LIGHTFAIR 2001 Pre-Conference Workshop

Thinking Photometrically Part II

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Abstract:

In this seminar, you will learn:

1. An explanation of the photometric measurement process and its relation to the accuracy and reliability of photometric reports.
2. An in-depth understanding of photometric reports, including IESNA LM-63, CIBSE TM14, and EULUMDAT file formats.
3. A non-technical analysis of lighting design software algorithms, with particular emphasis on understanding how they work and how to use them properly to produce photometrically accurate predictions and physically correct renderings.

Part I –Photometric Laboratories

1.1. Photometric Units

1.1.1. What Is Light?

"Let me give light, but let me not be light."

Wm. Shakespeare
The Merchant of Venice
Act V, Scene I

Light is *electromagnetic energy*, which includes radio waves, microwaves, infrared, visible, ultraviolet, X-rays and gamma rays. We can think of it as subatomic particles (called *photons*) flowing through space in all directions. Each photon has a certain energy that is determined by its wavelength.

More usefully, we can think of light as the *flow* of electromagnetic energy – so many photons per second, similar in principle to the flow of electrical current. For visible light, this flow is measured in lumens.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
ANSI/IES RP-16-95, *Nomenclature and Definitions for Illuminating Engineering.*
Photometry and Radiometry: A Tour Guide, www.helios32.com (Resources).

1.1.2. Illuminance

The illuminance of a surface is the amount of light incident upon the surface, divided by the area of the surface. It is measured in either *footcandles* (lumens per square foot) or *lux* (lumens per square meter).

We can measure illuminance with an incident light meter (FIG. 1). The photosensor absorbs light incident upon its surface and converts into an electrical current.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
ANSI/IES RP-16-95, *Nomenclature and Definitions for Illuminating Engineering.*

Photometry and Radiometry: A Tour Guide, www.helios32.com (Resources).

1.1.3. Luminance

The luminance of a surface is the amount of light leaving a surface in a given direction, divided by the area of the surface. It is measured in either candela per square meter (also known as *nits*) or candela per square foot (and also *foot-Lamberts*).

We can measure luminance with a spot (luminance) meter (FIG. 2). This is essentially an incident light meter with an opaque shield that limits the incident light to a single direction.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
ANSI/IES RP-16-95, *Nomenclature and Definitions for Illuminating Engineering.*
Photometry and Radiometry: A Tour Guide, www.helios32.com (Resources).

1.1.4. Luminous Intensity

The luminous intensity of an infinitesimally small point source is the amount of light leaving the point source in a given direction. It is measured in *candela* (lumens per steradian).

We cannot measure luminous intensity directly. Instead, we must measure illuminance at a known distance from the source and calculate the equivalent luminous intensity from the inverse square law (illuminance = intensity / distance-squared).

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
ANSI/IES RP-16-95, *Nomenclature and Definitions for Illuminating Engineering.*
Photometry and Radiometry: A Tour Guide, www.helios32.com (Resources).

1.1.5. Color

What we perceive as color are photons with different wavelengths, ranging from approximately 400 nanometers (blue) to 700 nanometers (red). Our eyes have a peak sensitivity at 555 nanometers (green).

Color is rarely considered in photometric measurements. However, the recent availability of lighting design and analysis software that includes color in its visualization capabilities has heightened designers' interest in this topic.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapters 3 and 4.
IES DG-1-90, *Color and Illumination*.
IES LM-58-94, *Spectroradiometric Measurements*.

1.1.6. BRDF and BTDF

BRDF (bidirectional reflectance distribution function) and BTDF (bidirectional transmittance distribution function) measurements represent the ratio of illuminance (from a point source in a given direction) to luminance for an opaque (BRDF) or transparent (BTDF) surface (FIG. 3).

BRDF measurements are sometimes used by luminaire manufacturers to mathematically model semi-specular reflectors, such as brushed aluminum. Recent developments in advanced optical materials such as *kinoform diffusers* will make both BRDF and BTDF measurements more important for luminaire designers.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 9.

1.2. Far-Field Photometry

1.2.1. Basic Principles

Goniophotometry is the measurement of the luminous intensity of a light source from different directions.

A goniophotometer consists of a mechanical device to support and optionally position the light source (a luminaire or lamp) and a photosensor, together with associated electrical and electronic equipment to acquire and process the photometric data.

Far-field photometry assumes that the light source is an infinitesimally small point source, for which the inverse square law applies (illuminance = intensity / distance-squared, or $E = I/d^2$). This assumption generally holds true (to within ±2 percent) for most architectural luminaires when the distance from the luminaire to the measurement point is at least five times the maximum width of the luminaire (FIG. 4). This is the oft-quoted five-times rule for photometric measurements and calculations.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
CIE 121-1996, *The Photometry and Goniophotometry of Luminaires*.

1.2.2. Rotating Mirror Photometers

The original far-field goniophotometers were "Ferris wheel" designs, with a 25-foot long boom that held the photosensor and rotated about the luminaire in the vertical plane. The luminaire was mounted on a platform that rotated in the horizontal plane.

This space-consuming design was later superceded by the commonly used rotating mirror goniophotometer (FIG. 5). The lamp or luminaire is mounted on a rotatable horizontal platform, and a large glass mirror is mounted on a boom that can be rotated vertically through a full circle about the luminaire. The mirror is tilted such that the light is reflected horizontally to a fixed photosensor. Angular settings must be reproducible to within ±0.25 degrees.

Other designs are also used on occasion, including goniophotometers with multiple fixed photosensors and movable track-mounted photosensors.

It is also possible to employ a fixed photosensor and rotate the lamp or luminaire both horizontally and vertically. However, this approach does not work for light sources whose luminous flux (lumen) output changes depending on the lamp or luminaire orientation.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
CIE 121-1996, *The Photometry and Goniophotometry of Luminaires*.

1.2.3. Searchlight Photometers

The inverse square law assumption does not apply to very narrow distribution floodlights and searchlights because the beam is highly collimated. Test distances may range from fifty to several hundred feet, and must sometimes be performed outdoors.

Depending on the size and weight of the searchlight, either the photosensor or the searchlight itself may be moved to obtain a luminous intensity distribution over the width of the beam. This may require aiming accuracies to within 0.1 degrees.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
IES LM-11-97, *Photometric Testing of Searchlights*.

1.2.4. Photometric Webs

The photometric data produced by goniophotometers is presented as the luminous intensity of a point source at the photometric center (nominally the center of rotation) of the lamp or luminaire for various vertical and horizontal directions. The spherical coordinate system used to describe these directions is referred to as the photometric web.

There are three different types of photometric webs, called Types A, B, and C (FIG. 6). Type A is typically used for automotive headlamp and signal lights, Type B for adjustable outdoor area and sports lighting luminaires, and Type C for architectural and roadway luminaires.

Type A is functionally equivalent to Type C, but it is produced by a Type A goniophotometer where the light source is rotated vertically and horizontally. For lamps and luminaires where the lamp lumen output may vary depending on the lamp orientation or trapped heat in the luminaire housing, a Type C goniophotometer is often used and the photometric web mathematically converted to Type A or Type B when required.

There is some confusion in the IESNA literature regarding the direction of horizontal rotation for Types A and B goniophotometers. Both the IESNA Lighting Handbook and IES LM-35-89 show the direction being both counterclockwise and clockwise in the same diagram. The IESNA Testing Procedures Committee is currently working on a revision of LM-35 to clarify this issue.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
IES LM-35-89, *IES Approved Method for Photometric Testing of Floodlights Using Incandescent Filament or Discharge Lamps*.
CIE 121-1996, *The Photometry and Goniophotometry of Luminaires*.

1.2.5. Integrating Spheres

The integrating sphere photometer is used to measure the total luminous flux emitted by a lamp or luminaire. This is useful for determining rated lamp lumens and luminaire efficiencies.

In the most common design (called an Ulbricht sphere), the light source is placed in the center of a large sphere that is painted on the inside with a high reflectance, matte white paint. The multiple reflections of light from this surface ensure that all portions of the surface have the same illuminance and luminance.

The surface luminance will be directly proportional to the total luminous flux emitted by the light source, regardless of its luminous intensity distribution. Once the luminance due to a light source with a known total luminous flux output has been measured, the integrating sphere can be used to determine the total luminous flux of other light sources.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.

1.3. Near-Field Photometry

1.3.1. Basic Principles

Far-field photometry is based on the five-times rule, but this rule is clearly violated by linear indirect fluorescent luminaires used in many offices.

As an example, consider a four-foot indirect fluorescent luminaire mounted 16 inches below the ceiling plane. Far-field photometry models this luminaire as a point source in the center of the luminaire. However, the inverse square law predicts a ceiling illuminance directly above the luminaire that is over *four times* what is actually measured.

This was not a problem when most lighting design calculations were performed by hand using the lumen method. The average workplane illuminance was still reasonably accurate. However, the introduction of IES RP-24-89, *VDT Lighting* (now incorporated in RP-1, *Office Lighting*) with its recommended ceiling luminance ratios suddenly brought point-by-point luminance calculations to the forefront.

Lighting design software such as Lighting Analysts' *AGI32*™ and Lighting Technologies' *Lumen Micro*™ alleviate this problem by dividing each luminaire into an array of point sources and evenly dividing the luminous intensity distribution between them. This however assumes that the distribution is homogeneous along the length of the luminaire, which is not always true.

A more accurate approach – called <u>near-field photometry</u> – is to physically measure the distribution of light at distance close to the luminaire. There are two very different techniques. One is practical, while the other is (at least for architectural lighting purposes) mostly theoretical.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
IES LM-70-00, *Guide to Near-Field Photometry*

1.3.2. LM-70 (Application Distance)

<u>Application distance photometry</u> measures the point-by-point illuminance on a plane positioned at a given distance from a luminaire. These measurements are then interpolated to generate an equivalent luminous intensity distribution that would produce these measurements if it were placed at the photometric center of the luminaire (FIG. 7).

The advantage of application distance photometry is that it produces photometric data that is fully compatible with existing lighting design software.

The disadvantage is that the measurements are applicable only for the given distance. For a linear indirect fluorescent luminaire, separate photometric data files are required for each mounting height.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
IES LM-10-96, *Photometric Testing of Outdoor Fluorescent Luminaires*.
IES LM-41-98, *Photometric Testing of Indoor Fluorescent Luminaires.*
IES LM-70-00, *Guide to Near-Field Photometry.*

1.3.3. Luminance Field

<u>Luminance field photometry</u> uses a scientific-grade digital camera (an <u>imaging photometer</u>) to measure the four-dimensional "field" of light surrounding a luminaire. Unlike application distance photometry, luminance field photometry can be used to predict the illuminance at any point in space, regardless of its distance from the luminaire.

The disadvantage of luminance field photometry is that it typically produces several megabytes of photometric data for a single luminaire. This makes it impractical for use for existing lighting design software.

Luminance field photometry can also be used to reconstruct digital images of the luminaire as seen from any viewpoint. This has made the technique useful for both imaging optical design (such as Radiant Imaging's *ProMetric*™ lamp measurement system) and Hollywood special effects (where it is known as *image-based rendering*, and has been used in movies such as *Matrix*).

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
Ashdown, I. 1993. "Near-Field Photometry: A New Approach," *Journal of the IES* 22(1):163–180 (Winter).
Ashdown, I. 1993. "Near-Field Photometric Method and Apparatus," US Patent 5,253,036.

1.4. Measurements

1.4.1. Basic Principles

Photometric measurements may involve a number of instruments, including:

a) Illuminance meters (illuminance and luminous intensity);
b) Luminance meters (luminance);
c) Integrating sphere photometers (total luminous flux);
d) Spectroradiometers (spectral power distribution);
e) Colorimeter (color temperature);
f) Wattmeter (power consumption);
g) Reflectometer (reflectance);
h) Densitometer (optical density); and
i) Radiometer (ultraviolet irradiance).

(As previously discussed in Sections 1.1.4 and 1.2.1, an illuminance meter is used in a goniophotometer to measure the illuminance at a fixed distance and various directions from a lamp or luminaire, and the inverse square law is used to determine the luminous intensity of an equivalent point source.)

An illuminance meter consists of a photosensor that converts incident light into an electrical current, an amplifier, and a display or recording device (FIG. 1). A luminance meter is simply a suitably calibrated illuminance meter with a shield or optical system to limit the photosensor's field of view to a very small angle (typically one degree).

There are various types of photosensors, including vacuum or gas-filled phototubes (useful for very low light levels) and solid-state detectors (including selenium and cadmium sulphide photoconductors and silicon photodiodes). Photometric laboratories typically use silicon photodiodes because of their ruggedness and stability.

Silicon photodiodes have a peak spectral response in the near infrared. Consequently, they must be provided with carefully designed color filters that change their spectral response to match that of the human eye under normal (photopic) lighting conditions. (By using other color filters, silicon photodiodes can also be used to measure spectral power distribution, color temperature, and ultraviolet irradiance).

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
CIE 18.2-1983, *The Basis of Physical Photometry*, Second Edition.

1.4.2. Photometer Calibration

Silicon photodiodes and other photosensors must be calibrated against a known standard. This is done by measuring its response to a light source with a known luminous flux output.

The problem is that it is extremely difficult to accurately measure the luminous flux output of a light source. This is typically done by government organizations such as the National Institute of Standards and Technology (NIST) and the Canadian National Research Council (NRC). The result is a "national measurement standard."

The government organizations use these standards to calibrate carefully selected incandescent lamps called "transfer standards." These light sources are used to compare national measurement standards (which must agree with the "primary standard" maintained by the International Bureau International of Weights and Measures), and to allow private and university optical metrology laboratories to calibrate their own "reference standard" lamps.

Finally, the metrology laboratories calibrate their own set of "working standard" lamps that are used in turn to calibrate photosensors that are used in photometers and radiometers.

Like any incandescent lamp, reference and working standards have finite burn times, after which they must be recalibrated or removed from service. Consequently, metrology laboratories may use transfer standards to calibrate reference photosensors. These are then used to calibrate the working standards.

Photometer manufacturers usually describe their products as being "NIST traceable." What this means is that their photosensors are calibrated through the chain of national measurement, transfer, reference, and working standards. Expected errors amount to a few percent.

The response of silicon photodiodes and other photosensors may change over time, and so photometric laboratories usually recalibrate their instruments every six to twelve months. (This work needs to be done by an accredited optical metrology laboratory, which is often the photometer manufacturer.)

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
CIE 69-1987, *Methods of Characterizing Illuminance Meters and Luminance Meters: Performance, Characteristics and Specifications*.

1.4.3. **Lamp Seasoning**

The lamps used in luminaire photometry are off-the-shelf commercial products. The primary requirement is that they should produce constant luminous flux during a test or test series when a constant line voltage is supplied. If multiple lamps are used in a luminaire, their light output must match to within ±1.5 percent.

The initial luminous flux of a lamp may be considerably higher than the average luminous flux over its lifetime. This requires that lamps be seasoned by burning them for 0.5 percent of their rated life (typically 100 hours for fluorescent lamps).

Ref: IES LM-54-99, *IESNA Guide to Lamp Seasoning*.

