

Figure 1

Radiometry is the measurement of radiation in the electromagnetic spectrum. This includes ultraviolet (UV), visible and infrared (IR) light.

Electromagnetic radiation is characterized by its frequency of oscillation. The frequency determines the "color" of the radiation (see Figure 1). The speed of light is a constant, and frequency is related to wavelength by the relationship:

$$C = \lambda \gamma$$

C = speed of light
 λ = wavelength
 γ = frequency

The preferred units of measure for wavelength are nanometers (nm) and micrometers (μm , or "microns").

The visible region of the electromagnetic spectrum can be divided into the basic colors of the rainbow: red, orange, yellow, green, blue, indigo and violet. Red light has the longest wavelength in the visible region (770 nm). Violet has the shortest (380 nm).

Ultraviolet light is shorter in wavelength than visible light. It extends from 10 nm to 400 nm. And like the colors of the visible region, UV can be subdivided into smaller regions. The UVA region ranges from 400 nm down to 320 nm and is the least harmful of UV radiation. The vacuum-ultraviolet (VUV) and UVC regions are shorter and are important to the study of cancer.

Infrared light extends from 770 nm to 100 microns. Its regions are known as near-IR, mid-IR and far-IR.

Measurements of optical radiation require specific methods to obtain accurate measurements. Graseby Optronics supplies calibrated detector/filter combinations that cover from 200-1800 nm (0.2 to 1.8 μm). To obtain accurate measurements, one must understand the light source (i.e. laser, lamp, LED); the optical medium (i.e. air, water, optics); and the particular response characteristics of the detector.

Important Terms

Radiometric Quantities and Units

Quantity	Symbol	Units	Abbrev.
Radiant energy	Q	joule \equiv watt-second	J \equiv W*s
Radiant energy density	U	joule/m ³	J/m ³
Radiant flux (power)	Φ , P	watts \equiv joule/second	W \equiv J/s
Irradiance	E	watts/m ²	W/m ²
Radiant exitance	M	watts/m ²	W/m ²
Radiance	L	watts/m ² *steradian	W/m ² *sr
Radiant intensity	I	watts/steradian	W/sr

In order to accurately describe an optical source, one must use the correct units and know how these units apply to detector-based radiometry. In practical light measurement applications, the receiver of optical radiation is a detection device which converts optical radiation to electrical current according to a known relationship.

At the left is a short breakdown of radiometric terms and their units of measure.

Radiant Energy

Radiant energy refers to the amount of power reaching a given point accumulated over time. This is referred to as **joules (watt-sec)**.

Radiant Flux

Radiant flux is the fundamental unit in detector-based radiometry. It is defined as the total optical power of a light source, and is expressed in **watts**.

To measure radiant flux, the detector must collect all emitted light. Examples of typical flux measurements are shown in Figure 2. Lasers, focused lasers and fiber optic cables require only the proper sensor head because the source and detector can be configured so that all radiation is incident within the active area of the sensor. Diverging light sources such as LEDs and lamps may require an integrating sphere to capture light radiating in several directions.

Irradiance

Irradiance is the amount of radiant flux incident on a known surface area. Its international unit of measure is **watts/m²**. However, because many sensor heads have a 1-cm² detector area, it's simpler to use **watts/cm²**.

There are two ways to control the size of the detector area. The first is to use a sensor head with a known detector area. The second is to place an aperture with a known area between the source and the detector. When source radiation doesn't completely fill the detector, an aperture is the only reliable method of controlling detector area.

The apparent size of the detector also varies according to the cosine law (see Figure 3). So, in order to obtain accurate measurements from a properly calibrated radiometer, you must place the detector surface normal to the source of radiation.

Radiant Exitance

Radiant Exitance, a property of the light source, is the total radiant flux from the source divided by the surface area of the source. Its unit of measure is **watts/m²**, which may be simplified to **watts/cm²**. This type of measurement only applies to extended light sources and is useful for making efficiency measurements of different light source materials.

To make radiant exitance measurements, one must know the surface area of the source and then measure the total radiant flux leaving the source.

Radiant Intensity

Radiant Intensity is the amount of flux emitted through a known solid angle. It is measured in **watts/steradian**.

To measure radiant intensity, start with the angle subtended by the detector at a given distance from the source (see Figure 4). Then divide the amount of flux by that solid angle.

Radiant intensity is a property of the light source and may not be relevant if the spatial distribution of radiation from the source is non-uniform. It is appropriate for point sources (and for close approximations, such as an LED intensity measurements) but not for collimated sources.

Radiance

Radiance is the radiant intensity emitted from a known unit area of the source. Units of radiance are used to describe extended light sources such as a CRT or an electroluminescent panel. Radiance is not an appropriate unit for characterizing point sources.

