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FUNDAMENTALS OF MEASURING OPTICAL RADIATION

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Fundamentals Of Measuring Optical Radiation

As optical measurements become increasingly complicated, good measurement technique becomes even more important.

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The instrumentation selected to measure the output of a radiating source must be equipped with the appropriate input (front-end) optics, and it must be calibrated using the appropriate standard. The type of input optics selected and the recommended standard for calibrating the measuring device depend on the optical and geometrical properties of the light source and on the optical parameter to be measured. These requirements apply for photometers, radiometers, and spectroradiometers. This paper defines some of the more commonly measured photometric, radiometric and spectroradiometric quantities, specifies the type ofinput optics generally required for measuring these quantities, and describes the standards recommended for calibrating the measuring device.

Table 1
Fundamental Radiometric Quantities

Quantity	Symbol	Defining Equation	Units
Radiant Energy	Q, Q_e	—	J (Joule)
Radiant Energy Density	W, W_e	$W = dQ/dV$	Jm^3
Radiant Power or Flux	Φ, Φ_e	$\Phi = dQ/dt$	W (Watt)
Radiant Exitance	M, M_e	$M = d\Phi/dA$	Wm^{-2}
Irradiance	E, E_e	$E = d\Phi/dA$	Wm^{-2}
Radiant Intensity	I, I_e	$I = d\Phi/d\omega$	Wsr^{-1}
Radiance	L, L_e	$L = d^2\Phi/d\omega\,(dA\cos\theta)$ $= dI/dA\cos\theta$	$Wm^{-2}sr^{-1}$
Emissivity	$\tilde{\varepsilon}$	$\tilde{\varepsilon} = M/M_{bb}$	—

Table 2
Fundamental Photometric Quantities

Quantity	Symbol	Defining Equation	Units
Luminous Energy	Q_v	$Q_v = K_m \int_o^\infty V(\lambda) Q_\lambda d\lambda$	1m s
Luminous Energy Density	W_v	$W_v = dQ_v/dV$	$1m\ s\ m^{-3}$
Luminous Flux	ϕ_v	$\phi_v = d\phi_v/dt$	1m
Luminous Exitance	M_v	$M_v = d\phi_v/dA$	$1m\ m^{-2}$
Illuminance	E_v	$E_v = d\phi_v/dA$	$1m\ m^{-2}$
Luminous Intensity	I_v	$I_v = d\theta_v/d\omega$	$cd = 1m\ sr^{-1}$
Luminance	L_v	$L_v = d^2\theta_v/d\omega\,(dA\cos\theta)$ $= dI_v/dA\cos\theta$	$cd\ m^{-2}$
Luminous Efficacy	K	$K = \Phi_v/\Phi$	$1m\ W^{-1}$

Basic Concepts

Radiometry can be defined as the science and technology of the measurement of electromagnetic radiant energy. It is more commonly referred to simply as "the measurement of optical radiation." Optical radiation consists of energy propagated in the form of electromagnetic waves or particles (photons) in the region between x-rays and microwaves.

Whereas radiometry and spectroradiometry are concerned with electromagnetic radiant energy as a function of wavelength, photometry is concerned with only that portion of the spectrum to which the human eye is sensitive (380 to 760 nanometers). More specifically, photometry relates to the measurement of radiant energy in the "visible" spectrum as perceived by the standard photometric observer. Loosely, the standard photometric observer can be thought of as the "average" human.

Radiometric Quantities

Eight radiometric quantities are frequently used in the measurement of optical radiation.

Radiant Energy is the total radiant energy emitted from a radiating source [and is measured in joules].

Radiant Energy Density is the radiant energy per unit volume [J/m³].

Radiant Power or Flux is the time rate of flow of radiant energy [watts].

Radiant Exitance is the total radiant flux emitted by a source divided by the surface area of the source [W/m²].

Irradiance is the total radiant flux incident on an element of surface divided by the surface area of that element [W/m²].