1.4.4. Reference Ballasts

A reference ballast is a variable inductor that is designed to limit the current flow to fluorescent and HID lamps. These were useful for ANSI-classified lamps designed for core-and-coil ballasts. With the introduction of electronic ballasts however, it has become more common to perform photometric tests with commercially available (*production*) ballasts.

The ballast factor is defined by ANSI as the relative light output of a lamp operated on a production ballast with respect to the same lamp on a reference ballast. Photometric laboratories should (but do not always) use production ballasts with measured ballast factors provided by the ballast manufacturer.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 6.
IES LM-41-98, *Approved Method for Photometric Testing of Indoor Fluorescent Luminaires*.

1.4.5. Lamp Warm-up

It is necessary to allow the lamps and associated ballasts (if any) to reach thermal equilibrium within the luminaire housings before performing photometric and electrical tests. Otherwise, the luminous flux output of the lamps will vary during the photometric tests.

The lamps are considered to be stabilized when their luminous flux output does not vary by more than 0.5 to 2.0 percent over a period of 30 to 60 minutes (depending on the lamp type). Stabilization times can vary from ten minutes to several hours.

Compact fluorescent lamps typically need five hours of preburning time (in the base-up position for single-ended lamps) to ensure that the mercury migrates to the coolest zone of the lamp.

Ref: IES LM-41-98, *Approved Method for Photometric Testing of Indoor Fluorescent Luminaires*.
IES LM-46-98, *IESNA Approved Method for Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps*.
IES LM-66-00, *IESNA Approved Method for the Electrical and Photometric Measurements of Single-Ended Compact Fluorescent Lamps*.

1.4.6. Temperature and Air Flow

The luminous flux output of fluorescent lamps, especially single-ended compact fluorescent lamps, is quite sensitive to temperature variations. It is therefore necessary to maintain the photometric laboratory at a constant temperature of 25° C ±1° C (77° F ±2° F). In addition, a slight air flow (maximum 15 feet per minute) is required to prevent thermal stratification while preventing drafts that might cool the lamps.

Ref: IES LM-41-98, *Approved Method for Photometric Testing of Indoor Fluorescent Luminaires*.
IES LM-46-98, *IESNA Approved Method for Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps*.
IES LM-66-00, *IESNA Approved Method for the Electrical and Photometric Measurements of Single-Ended Compact Fluorescent Lamps*.

1.5. Relative Photometry

1.5.1. Basic Principles

Luminous intensity distribution measurements of luminaires are performed using a procedure called relative photometry. This procedure consists of:

a) Measure the total luminous flux of the bare lamps;
b) Measure the luminous intensity distribution of the luminaire; and
c) Scale the luminous intensity values by the ratio of the measured lamp lumens to the rated lamp lumens.

The logic of relative photometry is that the luminous flux output from the test lamps inside the luminaire may vary from the rated lamp lumens provided by the lamp manufacturer, particularly if their operating temperature is not 25° C or a reference ballast is not used.

The total luminous flux emitted by the bare lamps can be measured using an integrating sphere photometer. However, integrating spheres large enough to enclose fluorescent luminaires are very expensive. An alternative method for linear fluorescent lamps is to measure the luminous intensity in a direction perpendicular to the lamp axis and calculate the total luminous flux according to an equation based on the test distance and lamp length. (The lamps may be measured singly or in a group if they are mounted to prevent significant interreflections and mutual heating effects.)

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.
CIE 121-1996, *The Photometry and Goniophotometry of Luminaires*.

1.5.2. T5 Lamps

Linear fluorescent T5 lamps present a challenge for photometric laboratories in that they are designed to produce their maximum light output at 35° C. The lamp manufacturers quite reasonably specify the rated lamp lumens for this operating temperature.

However, the IESNA and CIE photometric test procedures specify that bare lamps be tested at 25° C ±1° C. This results in the measured lamp lumens of the bare lamps being considerably less than the rated lamp lumens.

When the lamps are placed inside the luminaire housing, the lamp ambient temperature may rise to 35° C. This will increase the luminous flux output.

IES LM-41-98 requires that the photometric laboratory measure the luminous flux output of such lamps both at their operating temperature for the manufacturer's rated lamp lumens and at 25° C to determine a correction factor for the rated lamp lumens when scaling the measured luminous intensity distribution values. This should be clearly stated in the photometric data report.

In practice, some photometric laboratories use the lamp manufacturer's rated lumens measured at 35° C in their calculations, which may produce luminaire efficiencies in excess of 100 percent. Again, this should be clearly stated in the photometric data report.

Ref: IES LM-41-98, *Approved Method for Photometric Testing of Indoor Fluorescent Luminaires*.

1.5.3. Air-Handling Luminaires

The total luminous flux output of air-handling luminaires is generally dependent on the cooling air flow past the fluorescent lamps. IES LM-56-91 requires that the relative luminous flux output from such luminaires be measured (a single illuminance measurement is sufficient) each various air flow rates and plotted as part of the photometric data report.

Ref: IES LM-56-91, *Photometric and Thermal Testing of Air-Cooled Heat-Transfer Luminaires*.

1.5.4. Outdoor Fluorescent Luminaires

The total luminous flux output of outdoor luminaires with fluorescent lamps is generally dependent on the ambient temperature of the surrounding air. The photometric laboratory must measure the relative luminous flux output of the luminaire over a range of –30° C to 30° C in a temperature-controlled room.

Ref: IES-10-96, *Photometric Testing of Outdoor Fluorescent Luminaires*.

1.5.5. Manufacturing Tolerances

A photometric report should in theory represent the average photometric characteristics of a manufacturer's products. However, the test report is performed on only one sample luminaire for economic reasons. (A single photometric test typically costs on the order of $1,000 when all the incidental costs of manufacturing and shipping are taken into account.)

Normal manufacturing tolerances can have a significant effect on the photometric characteristics of a given product. Smaller manufacturers without in-house photometric laboratories may also test a prototype luminaire rather than the final production product to meet marketing deadlines. Also, a manufacturer may change the materials or finishes used in a product without redoing the photometric tests. Seemingly minor changes such as a different supplier of specular aluminum may have significant consequences in terms of luminaire efficiency and luminous intensity distribution.

1.5.6. Lamp-Ballast Combinations

Photometric reports for fluorescent and HID luminaires are based on particular lamp-ballast combinations. It is *very important* to recognize that any changes to these combinations may change the luminous flux outputs and hence the luminaire efficiencies of the installed luminaires. (This of course includes relamping and ballast replacement by maintenance staff.)

Ref: IES DG-8-95, *Ballasts and the Generation of Light*.

1.6. Future Trends

1.6.1. Imaging Photometers

An imaging photometer is a calibrated digital camera where the luminance of each pixel can be accurately determined. They have been used for luminance field photometry, automotive headlight and roadway lighting analysis, and lighting quality studies.

Imaging photometers may prove useful in lighting quality and glare analysis studies of existing lighting installations. What will be needed however are image analysis techniques that will analyze the digital images and produce a set of reliable metrics. Further academic research is required to develop these techniques.

Ref: Samuelson, C., I. Ashdown, P. Kan, A. Kotlicki, and L. A. Whitehead. 1999. "A Proposed Lighting Quality Metric Based on Spatial Frequency Analysis," *1999 IESNA Annual Conference Proceedings*.

1.6.2. Light-Emitting Diodes

The future of architectural lighting will likely involve high brightness light-emitting diodes (LEDs) and possibly fiber optics. Luminaire designers will be faced with the problem of efficiently coupling the luminous flux emitted by these devices into fiber optics and other small-scale optics. Considering some of the current research, this may involve both refractive and diffractive optical elements.

We may soon require innovative photometric measurement techniques on the scale of millimeters or less to provide the necessary photometric characterization of LEDs. Interestingly, this may require luminance field photometry – a technique that is possibly a decade ahead of its time.

1.6.3. Kinoform Diffusers

Kinoform diffusers will be introduced at *Lightfair 2001*. They are based on a novel optical material called *MesoOptics*™ that provides new design opportunities for luminaire manufacturers.

This material has unique optical properties that require bidirectional reflectance and transmittance distribution functions (BRDF and BTDF) to properly characterize. If kinoform diffusers are a commercial success, they may require both improved BRDF and BTDF measurement techniques and extended capabilities for luminaire design software.

Ref: Santoro, S., M. Crenshaw, and I. Ashdown. 2001. "Kinoform Diffusers," *IESNA 2001 Annual Conference Proceedings* (to appear).

1.6.4. Spectral Data

The issue of color is becoming increasingly important to the lighting industry. Theatrical and entertainment applications demand color, and high brightness LEDs are beginning to provide energy-efficient and maintenance-free light sources that offer strongly saturated colors.

The IESNA Computer Committee is currently considering an extension to the IES LM-63-2001 photometric data file format that will include spectral power distribution data for both lamps and luminaires. The availability of this information in an industry-standard format will encourage lighting design software developers to extend the capabilities of their products.

Ref: IES LM-58-94, *Spectroradiometric Measurements*.

1.6.5. Ultraviolet Emission

Ultraviolet radiation can quickly damage museum and art gallery displays. It is no surprise that fluorescent and HID lamps produce significant amounts of UV radiation – as much as 20 percent for some metal halide lamps. However, it is surprising that some quartz-halogen lamps produce three times as much UV radiation per lumen as do fluorescent lamps.

It is also interesting that the amount of UV radiation produced by the same fluorescent lamp from different manufacturers can exhibit a four-to-one difference in the amount of UV radiation they emit.

This information should be readily available from lamp manufacturers, but generally it is not. Hopefully increased awareness of the topic by lighting designers will encourage the lamp manufacturers to include it in their published technical information.

Ref: Bergman, R. S., T. G. Parham, and T. K. McGowan. 1995. “UV Emission from General Lighting Lamps,” *J. Illuminating Engineering Society* 24(1):13-24
IES RP-30-96, *Museum and Art Gallery Lighting*.
IES LM-LM-55-99, *Measurements of Ultraviolet Radiation from Light Sources*.

Part II – Photometric Reports

2.1. <u>File Formats</u>

2.1.1. Introduction

“Standards are good. Standards are great! Isn't it wonderful that we have so many standards to choose from?”

The Greek Philosopher Anonymous

A brief history of “industry standard” photometric data file formats …

In 1986, the Illuminating Engineering Society of North America published IESNA Transaction called "IES LM-63-1986: IES Recommended Standard File Format for Electronic Transfer of Photometric Data." It was quickly adopted by North American lighting manufacturers and the developers of lighting calculation software. It was revised in 1991 and 1995, and the latest revision (ANSI/IESNA LM-63-2001) is currently awaiting publication.

This was followed two years later by the Chartered Institution of Building Services Engineers, which published CIBSE TM14:1988, “CIBSE Standard File Format for the Electronic Transfer of Luminaire Photometric Data.” It is still widely used in the United Kingdom.

In 1990, Axel Stockmar of Light Consult Inc. (Berlin, Germany) proposed a photometric data file format called EULUMDAT. It has since become the de facto industry standard for European lighting manufacturers.

The International Lighting Commission (Commission Internationale de l’Eclairage) followed three years later with its publication of CIE 102-1993, “Recommended File Format for Electronic Transfer of Luminaire Photometric Data.” Despite being a well designed and comprehensive file format, it does not appear to be supported by any lighting manufacturer or commercial lighting design software product.

There are several other “industry standards” that are either in use or have been proposed, including EULUMDAT/2 (LCI, Germany), LTLI (Lys & Optik, Denmark), TBT (Toshiba, Japan), and CEN (European Committee for Standardization).

Fortunately for lighting software developers, the North American and European lighting communities have chosen IES LM-63 and EULUMDAT respectively, and United Kingdom manufacturers have chosen TM14. None of these file formats are ideal, but they have served their purpose for well over a decade.

Ref: IES LM-63-95, *IESNA Standard File Format for Electronic Transfer of Photometric Data*.
ANSI/IESNA LM-63-2001, *IESNA Standard File Format for Electronic Transfer of Photometric Data and Related Information* (to appear).
CIBSE TM14:1988, *CIBSE Standard File Format for the Electronic Transfer of Luminaire Photometric Data*.
Stockmar, A. W. 1990. "EULUMDAT – ein Leuchtendatenformat für den europäischen Beleuchtungplaner," Tagungsband Licht '90, pp. 641–644.
CIE 102-1993, *Recommended File Format for Electronic Transfer of Luminaire Photometric Data*.

2.1.2. IES LM-63-95

IES LM-63-95, "IESNA Standard File Format for Electronic Transfer of Photometric Data and Related Information," is currently used throughout North America for photometric data transfer and storage.

The LM-63-95 file format is presented in Appendix A. This presentation is intentionally incomplete, as many of the details are of interest only to lighting design software developers. For copyright reasons, only the information needed to interpret an existing and valid LM-63-95 data file is included.

Ref: IES LM-63-95, *IESNA Standard File Format for Electronic Transfer of Photometric Data*.

2.1.3. ANSI/IESNA LM-63-2001

IES LM-63-95 will soon be replaced by ANSI/IESNA LM-63-2001, "IESNA Standard File Format for Electronic Transfer of Photometric Data and Related Information."

LM-63-2001 should be compatible with existing lighting design software programs. The only significant changes that may affect backward compatibility are:

a) The first line of the file must be "IESNA:LM-63-2001";
b) All lines can be 256 characters in length;
c) All IESNA LM-63-2001 filenames must have the file extension "ies" or "IES";
d) All TILT filenames must have the file extension "tlt" or "TLT";
e) The definitions of some of the "luminous openings" have been modified; and
f) The allowance for horizontal angles starting at 90 degrees and ending at 270 degrees for Type C photometry has been removed.

Ref: ANSI/IESNA LM-63-2001, *IESNA Standard File Format for Electronic Transfer of Photometric Data and Related Information* (to appear).

2.1.4. EULUMDAT

EULUMDAT is the de facto industry standard photometric data file format for European countries other than the United Kingdom. Without a recognized standards organization to maintain it, EULUMDAT has remained unchanged since its introduction in 1990.

This is likely an indication that EULUMDAT meets the needs of the European lighting industry. Unfortunately, it also means that there is no publication available which officially documents the file format. The only documentation currently available is the on-line specification listed in the references.

The EULUMDAT file format is presented in Appendix B. It is an English language translation of the original German specification. It is also available on-line from www.helios32.com in the Resources section.

It is sometimes necessary to convert EULUMDAT files into equivalent IES LM-63 files. A public domain utility program called *EULUMCNV.EXE* is available from www.helios32.com in the Resources section.

Ref: *EULUMDAT Photometric Data File Format Specification*, www.helios32.com (Resources).
Stockmar, A. W. 1990. “EULUMDAT – ein Leuchtendatenformat für den europäischen Beleuchtungplaner,” Tagungsband Licht ’90, pp. 641–644.

2.1.5. CIBSE TM14:1988

CIBSE TM14:1988 is the official photometric data file format for the United Kingdom.

The TM14 file format is presented in Appendix C. For copyright reasons, only the information needed to interpret an existing and valid TM14:1998 data file is included.

Ref: CIBSE TM14:1988, *CIBSE Standard File Format for the Electronic Transfer of Luminaire Photometric Data*.