To measure radiance, you need to define the area of the source to be measured, and also the solid angle received (see Figure 5). This is usually simulated using an aperture and a positive lens in front of the detector.

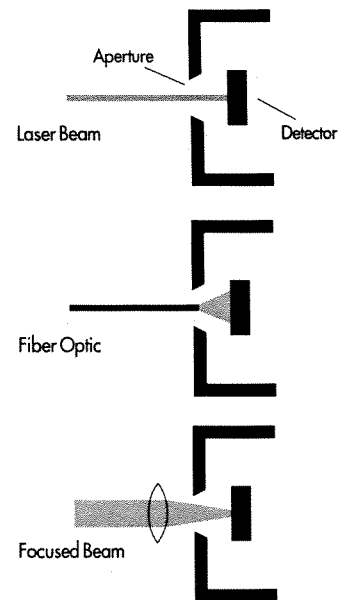


Figure 2

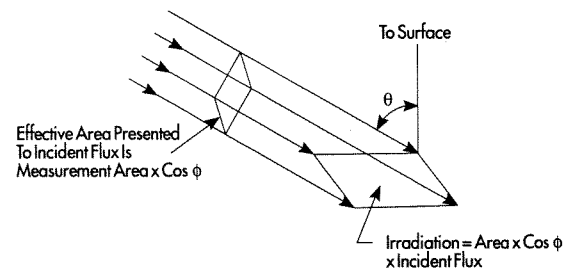


Figure 3

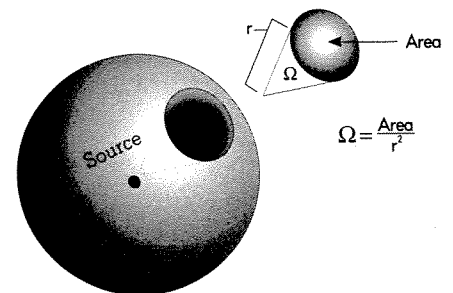


Figure 4

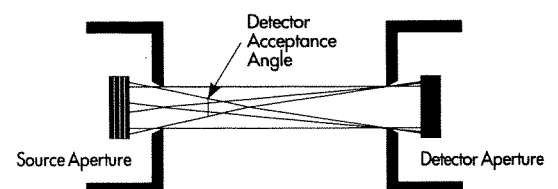


Figure 5

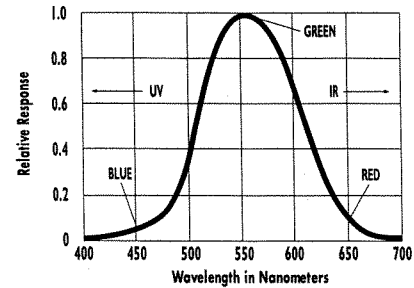
Photometry is the science concerned with measuring human visual response to light.

Because the eye is a highly complex organ, this is by no means a simple task. It involves the meeting of many disciplines: psychology, physiology, and physics among them.

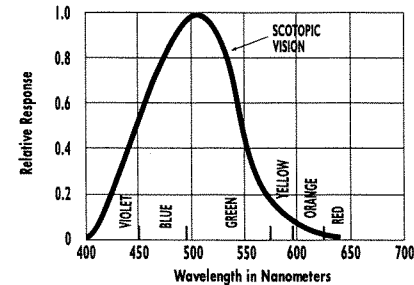
Photometry can be said to have become a modern science in 1924, when the Commission Internationale de l'Eclairage (CIE) met to define the response of the average human eye. The Commission measured the light-adapted eyes of a sizable sample group, and compiled the data into the photopic curve. Simply stated, the curve reveals that people respond strongest to the color green, and are less sensitive to the spectral extremes, red and violet.

The eye has an altogether different response in the dark-adapted state, wherein it also has difficulty determining color. This gave rise to a second set of measurements, and the scotopic curve.

Having defined the eye's spectral response, CIE sought a standard light source to serve as a yardstick for luminous intensity. The first source was a specific type of candle, giving rise to the terms footcandle and candlepower. In an effort to improve repeatability, the standard was redefined in 1948 as the amount of light emitted from a given quantity of melting platinum.



CIE photopic response curve.



CIE scotopic response curve.

Basic Concepts

The basic unit of photometry is the lumen, which is related to its radiometric analog, the Watt, by:

$$lm = 683 \times W \times V_{\lambda}$$

where V_{λ} is the relative luminosity, a coefficient scaled to visual response. Unity occurs at the eye's peak response wavelength, 555 nanometers.