Radiant Intensity is the total radiant flux emitted by a source per unit solid angle [W/steradian].

Radiance is the radiant intensity of a source divided by the area of the source [W/sr-m²].

Emissivity is the ratio of the radiant flux density of a source to that of a blackbody radiator at the same temperature.

Pure physical quantities for which radiant energy is evaluated in energy units are defined in Table 1. Each one of those corresponds to an analogous photometric quantity, for which radiant energy is evaluated by means of a standard photometric observer (as shown in Table 2). Each pair of quantities – radiometric and photometric – are represented by the same principal symbol (save "emissivity" and "luminous efficacy") and are distinguished only by the subscript. The subscript "e" (or no subscript) is used in the case of physical (radiometric) quantities and the subscript "v" is used for photometric quantities.

When quantities are considered for monochromatic radiant energy, they become functions of wavelength. Therefore, their designations must be preceded by the adjective "spectral," as in "spectral irradiance." The symbol itself, for each quantity, is followed by the symbol for wavelength (λ). For example, spectral irradiance has the symbol $E(\lambda)$ or $E_e(\lambda)$.

If spectral concentration of a quantity X is considered, it may also be preceded by "spectral" but the symbol is now subscripted. For example, $X_\lambda = dX/d\lambda$.

If the spectral distribution of the source is known, the following relationship between the lumen and the watt can be used to convert from one to the other.

$$\text{Lumens} = 683 \int_\lambda P_\lambda \times V_\lambda \times d\lambda$$

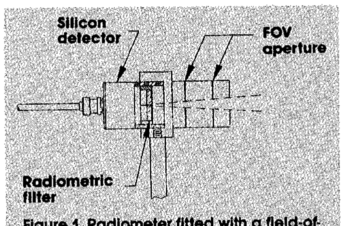

Figure 1. Radiometer fitted with a field-of-view baffle attachment.

where P_λ is the spectroradiometric power distribution of the light source (expressed in "watts per unit wavelength interval"), V_λ is the Photopic Luminous Efficiency Function (expressed in "lumens/watt"), and λ is the wavelength (usually expressed in nanometers).

When a photometric or radiometric measurement of a light source is made, it is *not* possible to convert from photometric to radiometric units or vice versa, *unless* the spectral distribution of the source is precisely known.

In the special case of a monochromatic light source – such as a laser – the equation simplifies as shown below. For example, in the case of a laser whose output is one watt at the peak of the Photopic Function (555 nm), the output is 683 lumens:

Lumens
$= P \times V_\lambda$
$= 1 \text{ watt} \times 683 \text{ lm/W} = 683 \text{ lumens}.$

Photometric Quantities

Although there are many common terms used to define photometric light output, the basic unit of measurement of light or photometric output is the lumen. All other photometric quantities involve the lumen. The eight fundamental photometric quantities concerned with the measurement of light are defined below and listed in Table 2.

Luminous Energy is the time integral of luminous flux [lumen-seconds].

Luminous Energy Density is the luminous energy per unit volume [lm-s/m³].

Luminous Flux is the total luminous power emitted from a source [lm].

Luminous Exitance is the ratio of the luminous flux emitted to the surface area of the source [lm/m²].

Illuminance is the density of the luminous flux incident on a surface. It is the luminous flux divided by the area of the surface when the surface is uniformly irradiated [lm/m²].

Luminous Intensity is the luminous flux per unit solid angle in the direction in question [lm/sr or candela].

Luminance is the ratio of the luminous intensity to the area of the source [cd/m²].

Luminous Efficacy is the ratio of the total luminous flux to the total radiant flux [lm/W)].

Input Optics

The term "input optics" refers to the front-end optics used to collect and transfer the incident optical radiation into the measurement system. In general, the same type of input optics can be used for measurement of corresponding photometric, radiometric, and spectroradiometric quantities. The most common types of input optics are listed below.