2.2. Derived Information

2.2.1. Introduction

There have been innumerable lighting calculation methods and metrics proposed in the literature over the past century. Of these, only a few have been officially recognized by the IESNA, CIE, or CIBSE, and fewer still have withstood the true test of proving useful to lighting designers.

The following subsections provide an overview of the methods and metrics currently recognized and in use.

2.2.2. Lumen Method

The Lumen Method was formerly used to calculate the average illuminance on a workplane in empty rectangular rooms. While the underlying mathematical theory involving radiative transfer theory was daunting, the equations were simple enough to solve by hand (with the help of Coefficients of Utilization tables provided by the luminaire manufacturers).

Today these same calculations are performed with the assistance of lighting design software programs. The advantage of these programs is that they can accurately model partitions and non-rectangular rooms. According to one lighting manufacturer however, over 90 percent of the day-to-day calculations they perform for their clients are for empty rectangular rooms.

Chapter 9 of the *IESNA Lighting Handbook* details the equations for calculating cavity ratios, effective cavity reflectances, luminaire coefficients of utilization, and exitance coefficients.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 9.

2.2.3. Light Loss Factors

Light loss factors are required in lighting calculations to allow for differences between laboratory measurements and installation (field) conditions. They include recoverable losses associated with regular cleaning and maintenance, and non-recoverable losses associated with lamp and luminaire depreciation.

Chapter 9 of the *IESNA Lighting Handbook* details the individual light loss factors that need consideration. These include:

Nonrecoverable	Recoverable
Luminaire ambient temperature factor	Lamp lumen depreciation factor
Heat extraction thermal factor	Luminaire dirt depreciation factor
Voltage-to-luminaire factor	Room surface dirt depreciation factor
Ballast factor	Lamp burnout factor
Ballast-lamp photometric factor	
Equipment operating factor	
Lamp position (tilt) factor	
Luminaire surface depreciation factor	

It should be noted that the ballast-lamp photometric factor was removed from the 1995 revision of IES LM-63 because most lighting manufacturers were incorporating the factor into the ballast factor and setting the ballast-lamp photometric factor to unity in their photometric data reports.

This however was prior to the introduction of T5 fluorescent lamps whose rated lamp lumens are measured at 35° C.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 9.

2.2.4. VCP (Visual Comfort Probability)

The Visual Comfort Probability (VCP) metric predicts the probability that a normal observer will not experience discomfort when viewing a lighting system under defined conditions. (Discomfort glare is the sensation of discomfort caused by luminances that are high relative to the average luminance in the field of view.)

The problem with this metric is that it was designed and tested for lensed direct fluorescent luminaires *only*. To quote the *IESNA Lighting Handbook* (Ninth Edition), “VCP should not be applied to very small sources such as incandescent and high-intensity discharge luminaires, to very large sources such as ceiling and indirect systems, or to nonuniform source such as parabolic reflectors.”

The IESNA Calculation Procedures Committee voted to deprecate VCP in 1995. Unfortunately, the IESNA does not have rules and regulations to cover such actions, and so VCP keeps reappearing in the IESNA literature. On the other hand, nobody appears to be using this metric anymore.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 9.
IES LM-42-72, *Computing Visual Comfort Ratings for Interior Lighting*.

2.2.5. UGR (Unified Glare Rating)

The European counterpart of VCP is the CIE Unified Glare Rating (UGR). It is widely available in European lighting design software. While it cannot be applied to indirect lighting and luminous ceilings, it can be used with most direct lighting sources. The only limitations are that these sources have a solid angular extent between 0.0003 steradian (equivalent to an incandescent downlight viewed from 30 feet) and 0.10 steradian (equivalent to a 3-foot square luminaire viewed from 10 feet).

According to the *IESNA Lighting Handbook* (Eighth *and* Ninth editions), the “IESNA is currently considering UGR for future recommendations.” Given that the IESNA Calculation Procedures Committee was disbanded due to lack of interest in 2000, it is unlikely that this will occur. However, lighting design software programs such as Lighting Analysts’ *AGI32*™ have recently implemented the UGR metric, and so it is available to North American lighting designers.

Ref: CIE 117-1995, *Discomfort Glare in Interior Lighting*.
CIE 112-1994, *Glare Evaluation System for Use within Outdoors Sports and Area Lighting*.

2.2.6. CRI (Color Rendering Index)

The CIE Color Rendering Index (CRI) indicates how well a light source renders eight standard colors compared to perfect reference lamp with the same color temperature. It was developed in 1962 by the IESNA Color Committee to compare fluorescent lamps, and officially adopted by the International Lighting Commission (CIE) in 1964.

The CRI scale ranges from 1 to 100, with 100 representing perfect rendering properties with no visible color shifts. CRI values are generally available from the fluorescent and HID lamp manufacturers.

Ref: CIE 13.3-1995, *Method of Measuring and Specifying Colour Rendering Properties of Light Sources.*

2.2.7. STV (Small Target Visibility)

The Small Target Visibility (STV) criterion is the weighted average of the individual visibilities of an array of small targets on a roadway considering:

a) Target luminance;
b) Immediate background luminance;
c) Adaptation level of the adjacent surroundings; and
d) Disability glare.

The STV metric was introduced with the publication of IES RP-8-00, *Roadway Lighting*. It can be determined for existing installations using field measurements or predicted for roadway designs using appropriate lighting design software.

Ref: IES RP-8-00, *Roadway Lighting*.

2.2.8. Average Luminaire Luminance

Average luminaire luminance values are needed for VCP and UGR calculations. IES LM-37-97 provides useful equations for a variety of common luminaire designs.

These equations will presumably be implemented in the future by lighting design software programs. In theory, they should be able to determine the appropriate equation for a given luminaire based on the luminous opening information contained in its IES LM-63 or CIBSE TM14 photometric data file.

Ref: IES LM-37-97, *Determining Average Luminance for Indoor Luminaires*.

2.3. Future Trends

2.3.1. IESNA LM-73

It has long been recognized that lighting designers need more information from the lighting manufacturers than can be provided within the established photometric data files formats. The IESNA Computer Committee has been working on the development of IES LM-73 for a number of years, and expects to have a completed document ready for publication this year.

In addition to photometric data currently provided by the LM-63 file format, LM-73 will contain manufacturers' information on lamps, ballasts, and controls applicable to the luminaire. It will also optionally contain mechanical drawings and digital photographs.

Whether the lighting industry embraces LM-73 is an open question. It is instructive to note that the author of the EULUMDAT file format published a well-conceived extension called EULUMDAT/2 in 1998. Three years later, the European lighting manufacturers and lighting software developers are still using EULUMDAT.

Ref: Stockmar, A. W. 1998. “EULUMDAT/2 – Extended Version of a Well Established Luminaire Data Format,” *Proceedings of the 1998 CIBSE National Lighting Conference*, pp. 353–362.

2.3.2. Spectral Data

The recent availability of color rendering capabilities in lighting design software has led some lighting designers to consider photometrically accurate color design capabilities. In response, the IESNA Computer Committee is considering an extension to the IES LM-63-2001 photometric data file format that will include spectral power distribution data for both lamps and luminaires. Such an extension would also be included in the forthcoming LM-73.

2.3.3. XML and SOAP

XML is an acronym for Extensible Markup Language, while SOAP is a Microsoft-supported initiative called the Simple Object Access Protocol.

XML is the successor to HTML, the Hypertext Markup Language protocol that made the World Wide Web possible. An XML document is an ASCII text file that conveys whatever information the user chooses. The IESNA Computer Committee is currently investigating the development of XML versions of the LM-63 and LM-73 file formats.

Unlike proprietary file formats such as LM-63 and LM-73, XML can be read by any Web browser. The task of exchanging photometric and related information becomes much simpler, and changes to the file format specification do not need to wait five years between revisions to the published documentation.

SOAP enables programs to exchange XML documents as messages. It may be replaced with another protocol (the common fate of many Microsoft-supported initiatives), but the principle will remain the same: programs automatically exchanging data with other programs without operator intervention.

2.3.4. Distributed Applications

Together, XML and SOAP (or its successor) will enable distributed applications for lighting design, where a program may reside as various components on two or more computers. For example, a simple user interface program on a laptop computer may communicate with a sophisticated CAD program on a vendor’s server to access 3D drawings, download photometric and luminaire data files from several lighting manufacturers’ servers, and then invoke photometric calculation and architectural visualization services on demand from a lighting software company’s server. All of this will be done in a manner that is completely transparent to the user. There will be no concerns about insufficient disk space, missing data files, or software upgrades.

Part III – Lighting Design Software

3.1. Lighting Calculations

3.1.1. Introduction

“Forget the numbers! What is my design going to *look* like?”

Architectus Frustricus

Commercial lighting design software has evolved considerably over the past forty years. What began as time-shared applications on mainframe computers with teletype terminals now provides the ability to both analyze and visualize complex architectural and roadway lighting designs.

It is all too easy for both lighting designers and their clients to be seduced by the photorealistic quality of architectural visualizations, especially if it is what the client expects and wants. However, there is an important and essential difference between lighting design and architectural visualization software: the modeling of light.

Architectural visualization software is a wonderful tool in the hands of a skilled computer artist. However, the renderings can only present the artist's conception of how light behaves in a physical environment.

Until recently, lighting design software was a wonderful *analysis* tool for skilled lighting designers. Given a lighting layout and a geometric representation of an indoor or outdoor environment, it could produce endless tables of numbers and charts that only a lighting designers could love and understand.

Today, lighting design software is also a wonderful *design* tool, regardless of the lighting designer's skill and experience. Given a lighting layout and a geometric representation of an indoor or outdoor environment, it can produce digital images that rival photographs in their realism.

Unlike architectural visualization software, lighting design software models *light*. It relies on physical principles to predict how light will be reflected between and absorbed by surfaces in arbitrarily complex physical environments.

3.1.2. The "Almost" Qualifier

"Doctors can bury their mistakes. Architects can only grow ivy over theirs."

Architectus Frustricus

With the visualization capabilities of lighting design software, what you see in the renderings is (almost) what you will get in the physical environment when the lighting system is installed. If you have a great lighting design, the renderings will show you and your clients what it will look like. If you have a poor design … well, you have an opportunity to improve the design before showing it to your client.

The key point here is the "almost" qualifier. Lighting design software performs computer simulations of how light behaves in a physical environment. Like all computer simulations, it must make a number of simplifying assumptions. The resultant calculations and renderings can be *almost* correct, but only if the underlying assumptions remain valid.

Regardless of which lighting design program you use, it is important to understand these simplifying assumptions and the limitations they impose on the program capabilities.

3.1.3. Radiosity Versus Ray Tracing

Lighting design programs rely on one of two basic approaches to modeling light: radiosity (better known as *radiative flux transfer* in the lighting research community) and ray tracing.

Each approach has its advantages and disadvantages for lighting design, and lighting design programs may employ elements of both approaches for particular purposes. It is meaningless to ask which is better – it depends on what your design requirements are.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 9.

3.2. Radiosity

3.2.1. Introduction

Imagine an empty room with a single ceiling-mounted luminaire (FIG. 8), where each surface is subdivided into an imaginary mesh of elements. When the luminaire is energized, its emitted light will directly illuminate each element of the ceiling, walls, and floor.

Each surface element will absorb some of the light and reflect the rest back into the room. We can follow this indirect light as it bounces from surface element to surface element, keeping track of the total amount of light that is been reflected from each element.

When all of the light has been absorbed by the surface elements, we have the distribution of direct and indirect (that is, reflected) light throughout the room. We know how much light is reflected from each element, and so we can determine its luminance.

This is the radiosity approach to lighting design and analysis. It provides all the information we need to calculate point-by-point illuminance and luminance values, to prepare isolux plots, and to generate photorealistic images of the environment.

Ref: Ashdown, I. 1994. *Radiosity: A Programmer's Perspective*. New York, NY: John Wiley & Sons.

3.2.2. View Independence

The advantage of the radiosity approach is that once the radiosity calculations have been performed, we know the luminance of each surface element. No further radiosity calculations are required to view the environment from any viewpoint. In other words, radiosity is view-independent – using a desktop computer, we can interactively tour the environment in real time.

In principle, the radiosity approach can be used to model any type of surface. In practice, it is mostly limited to modeling ideal diffuse (or *Lambertian*) reflective and transmissive surfaces, where the surface luminance does not change with viewing angle.

Most architectural surfaces can be modeled as ideal diffuse reflectors – surfaces such as matte paint, carpet, ceiling tile, concrete, and so on. However, we also have specular and semi-specular reflectors such as glass and polished wood, stone, and metal to consider.

For most lighting design applications, non-diffuse surfaces are not important. They may contribute to the realism of some architectural renderings (such as reflections from a polished marble floor), but they do not significantly modify the overall distribution of light within the environment.

If necessary, a lighting design program can perform a "post-process" ray-tracing step to add physically realistic reflections and specular highlights to a radiosity-based rendering.

3.2.3. Discretization

Radiosity subdivides each surface into a mesh of elements and calculates the amount of light that is reflected for each "bounce" of light. The amount of time needed to perform these calculations is roughly proportional to the square of the number of elements. For example, if it takes ten minutes to perform radiosity calculations for an architectural interior with 25,000 elements, it may take forty minutes for 50,000 elements and nearly three hours for 100,000 elements.

On the other hand, the accuracy of the lighting calculations generally improves as the number of mesh elements increases. Each mesh imposes a grid of calculation points on the surface for the radiosity calculations. Photometric data such as illuminance and luminance for the surface must be interpolated between these points. If the mesh resolution (that is, the number of elements per unit area) is too coarse, the accuracy of point-by-point photometric values may be compromised.

A coarse mesh also tends to soften shadow details in radiosity-based renderings (FIG. 9). Worse, the shadows tend to follow the surface mesh outline rather than the geometric shadow edges that you would expect.

If you are primarily interested in photometric predictions, a coarse mesh may provide acceptable results while minimizing radiosity calculation times. This is particularly true for indirect lighting designs where the indirect light tends to fill in shadows and smooth luminance distributions across large surfaces. However, for direct lighting designs (and particularly for daylighting applications where direct sunlight is visible), a fine mesh may be needed to capture shadow details on some surfaces.

Apart from increased calculation times, a fine mesh may exhibit a degree of surface mottling in the rendered images (FIG. 10). These aliasing artifacts are particularly noticeable where there is mostly direct light from a single source. (The worst case occurs with façade lighting, where the incident light is at an extremely oblique angle.) If aliasing occurs, the only solution is to decrease the mesh resolution.

Some lighting design programs feature adaptive subdivision of surface meshes. The program examines the differences in luminance between elements of the same surface. If these differences exceed a preset threshold, the two elements (but not the entire mesh) are subdivided to better capture the shadow detail. (Direct sunlight will generally force adaptive subdivision to continue subdividing elements ad infinitum, so that a maximum allowable number of subdivisions per element is usually required.)

Adaptive subdivision has to be used with some care, as the program may silently generate hundreds of thousands of additional elements that will bring the radiosity calculations to a crawl.