Two useful laws in photometry recur: the inverse square law and the cosine law. The first defines the relationship between illumination from a constant-intensity light source and its distance from a surface. It states that the intensity per unit-area on the surface, varies in inverse proportion to the square of the distance between the source and surface, or:

$$\Delta lm/M^2 \propto 1/\Delta d^2$$

Accordingly, successive illuminance measurements are only as accurate as the control of source to surface distance. Further, if illuminance is known at one distance, it can, barring interference, be calculated for any distance.

The cosine law indicates the intensity of light on a surface of fixed area, varies with incident angle. In fact, the intensity falls off as the cosine of the angle. This results because the projected surface area, in the plane perpendicular to incidence, is proportionally reduced.

Thus in measurements of environmental lighting, sensors require cosine correction to account for off-axis light. Without it, considerable errors will occur, especially with bright sources at low incident angles (e.g.,

Wavelength (nm)	V_{λ} CIE Photopic Luminous Efficiency Coefficient	Photopic Lumen/Watt Conversion Factor
380	0.0000	0.05
390	0.0001	0.13
400	0.0004	0.27
410	0.0012	0.82
420	0.0040	2.73
430	0.0116	7.91
440	0.0230	15.7
450	0.0380	25.9
460	0.0600	40.9
470	0.0910	62.1
480	0.1390	94.8
490	0.2080	142.0
500	0.3230	220.0
510	0.5030	343.0
520	0.7100	484.0
530	0.8620	588.0
540	0.9540	650.0
550	0.9950	679.0
555	1.0000	683.0
560	0.9950	679.0
570	0.9520	649.0
580	0.8700	593.0
590	0.7570	516.0
600	0.6310	430.0
610	0.5030	343.0
620	0.3810	260.0
630	0.2650	181.0
640	0.1750	119.0
650	0.1070	73.0
660	0.0610	41.4
670	0.0320	21.8
680	0.0170	11.6
690	0.0082	5.59
700	0.0041	2.78
710	0.0021	1.43
720	0.0010	0.716
730	0.0005	0.355
740	0.0003	0.170
750	0.0001	0.820
760	0.0001	0.041

Photometric to radiometric conversion factors.

windows). This often accounts for the difference in readings between two photometers.

The cardinal challenge in photometry is to recreate the spectral response of the human eye. But electronic sensors have distinct response characteristics which bear no resemblance to the CIE standard observer. Therefore, these sensors must be spectrally corrected. Two techniques are conventionally used to accomplish this: wavelength scanning, and detector/filter matching.

Scanning can be accomplished with discrete-wavelength, scanning monochromators, or multi-channel detectors. In either case, the intensity of a light source is measured wavelength-by-wavelength, and then the results are mathematically fitted to the photopic curve. For this reason, such techniques do not occur in real time, and require microprocessor control. Scanning approaches offer high accuracy, but tend to be costly, and complex to operate.

Optical filtering offers a simple and cost-effective solution. With only one photo-current signal to process, single-channel electronics can be used. Also, recent advances in filter design, and improvements in solid-state detectors, allow this method to rival scanning systems for photometric accuracy.

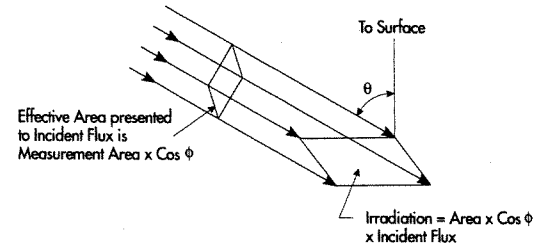
This filter-matching technique involves the layering of colored-glass filters over an optical detector. Each element functions to attenuate selective wavelengths until the detector's response simulates the CIE curve. Planar diffused silicon photodiodes offer the best photosensor characteristics, since they afford high sensitivity and linearity throughout the visible spectrum. Using silicon photodetectors, and advanced filter designs, UDT matches the CIE human eye response curve within 1% total area error. This is the best match achievable, according to CIE.

There is another more important specification of the quality of a photometric detector and that is the f_1' value. This is defined by the CIE and is a numerical value assigned to the average deviation of the photometric detector's response from the CIE curve. An $f_1' < 1.5\%$ is the best possible laboratory grade detector while an $f_1' < 3\%$ is considered suitable for most applications.

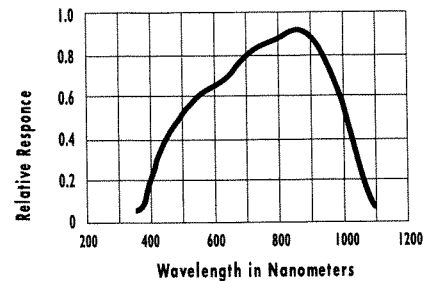
However, the relationship between a given detector and filter is delicate. Once the two have been matched, they should not be interchanged with other photometric detector/filter pairs. Each detector exhibits unique response characteristics that require a specific combination of filter layers and thicknesses.