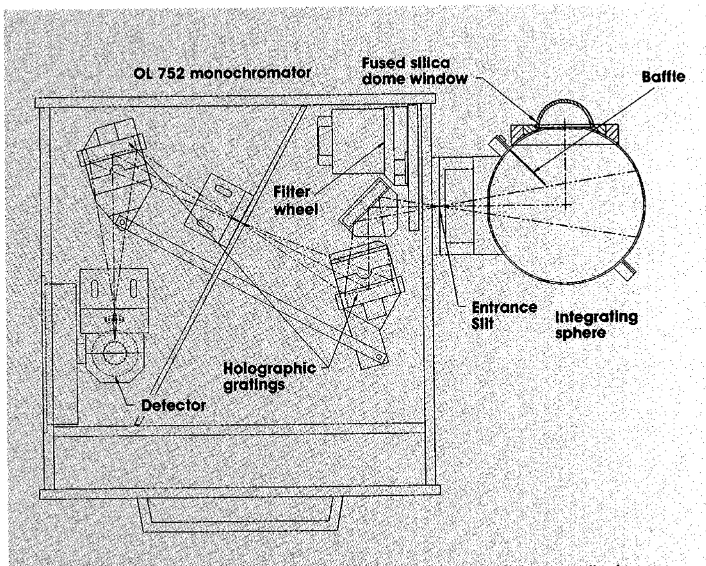

Figure 2. Double grating monochromator with integrating sphere cosine collector.

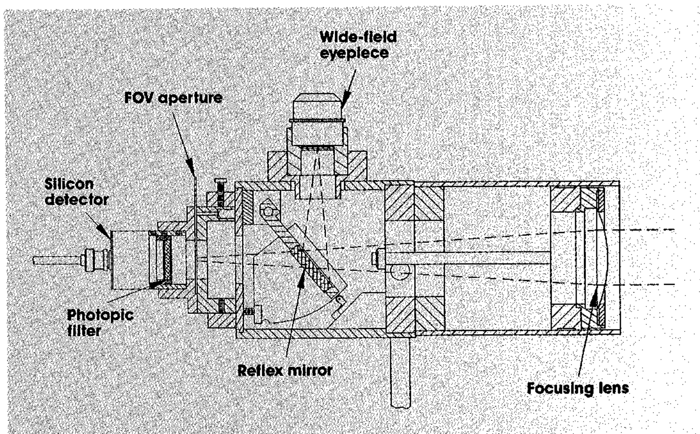

Figure 3. Photometer with reflex viewer telescope.

No Input Optics

Under certain measurement conditions, no special input optics are needed. For example, input optics are not required when measuring the illuminance, irradiance, or spectral irradiance of point sources or collimated sources. However, when making spectroradiometric measurements, the sensitivity of the spectroradiometer must be uniform over the angular field that the source subtends with the monochromator (or other optical dispersing element). Both the spatial transmission of the monochromator and the uniformity of the detector over its sensing area contribute to the spectroradiometer's overall spatial uniformity. Detector spatial nonuniformity is not a problem when measuring the illuminance or irradiance of a point or collimated source.

Both luminous flux and radiant flux can be measured without the use of input optics if the measured flux underfills the receiving area of the detector and if the detector's receiver is uniform in spatial sensitivity. Spectral radiant flux cannot be measured in this manner when using a monochromator-based spectroradiometer.

No input optics are required when using a spectroradiometer to measure the spectral radiance of large-area radiating sources, if the source is uniform in radiance and fills the field of view of the spectroradiometer. Although filling the field of view of a monochromator is relatively simple for measurements of spectral radiance, achieving this condition is more difficult when making measurements of luminance and radiance.

FOV Baffle Attachment

Field-of-view baffle attachments are mechanical devices that limit the acceptance angle of the measuring instrument. Such baffles enable the instrument to measure the luminance, radiance, or spectral radiance of large-area, uniformly radiating sources. The source must overfill the FOV of the measuring instrument. Provided that there is no measurable attenuation due to atmospheric absorption, the distance from the radiating source to the measuring instrument is not critical. Figure 1 shows an FOV baffle attached to a radiometer.