Some lighting design programs allow the user to import externally generated CAD drawings and blocks. This can be both a blessing and a curse. While it may be convenient to import complex objects rather than redraw them, these objects may be overly complex. For instance, a door block may include a round door handle with screw mounting details. These details may generate hundreds to thousands of triangular elements that serve no purpose in the radiosity-based calculations. They will have to be removed before the lighting design program can use the block.

There will always be tradeoffs between mesh resolution, calculation times, and image quality. In some radiosity-based lighting design programs, there may be little or no control offered to the user regarding surface mesh properties. Regardless, the results of incorrect meshing will typically be the same.

3.2.4. Shadow Leaks

It is convenient (but not essential) for radiosity-based lighting design programs to group adjacent elements of a planar surface mesh into patches (FIG. 8). The logic is that each element may receive its own light from the environment, but they reflect light back into the environment as a group from the center of the patch. Among other advantages, this technique markedly improves the radiosity calculation times.

However, problems occur when the patch is intersected by another surface. Imagine two rooms with a common floor that a separated by a wall (FIG. 11). The wall is located such that it asymmetrically divides a floor patch.

If only one of the rooms is illuminated, only the floor elements in that room will receive light. However, their reflected light is assumed to be radiated from the center of the patch

– which is in the other room. Thus, even though there is no light source in the second room, it will “receive” light from the first room.

The floor of the illuminated room may also exhibit a shadow leak from the other room. Once the element luminances have been determined, the program needs to smoothly interpolate the surface luminance between elements. It does this by interpolating the surface luminance at the mesh vertices. (The computer graphics hardware performs the additional interpolation needed to display smoothly shaded surfaces.)

Where the wall subdivides an individual element, two of its vertices will be in the first room and the other two in the second room. When the graphics hardware interpolates the surface luminance between these vertices, a shadow leak will occur.

The only solution to both of these problems is to model the floors of both rooms as separate surfaces.

3.2.5. Coplanar Surfaces

Coplanar surfaces occur where both surfaces lie in precisely the same plane and overlap each other (FIG. 12). When these surfaces are displayed, the graphics hardware has to determine which surface is closer to (and hence visible from) the camera.

To do this, the graphics hardware has to calculate the distance from the camera to the surface for each pixel. Because it must do this using finite precision arithmetic, the two surfaces appear at random where they overlap.

A more insidious problem is that the radiosity calculations need to perform the same calculations. Even if two overlapping surfaces are not visible in a rendering of the environment, they may significantly alter the calculated light distribution if their areas are large relative to the environment. (An example would be the common wall of two adjacent offices.)

The solution to this problem is to ensure that surfaces are not coplanar. If necessary, a hole should be cut in one of the surfaces to avoid overlap.

3.2.6. Convergence

Another advantage of radiosity-based light designs programs is that they can generate photorealistic images within seconds of initiating the radiosity calculations. The disadvantage is that while the displayed images may look photorealistic, they are not photometrically correct or even accurate.

Each step of the radiosity calculations represents a single “bounce” of reflected light from one patch to the rest of the environment. Generally the patch with the most amount of light waiting to be reflected is chosen for each step.

An image can be displayed after each step, but it must be recognized that some of the light is still unaccounted for in the displayed image.

The lighting design program may display a “percent completion” or convergence value while the radiosity calculations are being performed. The convergence is the amount of light still waiting to be absorbed. (The percent completion value may instead represent the fraction of the total number of steps that have been completed.)

The three images in FIG. 13 illustrate the changes in the images for different convergence values. As more bounces occur, the overall images become brighter. More important, the shadow details change as reflected light from different directions in reflected onto the shadowed surface elements.

As a rule of thumb, reasonably accurate visual images are available when 75 to 80 percent of the light has been absorbed, corresponding to a convergence value 0.25 to

0.20. (This scale will be reversed for percent completion values.) However, any photometric values will still be low by (on average) 20 to 25 percent. If you require photometric accuracies to within five percent, you will have to allow the radiosity calculations to reach five percent convergence.

The convergence value is a *global* average. If you need to determine for example the illuminance of a deep stairwell or long, poorly illuminated corridor, you will need to allow the radiosity calculations to run until the illuminance at the point of interest no longer changes significantly. Depending on the environment geometry and surface reflectances, this may take a very long time.

3.2.7. Light Sources

Radiosity-based lighting design programs typically model physical luminaires as a point light source. This works well for direct luminaires, but fails for indirect linear fluorescent luminaires and cove lighting (FIG. 14).

For these cases the program should subdivide the luminaire into an array of point sources. This can be done by the program automatically based on the distance to the nearest surface element, although some programs may require the user to manually set a subdivision parameter.

The program should also allow the user to specify (either automatically or manually) that the luminaire housing is transparent to the light emitted directly by the luminaire. The housing has already been considered by the photometric measurements of the physical luminaire.

3.2.8. Color Bleeding

Radiosity-based programs accurately model color bleeding, where the color of a brightly colored surface appears to bleed onto adjacent neutrally colored surfaces (FIG. 15).

The problem with this capability is that the results often contradict our intuition about how light and color should look in a given environment. In particular, the images often appear to be overly saturated.

The truth is that the human visual system is particularly adept at compensating for color casts. We look at a white wall and see “white,” even though the illuminant may vary from a 100-watt incandescent lamp to blue skylight. The color bleeding effects calculated by radiosity-based programs are photometrically accurate, and are what a spectrophotometer would measure in a physical environment.

3.3. Ray Tracing

3.3.1. Introduction

Once again, imagine an empty room with a single ceiling-mounted luminaire (FIG. 16). When the luminaire is energized, its emitted light will directly illuminate the ceiling, walls, and floor. Unlike the radiosity approach, we do not need a mesh of elements for each surface. Instead, we have geometric rays of light that each have an initial amount of energy.

Each opaque surface will absorb some energy from the rays and reflect the ray back into the room. Transparent surfaces will also absorb some energy, but they will instead refract and transmit the rays.

We can place a virtual camera at any position and orientation in the room and record the rays to generate an image. We can also substitute a photometer to measure illuminance or luminance.

This is the ray tracing approach to lighting design and analysis. Like the radiosity approach, it provides all the information we need to calculate point-by-point illuminance and luminance values, to prepare isolux plots, and to generate photorealistic images of the environment.

The ray tracing approach is generally slower than radiosity, especially for complex environments with many light sources. However, it has the ability to generate more realistic images, which is an advantage for architectural visualization and glare analysis studies.

Ref: Larson, G. W., and R. Shakespeare. 1998. *Rendering with Radiance: The Art and Science of Lighting Visualization*. San Francisco, CA: Morgan Kaufmann.

3.3.2. View Dependence

The brute force ray tracing approach described above needs to trace trillions of rays to ensure that enough rays will be seen by the camera or photometer. To overcome this problem, we can instead trace rays *backward* from the camera or photometer into the environment. We then need to consider only those rays that will be seen – millions instead of trillions.

The advantage of backward ray tracing is that it correctly and efficiently models any type of surface, including those with specular and semi-specular reflectance properties. For architectural visualization applications, ray tracing can provide extremely photorealistic renderings of glass and polished wood, stone, and metal.

The use of backward ray tracing means that the approach is view dependent. That is, a new set of rays must be traced for each camera or photometer position and orientation.

3.3.3. Number of Rays

The accuracy of a ray traced image or photometric prediction depends on the number of rays that are traced. Whereas the radiosity approach bounces light with each calculation step, ray tracing distributes the emitted light according to the paths each ray has traced.

The result is that the initial images (if the program to designed to generate them) look very grainy (FIG. 17). If isolux plots are plotted for a given surface, the contours will vary at random. As more and more rays are traced, the graininess (or image noise) decreases and the plots become smoother.

There is no equivalent to the radiosity convergence value for the ray tracing approach. All that can be done is to trace a sufficient number of rays to ensure that tracing further rays does not significantly change the image quality or photometric predictions. Unfortunately, the number of rays will depend on the environment, and the optimum number can only determined through experience.

Ray tracing programs also offer the option to limit the number of bounces for each ray, and for the number of additional rays that may be generated for each bounce from diffuse reflectance surfaces. Again, the optimal settings for these parameters will depend on the environment, and they can only be determined through experience.

3.3.4. RADIANCE

The premier lighting design program is the freely available *Radiance Lighting Simulation and Rendering System*. If you choose to master – and there is no other appropriate verb – this software tool, then you will need the book *Rendering with Radiance* to guide you through its innumerable settings and options.

Other ray tracing programs for lighting design will have their own settings and options to consider. Without knowing the details of the calculation methods used by these programs (and Radiance stands alone in being fully and exhaustively documented), it is impossible to make any generic comments regarding program use.

Ref: Larson, G. W., and R. Shakespeare. 1998. *Rendering with Radiance: The Art and Science of Lighting Visualization*. San Francisco, CA: Morgan Kaufmann.

3.4. Validation Issues

3.4.1. Introduction

Validation of lighting design software is difficult problem. The first comprehensive study was done at the University of Colorado at Boulder in 1988, where an empty room was prepared with freshly painted walls of known reflectance, and with luminaires and lamps with carefully measured photometric characteristics. Illuminance readings were then taken on a grid for each surface with a calibrated photometer.

Numerous other similar studies have since been done by various academic research groups, but there have not been any studies done of more complex environments. One reason is that the experiments are time consuming and expensive to perform; another is that it is difficult to decide on what constitutes a complex yet realistic and meaningful environment.

3.4.2. IESNA and CIE

The IESNA Computer Committee attempted to develop of suite of standard test environments in the early 1990s. This effort was abandoned when it became apparent that the number of environments to be considered would exceed the resources of any academic research institute to experimentally validate.

The CIE has several technical committees working on various aspects of lighting design software validation, including:

a) TC 3-11 Daylighting Calculation Methods
b) TC 3-29 Computer Procedures for Lighting Metrics and Visualization
c) TC 3-31 Electric Lighting for Real Spaces
d) TC 3-32 Validation of Algorithms for Daylight Outdoors
e) TC 3-33 Test Cases for Assessment of Accuracy of Lighting Computer Programs

As one of the committee chairs recently remarked however, most lighting software developers are reluctant to discuss their proprietary calculation algorithms and techniques. Without this information, it is difficult to compare the accuracy of lighting design programs.

In defense of the lighting software developers, each program has its strengths and weaknesses with respect to any given application. A program that has been optimized for rapid calculations of simple environments with a few luminaires, for example, may not compare favorably with programs designed to handle complex environments with hundreds to thousands of luminaires.

More subtle issues include how radiosity programs perform surface meshing, how ray tracing programs statistically analyze ray distributions, how the programs interpret photometric data files, and a thousand other minutiae. Given a suite of test cases, each program will produce different results, and in some cases may fail spectacularly.

Lighting software developers should welcome an IESNA or CIE recommended suite of test cases for both indoor and outdoor lighting designs if (and only if) they represent the results of carefully controlled measurements in real environments. Even so, the issues of non-diffuse surface reflectances and surface colors (which most lighting design programs cannot handle effectively) will complicate the interpretation of any results.

3.4.3. How Accurate?

The most important question: what degree of accuracy can we expect from lighting design programs? Unfortunately, the answer is "it depends."

The Joint Lighting Survey Committee of the Illuminating Engineering Society and the U.S. Public Health Service performed workplane illuminance measurements in eleven different empty rooms under actual conditions of use. Their conclusions were that the simple Lumen Method predicted illuminance values that were within 10 percent of those measured. However, they noted that "larger errors can be expected for spaces with unusual room cavity ratios or poor uniformity."

Slater (1989) performed a fastidious and exhaustive study of direct and indirect lighting in empty rooms. His conclusions were that radiosity-based lighting design programs should be expected to produce results that are accurate on average to within ±10 percent for direct lighting systems and ±20 percent for indirect lighting systems. (Although Slater did not explicitly say so, the larger error range for the indirect lighting systems was probably due mostly to near-field versus far-field photometry.)

These results assume that all luminaire photometric characteristics and room surface reflectances are known. Chari and Chakraborty (1989) considered the situation where this is not the case (which is almost always the case). They concluded that indoor lighting designs are accurate (for empty rooms) to within 4 to 8 percent, while outdoor lighting designs are accurate to within 10 to 22 percent. (Given the results for the other studies, these estimates may be too optimistic.)

Previous editions of the IESNA Lighting Handbook used to provide a long and detailed checklist of factors to consider when performing field measurements of installed lighting systems. It included photometer calibration, ambient temperature, luminaire voltage, ballast-lamp photometric factors, lamp burn-in and other light loss factors, surface reflectances, windows and doors, partitions and obstructions, accurate photometric data reports, and other issues.

Daylighting predictions are another issue altogether. Ubbeholde and Humann (1998) compared lighting design software predictions with illuminance measurements for an existing atrium for overcast and clear sky conditions. The results were somewhat disturbing. Point-by point errors for clear sky conditions were as much as 18 times, and for overcast sky conditions as much as 10 times the measured values. Much worse, the average error for clear sky conditions was about 10 times for two of the programs.

The question is whether to accept or ignore these results as being anomalous. As a counterexample, Bellia et al. (1994) compared two of the daylighting analysis programs investigated by Ubbeholde and Humann and found the error of their predictions to be less than 200 percent on average.

Both daylighting studies appear to be have been reasonably well designed and documented; the only apparent difference is that they used very different "empty rooms" for their models and measurements.

A better yardstick however comes from one of the commercial software developers, who had the benefit of understanding the inner workings of the program in question and its limitations. Jongewaard (1993) made the crucial observation that "when the luminances outside of the room can be determined accurately, the interior luminances can, in turn, be determined accurately." His validation experiments with scale models demonstrated prediction errors of less than ±8 percent.

One major problem is that the calculations are necessarily based on the various CIE or IESNA sky models, which predict illuminances based on average sky conditions. It is not uncommon for instantaneous measured illuminances to be more than twice or less than half of the mean illuminances predicted by clear and overcast sky models; the situation for partly cloudy skies is even worse.

Daylight calculations are also dependent on light that is reflected from outdoor surfaces. For example, sunlight that is specularly or even diffusely reflected from an adjacent building may act as a secondary directional light source. Unless these surfaces are included in the model, the accuracy of the daylight calculations may be severely compromised.

The results of Ubbelohde and Humann (1998) were for an existing building. Their CAD model pointedly did not include the exterior street environment. Given that daylight apparently entered the building mostly from one side, this may partially explain their results. (There are other factors, as explained in Jongewaard 1998 – high and narrow atriums can present a challenging problem for radiosity-based lighting design programs.)

To summarize, it is probably reasonable to accept Slater's estimate of ±10 percent accuracy for direct lighting systems, and ±20 percent for indirect lighting systems. For roadway lighting based mostly on direct illumination, perhaps ±10 percent accuracy should be expected.

None of these estimates, however, should be blindly accepted for complex environments with windows, mirrored walls, partitions and furniture, strongly colored or highly specular surfaces, non-uniform lighting, and other complicating factors. Lighting design programs can only be as accurate as the input data they are given to work with, and should be used with care and some skepticism in unusual situations.

