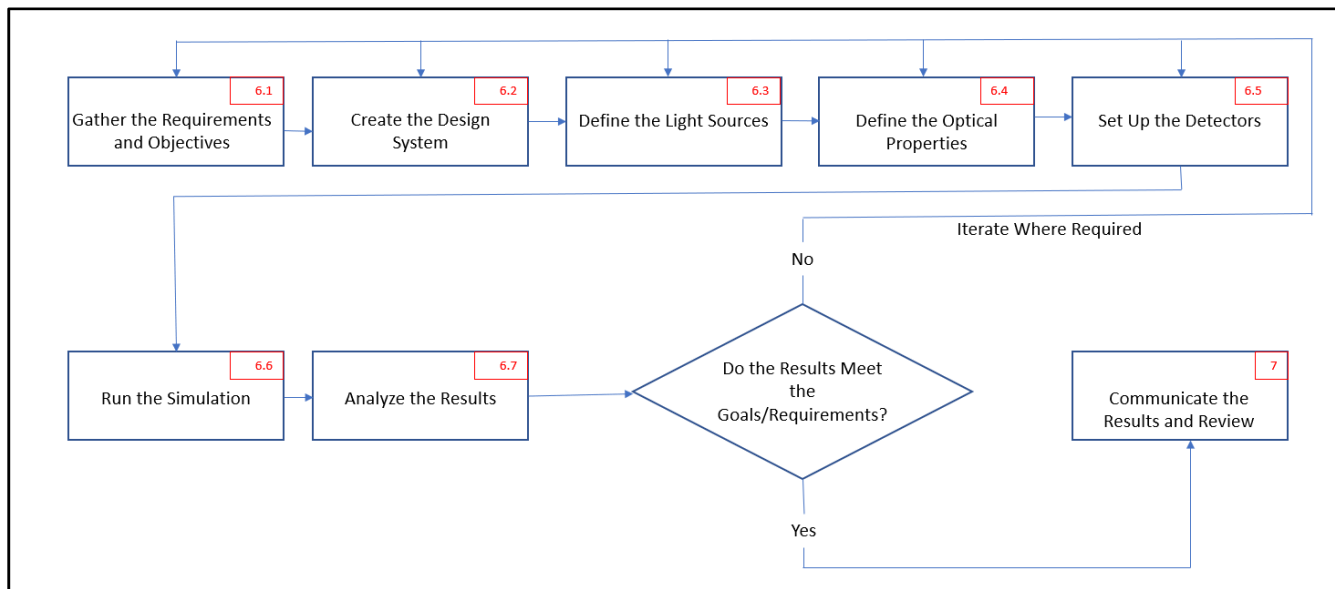


Figure 1 - The lighting simulation process

6.1 Gathering Requirements and Objectives for the Simulation

- Typically, the first step happens prior to any digital modeling. In order to effectively begin building a model, the best start occurs when the designer has a full set of the requirements and objectives of the simulation—what will the simulation show?
- Frequently in new designs, the requirements may change as the design develops or a complete set of requirements may not be available. Sometimes the simulation results will inform how a requirement is written but it's good to clearly understand the goal of the simulation and what constraints/requirements the simulation will assume.
- Having a clear understanding of the requirements and objectives will help guide decisions made when creating the simulation; this will also help stakeholders understand the simulation once results are available.
- Requirements can be diverse and include standard considerations such as technological limitations, light performance requirements, spatial requirements, environmental requirements, human factors requirements, and even aesthetic design intent. Prior to beginning the simulation, start by becoming familiar with and understanding these items. While not always possible, it can also be helpful to create a hierarchy of the true requirements from the nice-to-have objectives.
- Often, simplifying assumptions can be made to reduce the complexity of the optical model or to reduce the need for measured data, such as the complete reflectance distribution function for a surface. Sometimes, these assumptions may even be unconscious. The lighting designer should have a good understanding of the assumptions used in an optical model and their possible effects on the simulation results. It is often useful to document these assumptions for future reference.

6.2 Create the Design System

- Early Concept Sketch/Model
 - Once requirements and objectives are reviewed, early idea generation either through sketching or rough modeling will help explore solutions without being too time intensive.
- Constraints
 - It is often necessary to set up requirements or constraints. Depending on the requirement or constraint, this could be handled in various ways. An example would be that if there is a specific volume that the lighting sources must remain inside, a simple spatial model of that envelope could be created to have when working on placing the lighting sources. Planes, lines, and points can also be used to provide guidance to the lighting designer.