Cosine Collector

Cosine collectors sample radiant flux according to the cosine of the incident angle. These devices will accept all radiation from the entire hemisphere. Two general types of cosine collectors are available: transmitting- or reflecting-type diffusers. Reflecting-type diffusers are vastly superior with respect to both cosine collection and wavelength range of usefulness. The predominant reflecting cosine collector used for optical radiation measurements is the integrating sphere.

A properly designed and coated integrating sphere is extremely useful for making many photometric, radiometric, and spectroradiometric measurements. Spheres can be obtained with various geometries and with different coatings. A prerequisite for a good integrating sphere is a diffuse, highly reflective coating. The sphere geometry and type of coating used depend on the measurement application. $BaSO_4$ and PTFE have reflectance values approaching 100% in the visible spectrum and are useful over the range from 200 to 2500 nm. Less-efficient gold-coated spheres are available for measurement applications above 2500 nm.

Integrating spheres enable the measuring device to measure the illuminance, irradiance, or spectral irradiance of various shaped sources. They are essential when measuring the illuminance, irradiance, or spectral irradiance of sunlight, fluorescent lamps, or any other large-area or extended source. Integrating spheres are also quite useful when measuring the luminous, radiant, or spectral radiant flux of diverging or diffusely radiating sources. In such cases, all of the flux emitted by the source must be collected at the entrance port of the sphere. Figure 2 shows an integrating sphere cosine collector mounted at the entrance slit of a double grating monochromator.

Telescope

Telescope input optics are used when measuring sources at large distances from the measuring device. In terms of nomenclature, telescope input optics convert the instrument into a telephotometer, teleradiometer, or telespectroradiometer. A telescope enables the instrument to measure: luminous intensity, radiant intensity, and spectral radiant intensity (flux per steradian); luminance, radiance, and spectral radiance (flux per steradian per unit area); along with illuminance, irradiance, and spectral irradiance (flux per unit area).

When measuring flux per steradian or flux per unit area at the receiver, the source to be measured must underfill the field of view of the telescope. When measuring flux per unit area per steradian, the source must overfill the field-of-view of the telescope. In general, it is not essential to know the distance from the measuring device to the source to make these measurements. However, the distance from the calibration source to the detector must be accurately known when calibrating the system for illuminance, irradiance, or spectral irradiance response.

Telescopes can have reflective or refractive optics. The main advantage of reflective optics in a telescope used as the input to a measurement system lies in the wide wavelength ranges attainable. In contrast, refractive telescopes can only be used in the wavelength regions through which the optics transmit. In all cases, a convenient viewing system simplifies alignment. Figure 3 shows a photopically corrected silicon detector attached to a refractive telescope with a reflex viewer. This type of telescope is compact and can easily be used with a photometer, radiometer or spectroradiometer.

Microscope

Mounting a microscope to a measuring device enables the unit to measure the luminance, radiance, or spectral radiance of small radiating sources. It is essential that the microscope have an accurate viewing system. Microscopes can be obtained with various optics and objective lens. For some measurement applications, it may be more convenient to couple the microscope to the measuring instrument using a fiberoptic probe. Figure 4 shows a reflex microscope coupled to the entrance slit of a single grating monochromator by a fiberoptic probe.

Imaging Optics

Relatively simple imaging optics consisting of lenses or mirrors can be used for forming an image of the source on the measuring device. If the imaging optics do not have a viewing system, either the source or the measuring device can be moved until a sharp image is visually observed at the measuring instrument. Such optics can be used for measurements of luminance, radiance, and spectral radiance.