As for daylighting calculations, it is likely that Jongewaard (1993) is correct – the results are only as accurate as the accuracy of the input data. Done with care, it should be possible to obtain ±20 percent accuracy in the photometric predictions. However, this requires detailed knowledge and accurate modeling of both the indoor and outdoor environments. If this cannot be done, it may be advisable to walk softly and carry a calibrated photometer.

Ref: *IESNA Lighting Handbook*, Ninth Edition, Chapter 2.

Bellia, L., A. Cesarano, and S. Sibilio. 1994. "Daylight Contribution in Interior Lighting: Experimental Verification of Software Simulation Results," *International Journal of Lighting Research & Technology* 26(2):99-105

Chari, N. S., and S. Chakraborty. 1989. "Discrepancies in Measurement of Light in Laboratory and Field," *Proceedings of Lux Europa VI*.

DiLaura, D. L., D. P. Igoe, P. G. Samara, and A. M. Smith. 1988. "Verifying the Applicability of Computer Generated Pictures to Lighting Design," *Journal of the Illuminating Engineering Society* 17(1):36–61.

Joint Lighting Survey Committee of the Illuminating Engineering Society and the U.S. Public Health Service. 1963. "How to Make A Lighting Survey," *Illuminating Engineering* 57(2):87–100.

Jongewaard, M. P. 1993. "Daylight Calculations, Measurements and Visualization in Non-Empty Rooms," *Proceedings of Lux Europa 1993*, pp. 43–52.

Slater, A. I. 1989. "Illuminance Distributions: Prediction for Uniform and Non-Uniform Lighting," *International Journal of Lighting Research & Technology* 21(4):133–138.

Ubbelohde, M. S., and C. Humann. 1998. "A Comparative Evaluation of Daylighting Software: SuperLite, Lumen Micro, Lightscape and Radiance," *Proceedings of the International Daylighting Conference* (Daylighting '98), pp. 97–104.

3.5. Visualization

3.5.1. Introduction

When we look at the “photorealistic” images generated by lighting design and architectural visualization programs, we are not comparing them to physical environments. Rather, we are unconsciously comparing them to color photographs and full-color glossy magazine illustrations.

The color photographs we see reproduced in professional lighting magazines are not what the camera sees, and certainly not what we see. The colors are not the same, the contrast range and scale have been changed, the ambient lighting conditions are different, and the visual surround is completely different.

3.5.2. RGB Color Models

With the exception of a research-oriented lighting design and simulation program called *Genelux* (www.genelux.entpe.fr), all lighting design software program that generate color images use the RGB (red/green/blue) color model.

It is possible to simulate the appearance of (almost) any color using additive combinations of red, green, and blue light. This is the basis of color monitors for television and computers, with their red, green, and blue pixels. (Color photographs and magazine illustrations use subtractive combinations of complementary magenta, yellow, and cyan colors.)

Lighting design programs such as *Radiance*, Lighting Analysts’ *AGI32*, and Lighting Technologies’ *Lumen Micro 2000* (among others) model surface and light source colors as various percentages of red, green, and blue. They then calculate the distribution of light in an environment three times (once for each color) before combining the results to generate color images.

The problem with this approach is that it is difficult to accurately simulate the distribution of light for strongly colored light sources and materials. Consider a mercury vapor lamp illuminating a green fabric. The lamp has strong spectral peaks throughout its emission spectrum, but essentially nothing between 450 and 530 nanometers (which covers most of the green part of the spectrum). The fabric, on the other hand, may only reflect light within this color band (FIG. 18). Viewed under the lamp, the fabric will appear almost black.

The lamp color can be convincingly modeled with a suitable combination of blue and green. Similarly, the fabric color can be convincingly modeled using mostly green. This means however that the lighting calculations will show the green fabric reflecting a high percentage of the light emitted by the mercury vapor lamp!

The only solution to this problem is to divide the spectrum into narrow bands – say 80 bands that are each five nanometer wide – and perform lighting calculations for each band. The lighting calculations will proceed very slowly, but there is no other means of accurately calculating color in lighting design.

3.5.3. Texture Maps

While it can be argued that specular reflections and highlights produced by ray tracing add realism to computer-generated images, even more realism can be added by the judicious use of texture maps. (FIG. 19).

Texture maps are typically digitized photographs of physical surfaces, such as bricks, wood, and fabric that can be “applied” to surfaces in the environment using computer graphics techniques.

Texture maps generally do not affect the time for the radiosity or ray tracing calculations, and they do not significantly affect the accuracy of the photometric predictions.

3.5.4. Scotopic Vision

The sensitivity of our visual system changes, depending on the average luminance in our field of view. As the ambient light level decreases, we slowly lose our ability to perceive color, and our visual acuity and contrast sensitivity decreases. Glare from bright light sources also becomes a problem. At low (nighttime) light levels our vision changes from photopic to scotopic.

All of these visual effects have been modeled by computer graphics researchers, and they have been implemented in *Radiance* for scotopic visualization studies. However, they have yet to be implemented in most other commercial lighting design software products.

3.6. Miscellaneous

3.6.1. Luminous Shape

The three photometric data file formats discussed here – IESNA LM-63, EULUMDAT, and CIBSE TM-14 – include a "luminous shape" description that is used by lighting design software programs.

In each case, the "luminous shape" refers to the three-dimensional extent of the luminous portion of the luminaire; it does not refer to the overall physical dimensions. This can lead to some interesting problems for the lighting manufacturer and the lighting design software developer.

Most lighting design software programs need to know at least the length and width of the luminous shape. Radiosity-based programs use this information to subdivide the luminaire into an array of point sources, while ray tracing programs use it to determine where to emit light rays for direct illumination.

3.6.1.1. IESNA LM-63

IESNA LM-63 specifies the length, width, and height of the luminous shape. This shape was originally assumed to be a simple rectangular box. However, later versions of the file format added points, rectangles, circles, ellipses, spheres, circular and ellipsoidal cylinders, spheres, and ellipsoidal spheroids in various orientations.

Many lighting manufacturers model their luminaires as rectangular boxes, while a few opt for dimensionless points. Unfortunately, this latter choice may cause problems for lighting design software programs. It is occasionally necessary to edit IESNA LM-63 photometric data files by hand with a text editor so that at least the width and length values are non-zero. (See Appendix A for the IESNA LM-63-95 file format description.)

Ref: IES LM-63-95, *IESNA Standard File Format for Electronic Transfer of Photometric Data*.

3.6.1.2. EULUMDAT

Like IESNA LM-63, EULUMDAT specifies the length and width of the luminous shape (which it calls the "luminous area") in millimeters. However, it specifies four independent heights for this area, measured in the 0-, 90-, 180-, and 270-degree vertical plane.

Ref: *EULUMDAT Photometric Data File Format Specification*, www.helios32.com (Resources).
Stockmar, A. W. 1990. "EULUMDAT – ein Leuchtendatenformat für den europäischen Beleuchtungplaner," Tagungsband Licht '90, pp. 641–644.

3.6.1.3. CIBSE TM-14

CIBSE TM-14 takes a somewhat different approach by specifying a “glare shape code” that indicates a rectangular box, sphere, vertical cylinder of flat disk, horizontal cylinder, or “any other shape.” It then specifies the projected luminous areas of the base, side, and end of the luminaire.

While this information is useful for CIE Unified Glare Rating (UGR) calculations, it is difficult to interpret for use with lighting design software programs.

CIBSE TM14:1988, *CIBSE Standard File Format for the Electronic Transfer of Luminaire Photometric Data*.

3.6.2. Luminaire Orientation and Position

Given a luminaire with an asymmetric luminous flux distribution (such as a fluorescent wall-washer), it is essential to orient the luminaire correctly in a CAD model. Unfortunately, this can be more difficult than you might expect.

The first problem is that the various IESNA LM-series documents provide contradictory specifications on how the photometric web is to be oriented with respect to the physical outline of a luminaire.

For example, IESNA LM-63-95 implies (but does not specify) that the 0–180 degree vertical plane of the photometric web is oriented parallel to the lamp axis of linear fluorescent luminaires. If the luminous flux distribution is bilaterally symmetric about the 90–270 degree vertical plane (that is, perpendicular to the lamp axis), then the horizontal angles must be reported from 90 to 270 degrees.

However, IESNA LM-41-98 recommends (but does not specify) that the photometric web for such luminaires be oriented perpendicular to the lamp axis, with 0 degrees being the “beam side.”

Most (but not all) fluorescent lighting manufacturers have ignored IESNA LM-63-95 and followed the recommendation of IESNA LM-41-98. This means that the lighting design software program user must manually examine the IESNA LM-63 text file to see whether the photometric web is oriented parallel or perpendicular to the lamps axis. If this information is not stated in the file header, the user may have to contact the luminaire manufacturer.

The second problem is that the “beam side” of a wall washer may point towards or away from the wall. Again, it may not be possible to determine this information from the IESNA LM-63 text file.

In Europe, most luminaires are tested in accordance with CIE 121-1996. Unfortunately, the situation for luminaire whose luminous flux distribution is bilaterally symmetric about the 90–270 degree vertical plane is even more ambiguous. Because EULUMDAT is a *de facto* industry standard without any accompanying documentation, it is not possible to determine what the photometric web orientation is with respect to the physical luminaire geometry.

The third problem is that the luminous shape is assumed to be centered on the “photometric center” of the luminaire. This is defined in CIE 121-1996 as “the point in a luminaire or lamp from which the photometric distance law operates most closely in the direction of maximum intensity.” Unfortunately, it does not say how this is determined.

IES LM-41-98 is more specific. It notes that the photometric center (which it calls the photometric “centroid”) is located as follows:

Luminaire Type	Luminous Flux Distribution	Photometric Center
Recessed	Direct	Ceiling plane
Suspended	Direct	Luminous opening
Suspended	Indirect	Luminous opening
Suspended	Direct / Indirect	Luminaire centroid
Suspended	Exposed lamps	Geometric center of lamp(s)
Surface-mount	Direct	Luminous opening
Surface-mount	Other	Geometric center of lamp(s)

Unfortunately, this information is not included in the IESNA LM-63-95 photometric data file format. (It will however be included in the forthcoming IESNA LM-63-2001 under the keyword LAMPPOSITION.) The light design software user can only assume that these guidelines were followed when the photometric tests were performed.

For most lighting design applications involving suspended luminaires, it usually does not matter whether the photometric center is misaligned an inch or so from its physical location within the CAD model. The ceiling luminance distribution calculations may be affected, but the errors will be well within the uncertainties due applying far-field photometric measurements (see Section 1.3, *Near-Field Photometry*).

The situation for recessed and surface-mounted luminaires is very different. If the lighting design software program includes visualization capabilities, it will probably allow the user to model the physical outline of the luminaire and specify a position and orientation for the luminous shape within it.

It is extremely important in this situation to ensure that the luminous shape is located below the ceiling plane in the room. Otherwise, if the ceiling surface is “two-sided” (that is, it is opaque when viewed from both sides in the CAD model), it will block the light emitted by the luminaire.

This problem will be obvious if the photometric center is located above the ceiling plane. However, if it is coincident with the ceiling plane, this becomes another example of the coplanar surface problem (see Section 3.2.5, *Coplanar Surfaces*). Whether the light is blocked by the ceiling will depend on floating point round-off errors, which in practice means that the problem will occur randomly. It may not even be evident in a large open room with many luminaires unless you look closely at the isolux distribution plots for the floor.

Luminaire orientation and positioning is an important issue for lighting design software users. The best advice is to be very careful. In particular, do not make assumptions regarding the photometric web orientation for wall washer and similar luminaires, and be careful when positioning recessed and surface-mounted luminaires

Ref: CIE 121-1996, *The Photometry and Goniophotometry of Luminaires*.
IES LM-41-98, *Photometric Testing of Indoor Fluorescent Luminaires.*
IES LM-63-95, *IESNA Standard File Format for Electronic Transfer of Photometric Data*.
ANSI/IESNA LM-63-2001, *IESNA Standard File Format for Electronic Transfer of Photometric Data and Related Information* (to appear).

3.7. Future Trends

3.7.1. Validation

There are currently no standardized test suites against which the photometric predictions of light design software can be compared. While it may be difficult to prepare and experimentally measure suitable test environments, this work will eventually have to be done by an independent agency.

3.7.2. Image Analysis

Lighting design software is currently used to perform traditional photometric calculations such as workplane and ceiling illuminance distributions. However, it is also possible to perform CIE Unified Glare Rating (UGR) calculations. (This is already done by some commercial European lighting software products.)

Considerable research is currently being done on developing better glare and lighting quality metrics. It would not be difficult to implement these metrics within lighting design software programs. One advantage would be that the software could automatically generate and analyze images, and warn the lighting designer if any views of the environment do not meet lighting quality requirements.

3.7.3. Distributed Applications

Lighting design software currently exists as standalone programs on personal computers. These will likely be replaced in the near future with distributed applications that exist as software modules and manufacturers' data on one or more remote Web servers. From the beginning of lighting design software as time-shared applications on remote mainframe computers, we will have come full circle.

3.7.4. Virtual Reality

Will lighting design become a shared experience between light designer and client with virtual reality headsets? Not in the near future – we have too many other exciting opportunities to explore.

Appendix A – IES LM-63-95 Photometric Data File Format

The IES LM-63-95 photometric data file format was developed by the Illuminating Engineering Society of North America. The following is an abbreviated description intended for interpretation of existing and valid LM-63-95 files only.