- Modeling System Parts in Optical Software
 - After understanding the requirements and objectives, the next step will be to start gathering the data needed for the simulation. For many lighting systems, geometry surrounding the lighting elements will affect how light travels through the system. A typical first step is to find or build models that accurately reflect the surrounding system's characteristics.
- Importing CAD Geometry
 - Many light modeling programs are incorporated into or associated with CAD software; or have their own internal modeling capability. However, in many other cases, full geometric modeling is done in a separate CAD package and imported into the optical software. In these cases, special attention should be paid if the data received is in a file format that isn't native to the lighting simulation package. Most optical software supports standard CAD import/export formats such as IGES and STEP, but it may take some experimentation to determine which format works best for your particular combination of CAD software and optical simulation software.
 - If translated, ensure that the models perform as intended in the lighting simulation software and that no repairs to the models have to be made.
- Simplifying the Model
 - Many times, a lighting designer will receive the full engineering definition of a model for the system. Often, many of these details are irrelevant to how the light will perform in the system. In order to simulate the performance effectively, it can save time in the overall process to simplify the model at the start to only what is needed for the lighting evaluation. If the geometry will be opaque for example, internal details to the model can be removed with no change in fidelity of the simulation. Sometimes, it is cleaner and more accurate to re-model a surface or small volume rather than using the given data. This can result in a lighter, faster, and simpler model that will make further steps more efficient but must be considered carefully based on the requirements of the simulation and the level of fidelity needed.
- Assign Optical Properties
 - The optical properties of various geometric entities can be defined when they are created or imported, or later in the optical simulation process. See 6.4 for more details.
- Set Up Requirement/Constraint Checks
 - If the system's geometry may be modified to improve the performance, it can sometimes be beneficial to set up the assembly with constraints that enable easy and systematic changes. This will help when iterating through different lighting performance concepts.

6.3 Create Light Source Model

Light sources come in many different forms, from incandescent filaments to fluorescent tubes, to LEDs. Depending on the light source used, different methods can be used to simulate that source in an optical model. Many optical software packages come with a built-in library of common light sources. Light sources can also be modeled in the optical software or measured light source data can be imported into the software (see 7.1.6). The following discussion explains the most commonly used light source models and where each one might be used.

6.3.1 Light Source Geometry

6.3.1.1 Point Source

Light source where all light is emitted from a point. Point sources are useful for preliminary modeling to help develop geometry. These sources are generally defined by zenith and azimuthal angles and an intensity that is the same in all directions. It is usually best to replace point sources with more realistic sources for final simulations.

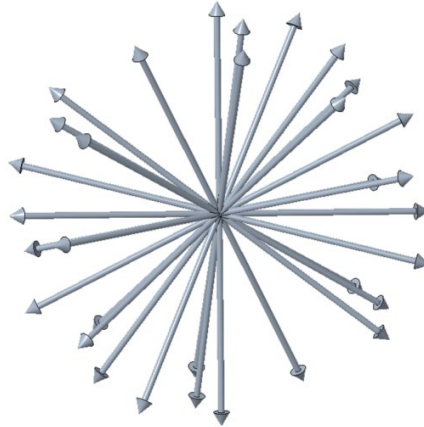


Figure 2 - Illustration of a point source with rays

6.3.1.2 Area/Surface Source

Light source where all light is emitted from an area. The area can be a 3-dimensional surface or an area on a flat plane. A flat area source could be used to simulate the top surface of an LED die, for example. A fluorescent tube could be simulated by a cylindrical surface. An area source could also be used to simulate the lens surface of a light fixture with a known output, such as a dome light.

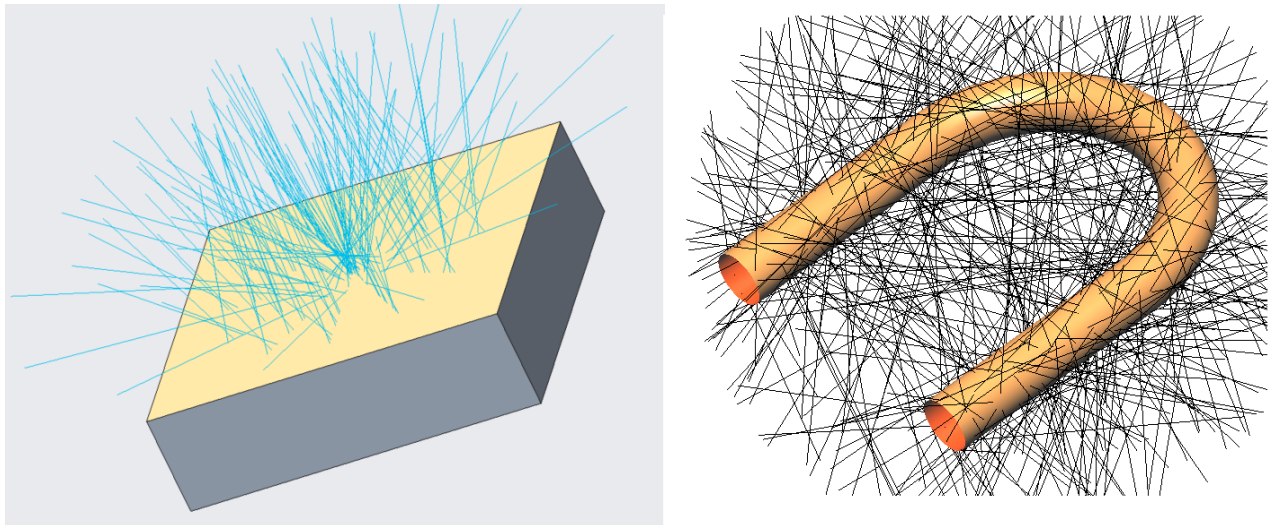


Figure 3 - Area/surface sources

6.3.1.3 Volume Source

Light source where the rays originate within a defined volume. For example, a filament could be modeled as a cylindrical volume that matches the diameter and length of the filament. Another example would be an LED dome, which can be modeled as a hemispherical volume. The distribution and orientation of rays within the volume can be manipulated to simulate a specific light source.