Fiberoptic Probes

Fiberoptic probes can also be coupled directly to the measuring device. They are particularly useful when positioning or aligning the measuring device with respect to the source is difficult. In most cases, fiberoptic probes are used for measurements of luminance, radiance, and spectral radiance. When using a fiberoptic input, be sure that the transmittance is suitable and that the probe is uniformly irradiated.

Calibration Standards

The accurate measurement of optical radiation involves not only the use of a stable, well-characterized photometer, radiometer, or spectroradiometer with appropriate input optics. Accurate measurements also require the use of a standard. This standard may be in the form of a radiating source whose radiant output and geometrical properties are accurately known. Or it may be a detector whose response is accurately known. For most applications, a standard source should be used to calibrate the measurement system.

Various photometric, radiometric, and spectroradiometric standards are available from a number of commercial calibration laboratories. Most of these standards are traceable to standards supplied by the various national standards laboratories.

Lamp Standards Of Spectral Radiance

Lamp standards of spectral radiance consist of a specially modified tungsten ribbon-filament lamp with an optical-grade sapphire window. The standards are designed for calibrating spectroradiometers with imaging input optics for spectral radiance response over all or part of the wavelength range from 250 to 6000 nm. The relatively small (2×8 mm) tungsten filament precludes the use of these standards for calibrating telespectroradiometers. In addition, the distance from the lamp filament to the sapphire window is typically too large to allow effective calibration of a microspectroradiometer.

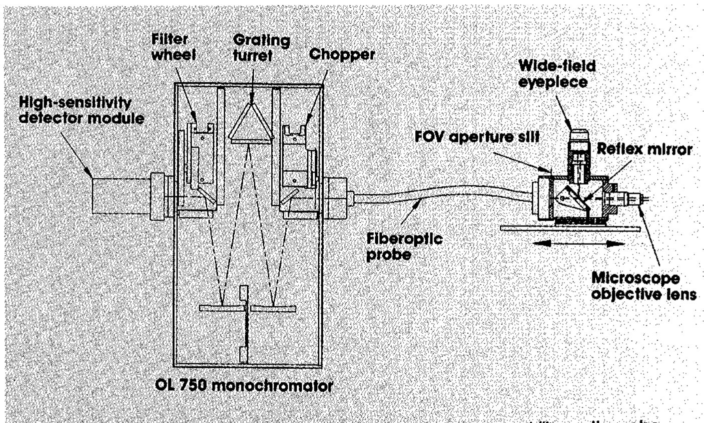

Figure 4. Single grating monochromator with reflex microscope and fiberoptic probe.

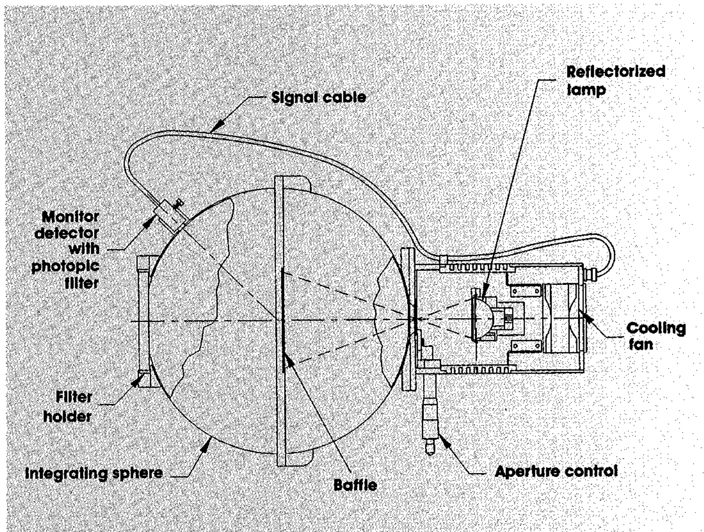

Figure 5. Integrating sphere calibration standard.