This file format will soon be superceded by ANSI/IESNA LM-63-2001, *IESNA Standard File Format for the Electronic Transfer of Photometric Data and Related Information*. A printed version of this document will be available from:

Illuminating Engineering Society of North America
120 Wall Street, 17th Floor
New York, NY 10005

URL: www.iesna.org

Identifier	Description
01	IESNA:LM-63-1995
02	<Keyword 1>
03	<Keyword 2>
04	...
05	<Keyword n>
06	TILT=<file-spec> or <INCLUDE> or <NONE>
07	<lamp-to-luminaire geometry>
08	<# of pairs of angles and multiplying factors>
09	<angles>
10	<multiplying factors>
11	<# of lamps> <lumens per lamp> <candela multiplier> <# of vertical angles><# of horizontal angles> <photometric type> <units type> <width> <length> <height>
12	<ballast factor> <future use> <input watts>
13	<vertical angles>
14	<horizontal angles>
15	<candela values for all vertical angles at first horizontal angle>
16	<candela values for all vertical angles at second horizontal angle>
17	...
18	<candela values for all vertical angles at nth horizontal angle>

The following is an example of an IES LM-63-95 photometric data file (adapted from IES LM-63-95):

```
IESNA:LM-63-1995
[TEST] ABC1234 ABC Laboratories
[MANUFAC] Aardvark Lighting Inc.
[LUMCAT] SKYVIEW 123-XYZ-abs-400
[LUMINAIRE] Wide beam flood to be used without tilt
[LAMPCAT] MH-400-CLEAR
[LAMP] Metal Halide 400 watt
[BALLASTCAT] Global 16G6031-17R
[BALLAST] 400W 277V MH
[MAINTCAT] 4
[OTHER] This luminaire is useful as an indirect flood
[MORE] and to reduce light pollution in down light
[MORE] applications.
[SEARCH] POLLUTION SPORTS INDIRECT
[BLOCK]
```

```
[LUMCAT] TENNISVIEW 123-XYZ-abc-400
[LUMINAIRE] Wide beam flood for indirect applications.
[ENDBLOCK]
TILT=INCLUDE
1
13
0 15 30 45 60 75 90 105 120 135 150 165 180
1.0 .95 .94 .90 .88 .87 .98 .87 .88 .90 .94 .95 1.0
1 50000 1 5 3 1 1 .5 .6 0
1.0 1.0 495
0 22.5 45 67.5 90
0 45 90
10000 50000 25000 10000 5000
10000 35000 16000 8000 3000
10000 20000 10000 5000 1000
```

NOTES

1. All data is stored in ASCII format.
2. The maximum length of any label / keyword line (including the <CR><LF> terminating pair) is 82 characters. The maximum length of any other line (including the <CR><LF> terminating pair) is 132 characters.
3. Label lines (02 to 05 inclusive) contain descriptive text about the luminaire, the lamp(s) used, and other descriptive comments.
4. Each label line begins with a defined IES keyword in square brackets. (User-defined keywords are also permitted.) The suggested minimum is:

[TEST]	Test report number and laboratory
[MANUFAC]	Luminaire manufacturer
[LUMCAT]	Luminaire catalog number
[LUMINAIRE]	Luminaire description
[LAMPCAT]	Lamp catalog number
[LAMP]	Lamp description

5. The "TILT=" line uniquely delimits the end of label / keyword lines in the photometric data file. There are three variants of this line: "TILT=NONE", "TILT=INCLUDE", and TILT=<filename>".
6. If “TILT=NONE” is present, the lines:
   <lamp-to-luminaire geometry>
   <# of pairs of angles and multiplying factors>
   <angles>
   <multiplying factors>
   do not appear in the photometric data file.
7. If “TILT=INCLUDE” is present, the lines:
   <lamp-to-luminaire geometry>
   <# of pairs of angles and multiplying factors>
   <angles>
   <multiplying factors>
   appear in the photometric data file.
8. If “TILT=<filename>” is present (where <filename> is a valid file name), the lines:
   <lamp-to-luminaire geometry>
   <# of pairs of angles and multiplying factors>
   <angles>
   <multiplying factors>
   do not appear in the photometric data file. However, they are present in the identified and separate TILT photometric data file.
9. The <lamp-to-luminaire geometry> value (07) indicates the orientation of the lamp within the luminaire. It will be one of:

1 Lamp base is either vertical base up or vertical base down when the luminaire is aimed straight down.
2 Lamp is horizontal and remains horizontal when the luminaire is aimed straight down or rotated about the zero-degree horizontal plane.
3 Lamp is horizontal when the luminaire is pointed straight down, but does not remains horizontal when the luminaire is rotated about the zero-degree horizontal plane.

The <lamp-to-luminaire geometry> line is absent if "TILT=NONE".

10. The <# of pairs of angles and multiplying factors> (08) value indicates the total number of lamp tilt angles and their corresponding candela multiplying factors. It is absent if "TILT=NONE".
11. The tilt <angles> line (09) enumerates the lamp tilt angles. It is absent if "TILT=NONE".
12. The tilt <multiplying factors> line (10) enumerates the candela multiplying factors for the corresponding lamp tilt angles. It is absent if :TILT=NONE".
13. The <# of lamps> value (11) indicates the total number of lamps in the luminaire.
14. The <lumens per lamp> value (11) indicates the rated lumens per lamp on which the photometric test was based. If the luminaire has two or more lamps with different rated lumens per lamp, this value represents the average lumens per lamp for the luminaire.
15. The <candela multiplier> value (11) value indicates a multiplying factor that is to be applied to all candela values in the photometric data file (15 to 18 inclusive).
16. The <# of vertical angles> value (11) indicates the total number of vertical angles in the photometric data.
17. The <# of horizontal angles> value (11) indicates the total number of horizontal angles in the photometric data.
18. The <photometric type> value (11) indicates the type of photometric web used for the photometric measurements. It is one of:
    1 Type C photometry
    2 Type B photometry
    3 Type A photometry
19. The <units type > value (11) indicates the units used for the dimensions of the luminous opening in the luminaire. It is one of:
    1 Feet
    2 Meters
20. The <width> value (11) indicates the distance across the luminous opening of the luminaire as measured along the 90-270 degree photometric plane.
21. The <length> value (11) indicates the distance across the luminous opening of the luminaire as measured along the 0-180 degree photometric plane.
22. The <height> value (11) indicates the average height of the luminous opening of the luminaire as measured along the vertical axis.
23. The luminous opening is normally considered to be rectangular. However, other predefined shapes can be modeled by specifying one or more of the above dimensions as zero or negative floating point numbers as follows:

Width	Length	Height	Description
0	0	0	Point
W	L	H	Rectangular (default)
–D	0	0	Circular (where d = diameter of circle)
–D	0	–D	Sphere (where d = diameter of sphere)
–D	0	H	Vertical cylinder (where d = diameter of cylinder)
0	L	–D	Horizontal cylinder oriented along luminaire length
W	0	–D	Horizontal cylinder oriented along luminaire width
–W	L	H	Ellipse oriented along luminaire length
W	–L	H	Ellipse oriented along luminaire width

–W	L	–H	Ellipsoid oriented along luminaire length
W	–L	–H	Ellipsoid oriented along luminaire width

24. The <ballast factor> value (12) indicates the ratio of the lamp lumens when operated on a commercially-available ballast, to the rated lamp lumens as measured by the lamp manufacturer using a standard (reference) ballast. All candela values in the photometric data file (15 through 18) must be multiplied by the ballast factor before the candela values are used in an application program.
25. The <future use> value (12) is reserved for future use.
26. The <input watts> value (12) indicates the total power (measured in watts) consumed by the luminaire, as measured during the photometric test.
27. The <vertical angles> values enumerate the vertical angles.
28. For Type C photometry, the first vertical angle will be either 0 or 90 degrees, and the last vertical angle will be either 90 or 180 degrees.
29. For Type A or B photometry, the first vertical angle will be either –90 or 0 degrees, and the last vertical angle will be 90 degrees.
30. The <horizontal angles> values enumerate the horizontal angles.
31. For Type C photometry, the first value is (almost) always 0 degrees, and the last value is one of the following:
    - 0 There is only one horizontal angle, implying that the luminaire is laterally symmetric in all photometric planes.
    - 90 The luminaire is assumed to be symmetric in each quadrant.
    - 180 The luminaire is assumed to be bilaterally symmetric about the 0-180 degree photometric plane.
    - 360 The luminaire is assumed to exhibit no lateral symmetry
32. A luminaire that is bilaterally symmetric about the 90-270 degree photometric plane will have a first value of 90 degrees and a last value of 270 degrees.
33. For Type A or B photometry where the luminaire is laterally symmetric about a vertical reference plane, the first horizontal angle will be 0 degrees, and the last horizontal angle will be 90 degrees.
34. For Type A or B photometry where the luminaire is not laterally symmetric about a vertical reference plane, the first horizontal angle will be -90 degrees, and the last horizontal angle will be 90 degrees.
35. The <candela values> (15 to 18 inclusive) enumerate the measured values. There is one line for each corresponding horizontal angle, and one candela value for each corresponding vertical angle.

Appendix B – EULUMDAT Photometric Data File Format

The following photometric data file format was developed by Axel Stockmar of LCI Light Consult International (Berlin, Germany). It is become the de facto photometric data file format for most European lighting manufacturers.

Thanks to Dag Barosen of Fjellanger Wideroe AS (Trondheim, Norway) for providing most of the information contained in this translation of the original German specification.

PROPOSAL FOR A DATA FORMAT FOR EXCHANGE OF LUMINAIRE DATA (INTERIOR, EXTERIOR, AND/OR ROAD LIGHTING LUMINAIRES) UNDER THE OPERATING SYSTEMS MS-DOS 2.xx/3.xx UNDER CONDITION OF UNEQUIVOCAL COORDINATION BETWEEN LUMINAIRE AND DATA SET.

NOTE: Each of the following fields is an ASCII string that is terminated with an MS-DOS <CR><LF> pair.

```
Item Designation                                          Number of characters
------------------------------------------------------------------------------
 1   Company identification/data bank/version/format identification     max. 78
 2   Type indicator Ityp 1 ... point source with symmetry                     1
                               about the vertical axis
                         2 ... linear luminaire
                         3 ... point source with any other symmetry
                               (only linear luminaires, Ityp = 2,
                               are being subdivided in longitudinal
                               and transverse directions)
 3   Symmetry indicator Isym   0 ... no symmetry                              1
                               1 ... symmetry about the vertical axis
                               2 ... symmetry to plane C0-C180
                               3 ... symmetry to plane C90-C270
                               4 ... symmetry to plane C0-C180 and
                                     to plane C90-C270
 4   Number Mc of C-planes between 0 and 360 degrees                          2
     (usually 24 for interior, 36 for road lighting luminaires)
 5   Distance Dc between C-planes                                             5
     (Dc = 0 for non-equidistantly available C-planes)
 6   Number Ng of luminous intensities in each C-plane (usually 19 or 37)     2
 7   Distance Dg between luminous intensities per C-plane                     5
     (Dg = 0 for non-equidistantly available luminous
     intensities in C-planes)
 8   Measurement report number                                          max. 78
 9   Luminaire name                                                     max. 78
10   Luminaire number                                                   max. 78
11   File name                                                                8
12   Date/user                                                          max. 78
13   Length/diameter of luminaire (mm)                                        4
14   Width of luminaire b (mm)                                                4
     (b = 0 for circular luminaire)
15   Height of luminaire (mm)                                                 4
16   Length/diameter of luminous area (mm)                                    4
17   Width of luminous area b1 (mm)                                           4
     (b1 = 0 for circular luminous area of luminaire)
18   Height of luminous area C0-plane (mm)                                    4
```

19	Height of luminous area C90-plane (mm)	4
20	Height of luminous area C180-plane (mm)	4
21	Height of luminous area C270-plane (mm)	4
22	Downward flux fraction DFF (%)	4
23	Light output ratio luminaire LORL (%)	4
24	Conversion factor for luminous intensities (depending on measurement)	6
25	Tilt of luminaire during measurement (road lighting luminaires)	6
26	Number n of standard sets of lamps (optional, also extendable on company-specific basis)	4
26a	Number of lamps	n * 4
26b	Type of lamps	n * 24
26c	Total luminous flux of lamps (lm)	n * 12
26d	Color appearance / color temperature of lamps	n * 16
26e	Color rendering group / color rendering index	n * 6
26f	Wattage including ballast (W)	n * 8
27	Direct ratios DR for room indices k = 0.6 ... 5 (for determination of luminaire numbers according to utilization factor method)	10 * 7
28	Angles C (beginning with 0 degrees)	Mc * 6
29	Angles G (beginning with 0 degrees)	Ng * 6
30	Luminous intensity distribution (cd/klm) when Isym = 0, Mc1 = 1 and Mc2 = Mc when Isym = 1, Mc1 = 1 and Mc2 = 1 when Isym = 2, Mc1 = 1 and Mc2 = Mc/2+1 when Isym = 3, Mc1 = 3*Mc/4+1 and Mc2 = Mc1+Mc/2 when Isym = 4, Mc1 = 1 and Mc2 = Mc/4+1	(Mc2-Mc1+1) * Ng * 6

Appendix C – CIBSE TM14:1988 Photometric Data File Format

The CIBSE TM14:1988 photometric data file format was developed by the Chartered Institution of Building Services Engineers (London, UK). The following is an abbreviated description intended for interpretation of existing and valid TM14:1988 files only.

A printed version of CIBSE TM14:1988, *CIBSE Standard File Format for the Electronic Transfer of Luminaire Photometric Data* is available from:

Chartered Institution of Building Services Engineers
Delta House, 222 Balham High Road
London SW12 9BS

URL: www.cibse.org

Identifier	Description
01	CIBSE/1
02	Test report number and laboratory
03	Luminaire catalogue number and/or identification
04	Luminaire description
05	Lamp description
06	Other lamp information
07	Not assigned
08	Not assigned
09	<number of lamps> <photometric type> <width> < length> < height>
10	<ballast lumen factor> <input power> < input VA>
11	< design attitude>
12	< number of vertical angles> < number of horizontal angles>
13	<vertical angles>
14	<horizontal angles>
15	<luminous intensity values for all vertical angles at 1st horizontal angle>
16	<luminous intensity values for all vertical angles at 2nd horizontal angle>
17	…
18	<luminous intensity values for all vertical angles at last horizontal angle>
19	<glare shape code> <base luminous area> <side luminous area> <end luminous area>

NOTES

36. All data is stored in ASCII format.
37. All dimensions are in meters.
38. Label lines (02 to 08 inclusive) contain descriptive text, and must be a maximum of 60 characters in length. Blank lines are permitted.
39. The photometric type must be either ‘1’ for Type 1 (C,γ) or ‘2’ for Type 2 (H,V) photometric webs. (Type 1 is typically used for roadway, area, and indoor luminaires, while Type 2 is used for floodlights.)
40. The <width>, <length>, and <height> values (09) refer to the physical luminaire dimensions.
41. The <ballast lumen factor> (10) is equivalent to the IES LM-63 ballast factor.
42. The <input power> (10) is in watts.
43. The <input VA> (10) is in volt-amps. It is the product of the measured input voltage and input current.
44. The <design attitude> (11) is equivalent to the IES LM-63 lamp tilt angle.
45. For Type 1 photometry the first <vertical angles> value (13) is either 0° or 90°, and the last value is either 90° or 180°. For Type 2 photometry the first vertical angle is the lowest angle in the luminous intensity array.

46. For Type 1 interior lighting photometry, if the first <horizontal angles> value (14) is 0 degrees, the last value will be one of:
    - 0°: The luminaire is assumed to be laterally symmetrical in all planes.
    - 90°: The luminaire is assumed to be symmetrical in each quadrant.
    - 180°: The luminaire is assumed to be symmetrical about the plane 0° – 180°.
    - ***: where *** is greater than 180° and less than or equal to 360°. In this case the luminaire is assumed to show no rotational symmetry.
47. For Type 1 interior lighting photometry the first <horizontal angles> value (14) is 90 degrees, and the last value will be 270 degrees, with the luminaire assumed to be symmetric about the 90–270 degree plane.
48. For Type 1 roadway luminaires, the zero-degree horizontal angle is assumed to be oriented parallel to the road.
49. For Type 2 photometry, if the first <horizontal angles> value (14) is 0 degrees and the last value is less than or equal to 90 degrees, the luminaire is assumed to be laterally symmetric about the vertical reference plane.
50. For Type 2 photometry, if the first <horizontal angles> value (14) is between –90 degrees and 0 degrees and the last value is between 0 and 90 degrees, the luminaire is not laterally symmetric about the vertical reference plane.
51. Luminous intensity values (15 to 18 inclusive) are in candela per 1,000 total bare lamp lumens.
52. The <glare shape code> (19) is one of the following:
    - 1 Rectangular box
    - 2 Sphere
    - 3 Vertical cylinder or flat disk
    - 4 Horizontal cylinder
    - 99 Any other shape
    - 100 Not applicable
53. The luminous area values (19) are the projected luminous areas of the base, side, and end of the luminaire.
54. Glare calculations are performed in accordance with CIBSE TM10:1985, *Calculation of Glare Indices*.