Lamp Standards Of Illuminance And Spectral Irradiance

These standards consist of tungsten halogen lamps with coiled filaments enclosed in a small quartz envelope. The standards come in sizes ranging from 45 to 1000 watts and can be calibrated for spectral irradiance over all or part of the wavelength range from 250 to 4500 nm. The standards can also be obtained with calibrations for illuminance, color temperature, and total irradiance. These standards are extremely useful for calibrating photometers, radiometers, or spectroradiometers equipped with no input optics or with cosine collectors for illuminance, irradiance, or spectral irradiance response. In addition, if the measuring device has an integrating sphere input, the irradiance standards can be used to calibrate the measuring instruments for luminous flux, radiant flux, or spectral radiant flux response by multiplying the flux per unit area incident at the entrance port of the integrating sphere by the area of entrance port.

Ultraviolet Irradiance Standard

This standard consists of a 40-watt deuterium lamp with an ultraviolet-transmitting Supersil window. The lamp is calibrated for spectral irradiance over the wavelength range of 200 to 400 nm. It serves as a convenient standard for calibrating ultraviolet radiometers and spectroradiometers equipped without input optics or with an integrating sphere cosine collector for irradiance or spectral irradiance response.

Integrating Sphere Calibration Standard

These standards combine a tungsten filament lamp with an integrating sphere. They can be constructed with the lamp (or lamps) located inside the sphere or with the lamp located external to the sphere. The flux per unit solid angle in any direction radiating from the exit or radiating port of a well-designed sphere source is proportional to the cosine of the angle between that direction and the normal to the radiating port. It essentially has the same radiance or luminance in all directions. This is a practical manifestation of Lambert's Cosine Law; a source having these properties is said to be a "lambertian radiator".

Integrating sphere calibration sources are particularly useful in calibrating instrumentation equipped with field of view baffle attachments, telescopes, or microscopes for luminance, radiance or spectral radiance response. Integrating sphere sources can be constructed in various configurations. Sphere sources having a 4:1 ratio in sphere diameter to radiating port diameter typically exhibit a $\pm 0.5\%$ nonuniformity in near-normal radiance. The radiance of integrating sphere sources increases with decreasing size. Figure 5 shows a 6-inch diameter in-line sphere with a 1.5-inch-diameter exit port. This particular design enables various sized spheres to be mounted on the source unit. Integrating sphere sources are available with manual or automatic control for setting both the luminance and the color temperature. Calibration for spectral radiance is available over all or part of the 300 to 2500-nm wavelength range.

Blackbody Radiator

Blackbody radiators are sources that radiate according to the Planck Radiation Equation:

$$L\lambda = c_1/\pi n^2\lambda^5 \, [\exp(c_2/n\lambda T) - 1]$$

where c_1 is the first radiation constant (3.7418×10^{-12} W-cm^2), c_2 is the second radiation constant (1.4388 cm-K), n is the refractive index of air (1.00027), λ is the wavelength in air, and T is the thermodynamic temperature (K).

Blackbodies are primarily used for calibrating radiometers and spectroradiometers for spectral radiance response in the infrared region beyond about 2500 nm. They can also be used for irradiance and spectral irradiance calibrations, if the effect of atmospheric attenuation is taken into consideration.

Standard Detector

Standard detectors are available for both photometric and radiometric measurement applications. Silicon detectors equipped with high accuracy photopic correction filters can be used directly for illuminance measurements. Detectors calibrated for spectral response can be used to measure the irradiance of various monochromatic sources provided that the wavelength of the emitting source is known.

Summary

During the last decade, the field of optical radiation measurements has grown at a dynamic pace. Scientists and engineers in many unrelated fields must make accurate measurements of optical radiation. The increased demand for instrumentation capable of performing many different kinds of measurements has led to the proliferation of many of the accessories described herein. In all case, the configuration of the measurement system and standard used to calibrate the measurement system depends on the application. Whenever possible, select a calibration standard similar to the source to be measured when calibrating an optical radiation measurement system. *L&O*

William E. Schneider is president of Optronic Laboratories Inc., Orlando, Fla.

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