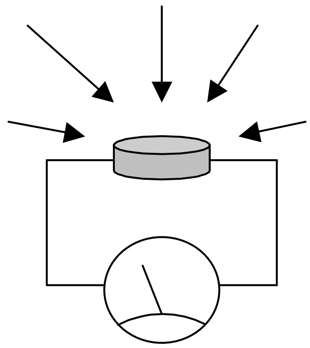


Figure 1 Incident light meter

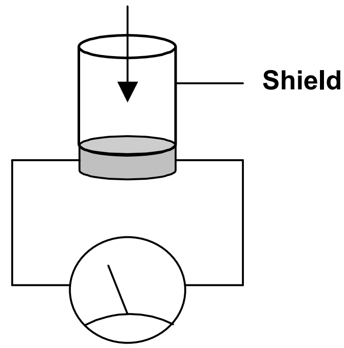


Figure 2 Spot (luminance) meter

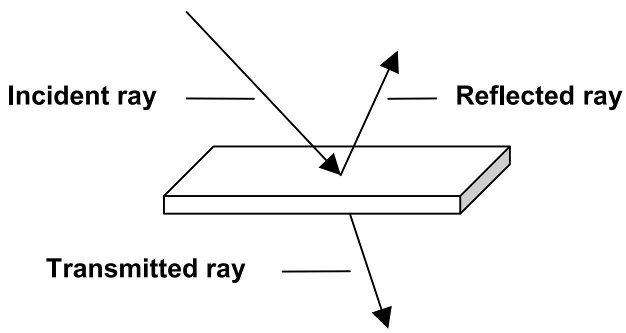


Figure 3 BRDF / BTDF measurements

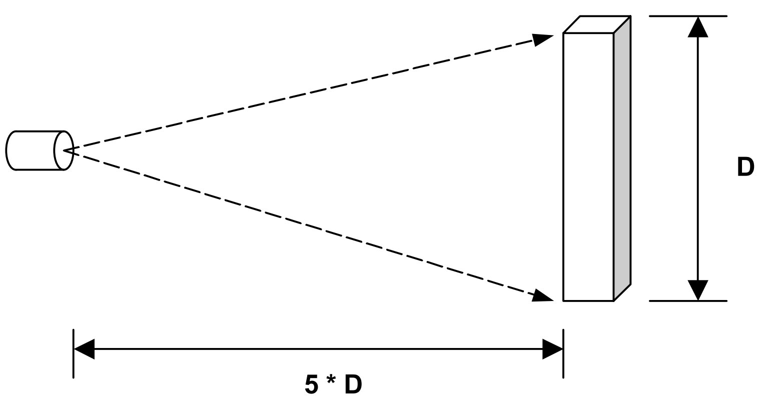


Figure 4 Five-times rule

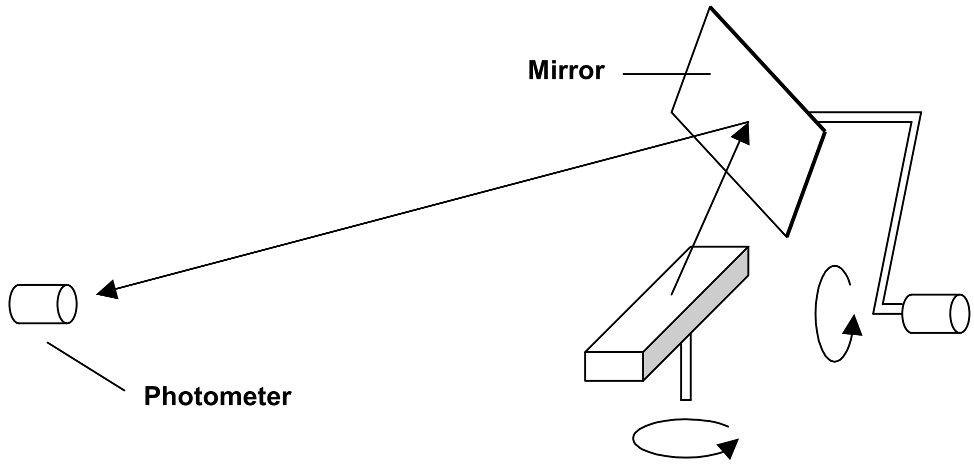


Figure 5 **Rotating mirror goniophotometer**

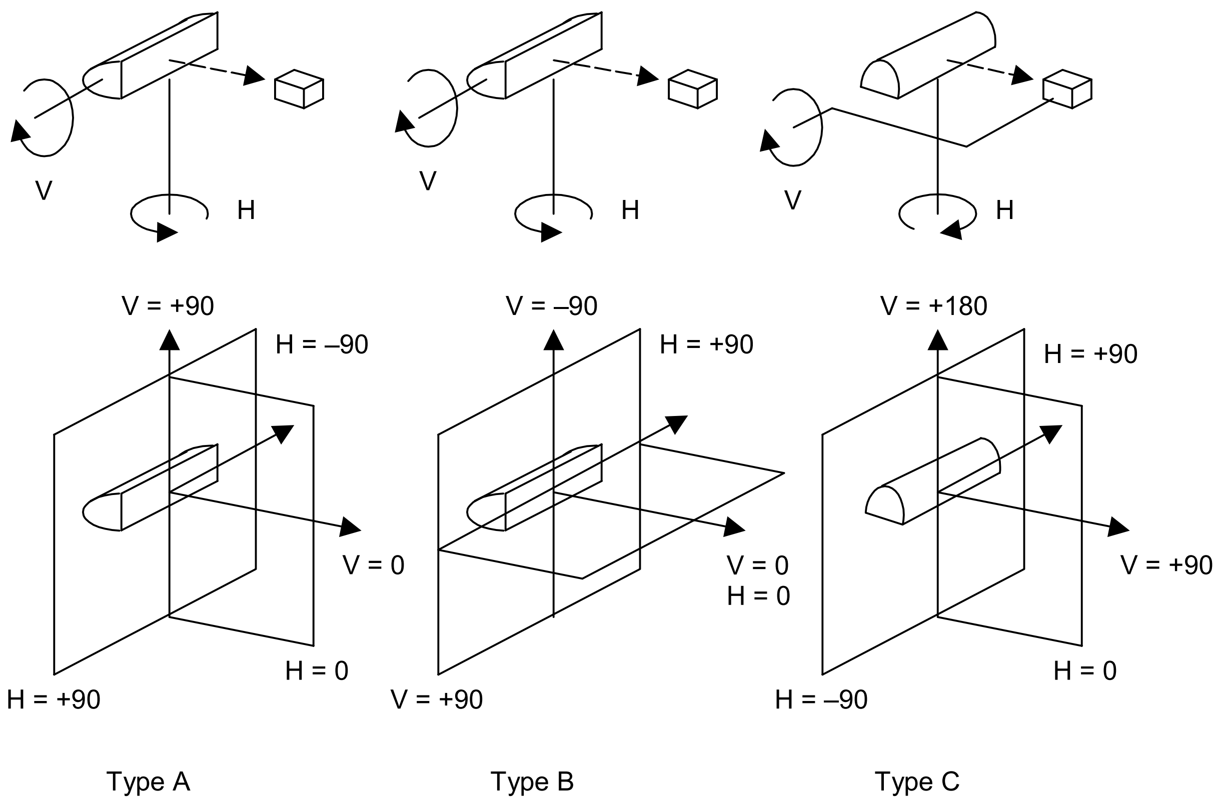


Figure 6 **Photometer Types**

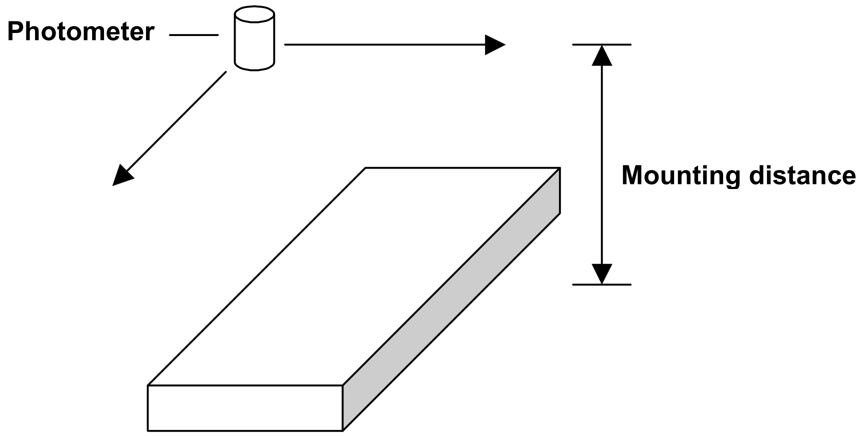
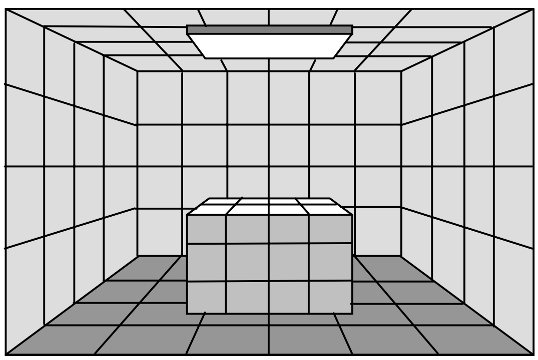


Figure 7 **Application distance photometry**



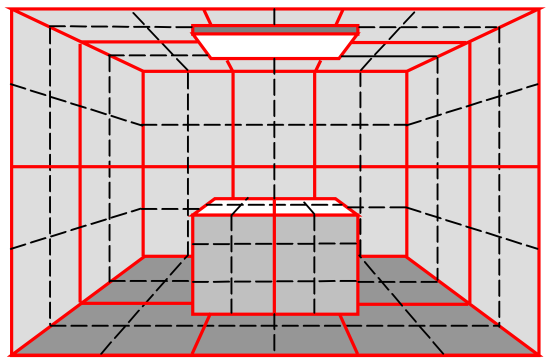
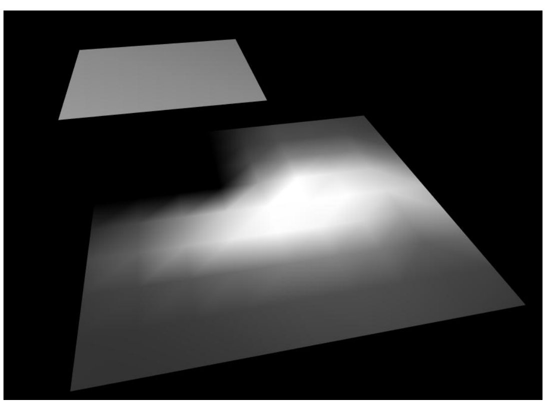
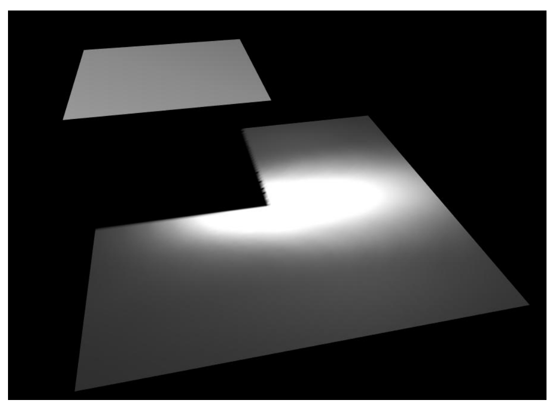


Figure 8 **Empty room (radiosity)** **Empty room (showing patches)**

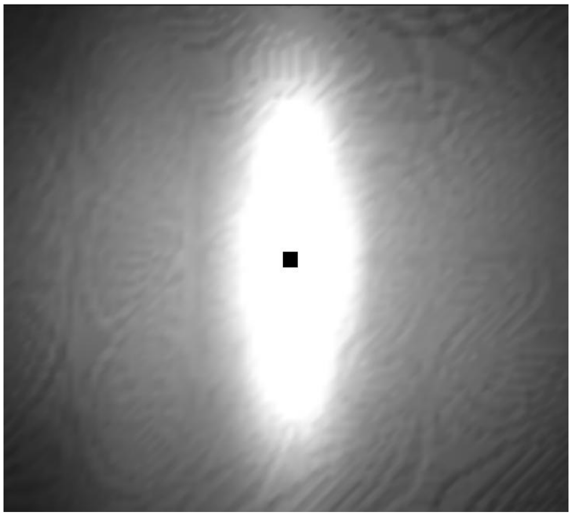


Coarse surface mesh



Fine surface mesh

Figure 9 **Missing shadow details**



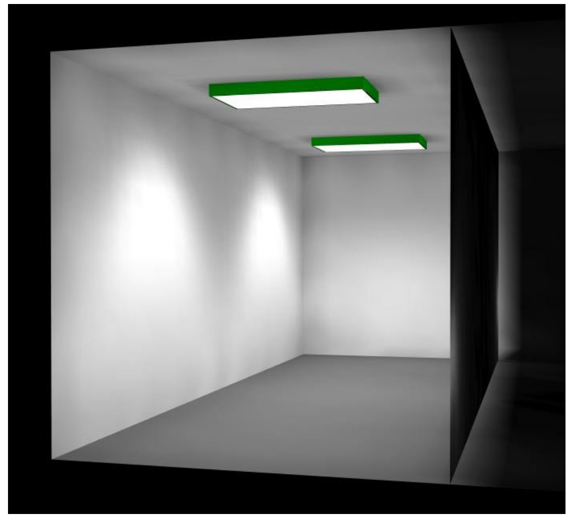


Figure 10 **Surface mottling** **Figure 11** **Light leakage problems**

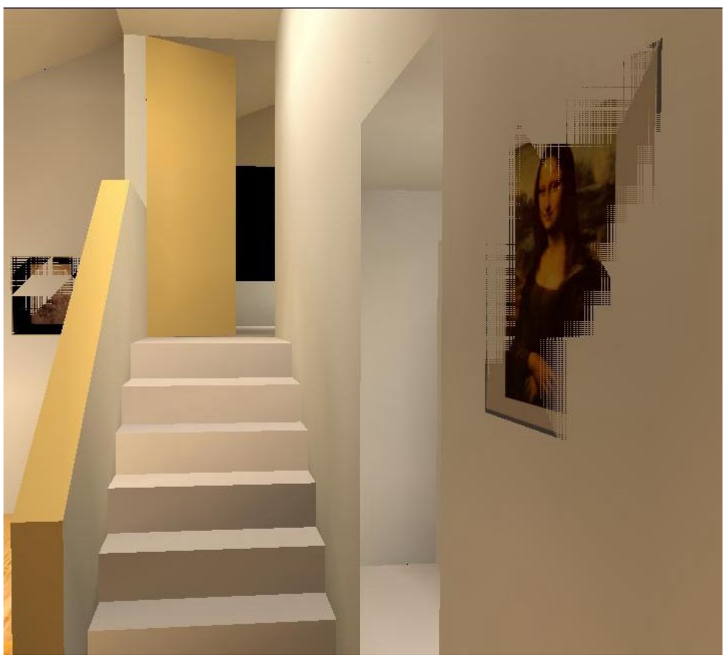
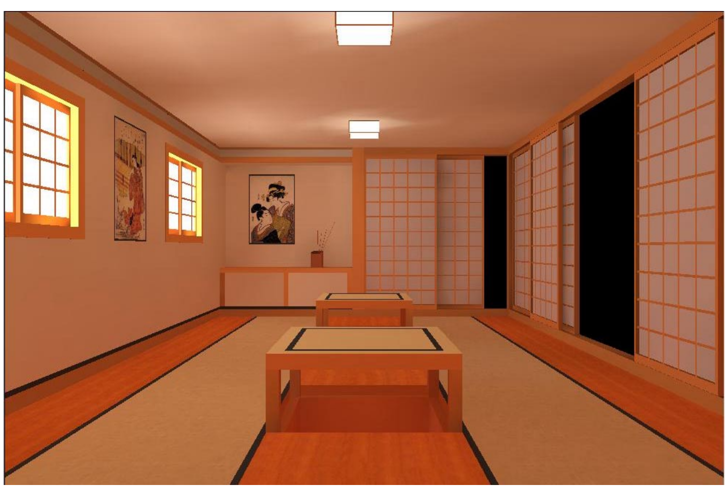


Figure 12 **Coplanar surface problems**

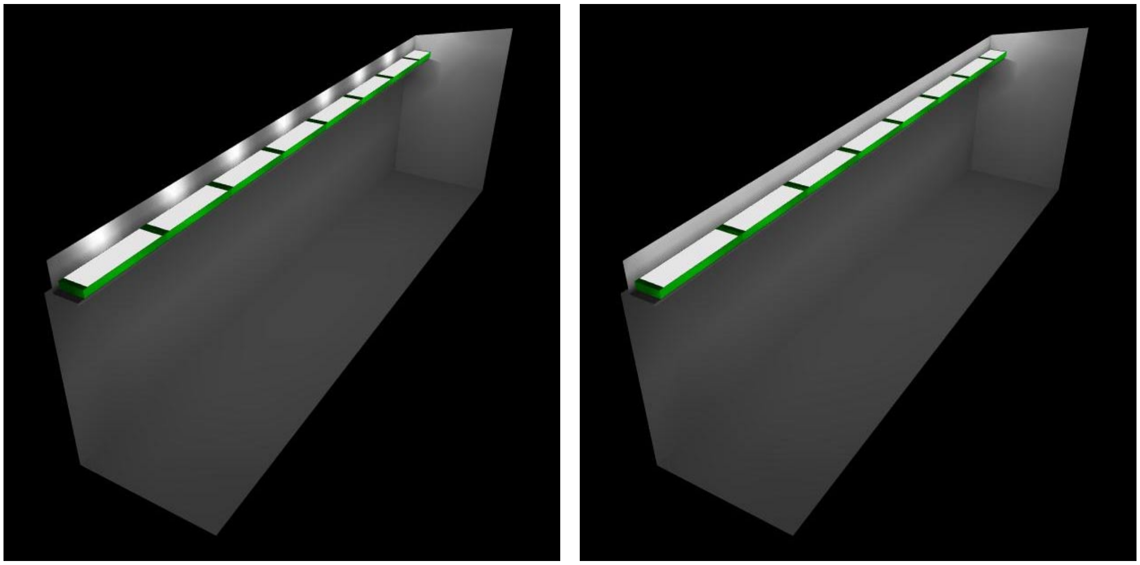
Number of Steps: 50 Convergence: 0.50

Number of Steps: 227 Convergence: 0.25



Number of Steps: 2221 Convergence: 0.01

Figure 13 Convergence



Without luminaire subdivision　　　With luminaire subdivision

Figure 14　Modeling cove lighting

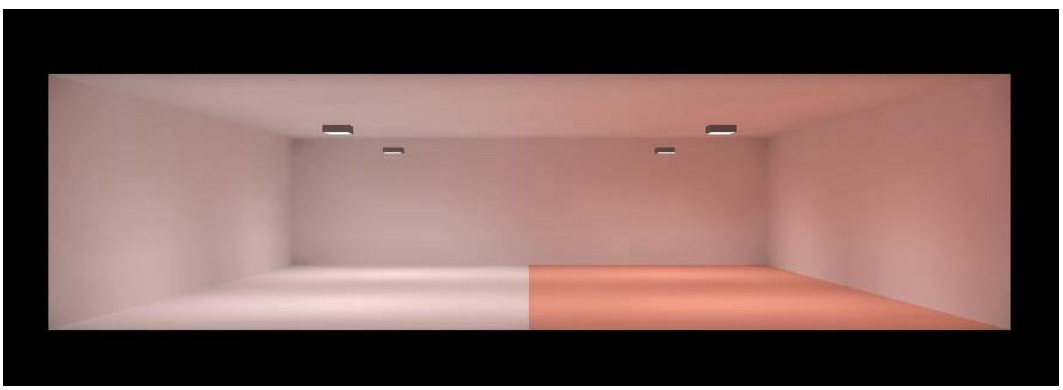


Figure 15　Color bleeding example

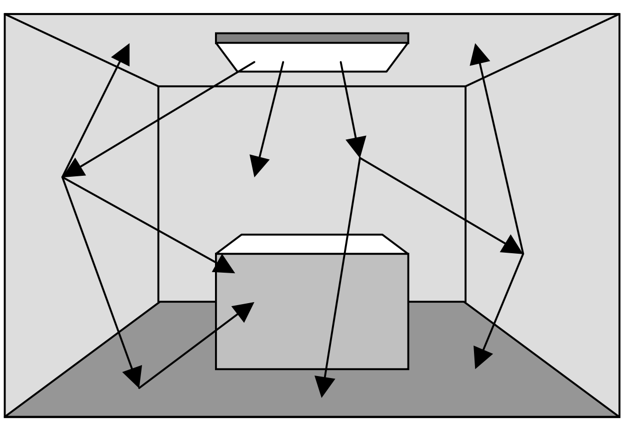


Figure 16　Empty room (ray tracing)

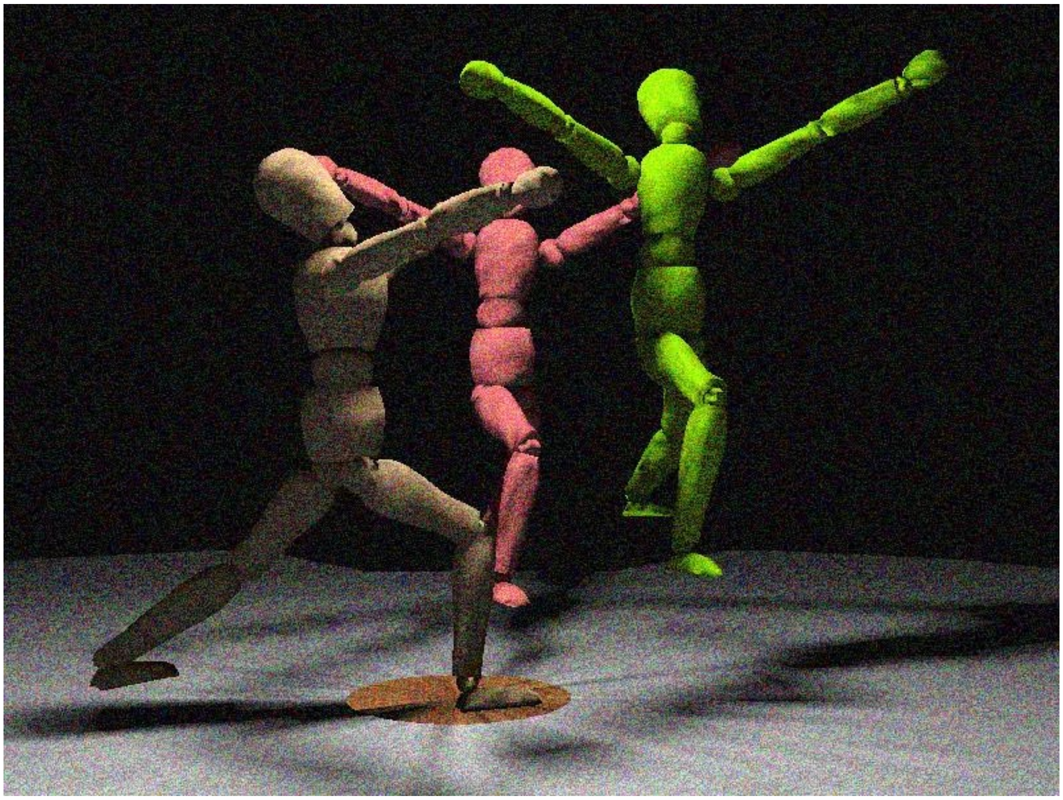


Figure 17 **Noise due to insufficient number of rays**

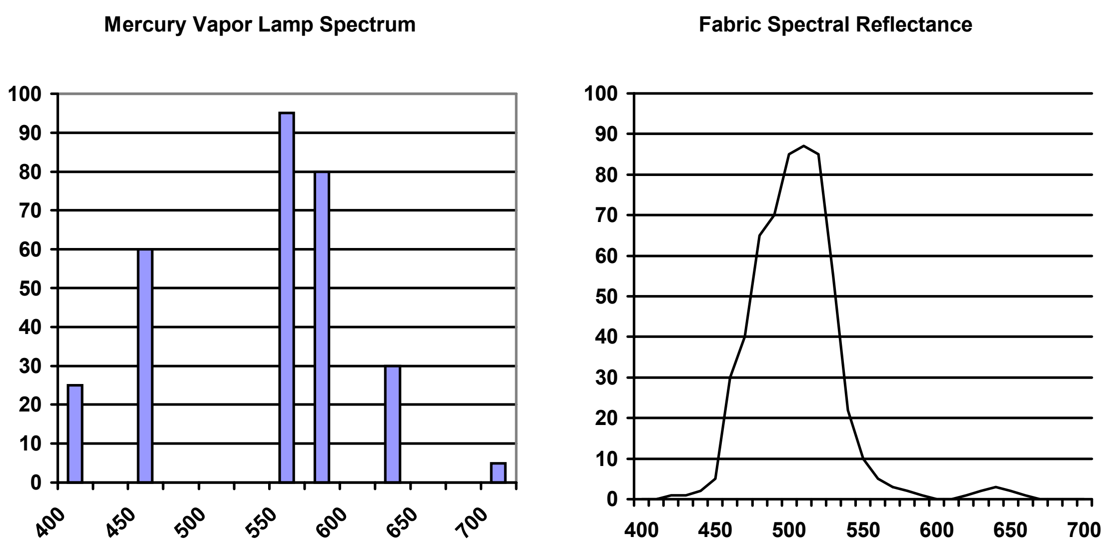
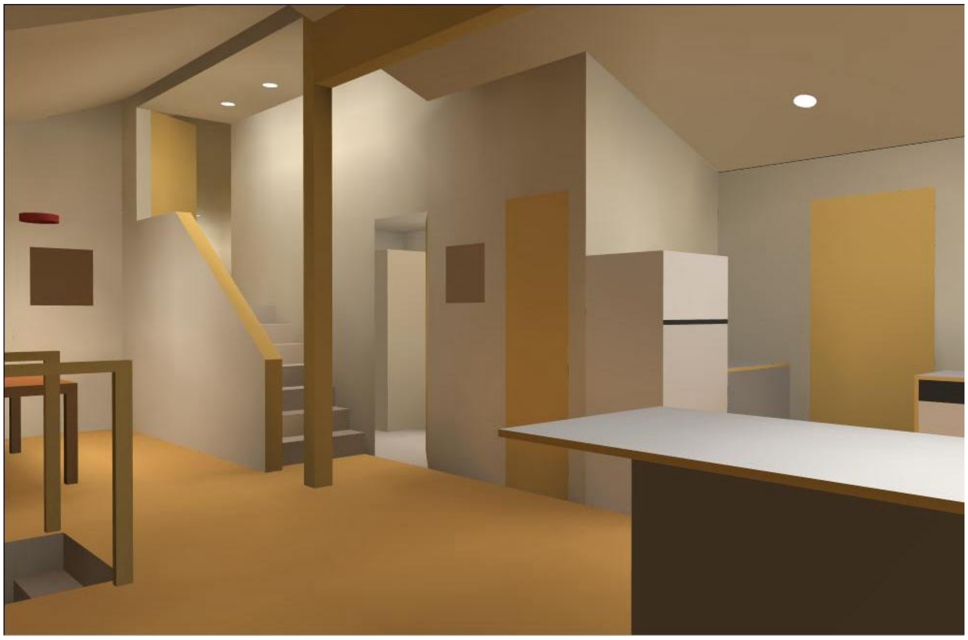
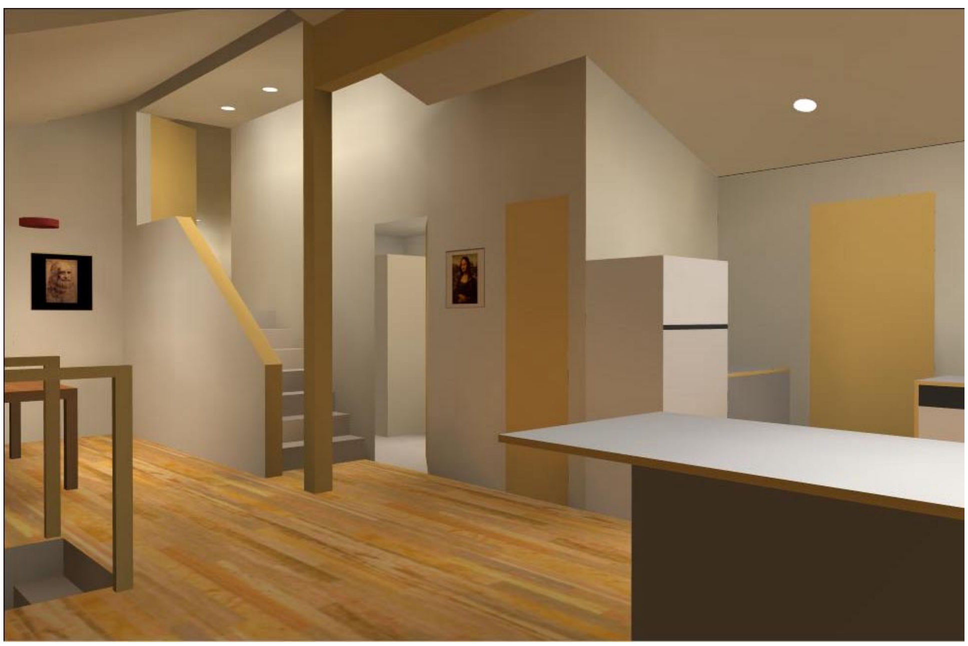


Figure 18 **Color rendition errors**



Radiosity-generated image without texture maps



Radiosity-generated image with texture maps

Figure 19 Texture maps