Once the detector's response is fixed, it is calibrated using the transfer of standards technique. This requires a detector of known response, which can be obtained from the National Institute of Science and Technology (NIST). A detector/filter pair is positioned before an optical source with constant wavelength and intensity characteristics (usually a tungsten halogen lamp). The electrical output of the detector under test is then compared to the standard detector's output.

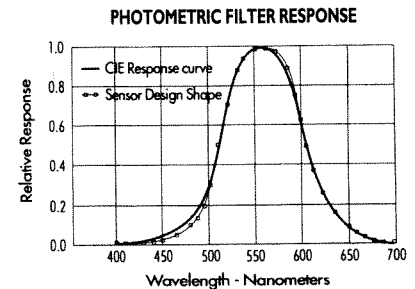
Once the sensor's luminous response is determined, it can be matched to a precision gain-controlled electronic amplifier and readout system.



The intensity of off-axis light decreases relative to the cosine of incident angle.



The typical spectral response of silicon photodetectors.



UDT photometric filters match the CIE curve to within 1% total area error.

Calibration by Transfer of Standards

R_t = Responsivity of the test detector (A/lm).

R_r = Responsivity of the reference detector (A/lm).

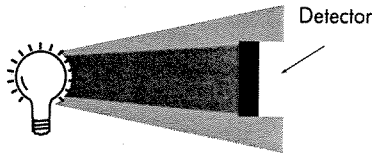
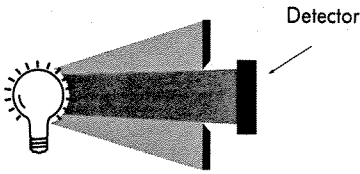
I_t = Measurement of test detector (A).

I_r = Measurement of reference detector (A).

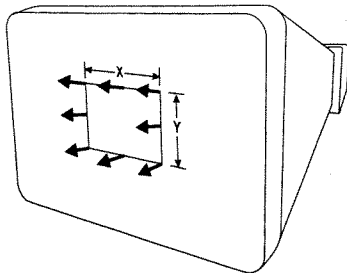
$$R_t \left(\frac{A}{lm} \right) = R_r \left(\frac{A}{lm} \right) \left(\frac{I_t (A)}{I_r (A)} \right)$$

Photometric Quantities and Units

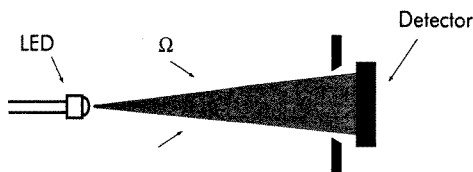
Quantity	Symbol	Units	Abbreviations
Luminous energy	Q_v	lumen-second ... talbot	lm·s ... talbot
Luminous density	U_v	lumen-second/m ²	lm·s/m ²
Luminous flux	F_v	lumen	lm
Illuminance	E_v	lumen/m ² ... lux	lm/m ² ... lx
		lumen/cm ² ... phot	lm/cm ² ... ph
		lumen/ft ² ... footcandle	lm/ft ² ... fc
Luminous exitance	M_v	same units as illuminance	
Luminance (brightness)	L_v	candela/m ² ... nit	cd/m ² ... nt
		candela/cm ² ... stilb	cd/cm ² ... sb
		candela/π ft ² ... footlambert	cd/π ft ² ... fL
		candela/π m ² ... apostilb	cd/π m ² ... asb
		candela/π cm ² ... lambert	cd/π cm ² ... L
Luminous intensity	I_v	lumen/steradian ... candela	lm/st ... cd



In illuminance measurements, area is determined by the detector unless there is an external aperture.



Luminous exitance is calculated by measuring luminous flux and dividing by the source's area.



Luminous intensity is a measure of the flux emitted into a solid angle.

Luminous Flux

Luminous flux is expressed in lumens, the fundamental unit of photometry. It is a measure of the total optical output of a visible light source.

The measurement requires all of a source's power to be concentrated on a detector. This can be a problem with divergent sources like LEDs, and lamps. In these cases, integrating spheres are often used.

Illuminance

Illuminance is a measure of the amount of visible light incident upon a prescribed surface area. In English units, one lumen of flux falling on one square foot is termed a footcandle. The metric equivalent, one lumen per square meter, is called a lux (10.76 lux = 1 footcandle).

Of course, detectors don't have such large areas. So the area of the detector is multiplied proportionally. Special attention is due when the detector is under-filled or used behind corrective optics, since the sensor's area no longer defines the surface being illuminated.

For example, illuminance measurements are particularly susceptible to errors introduced by off-axis light. So cosine-correcting diffusers are used with the detector head. Since the cosine diffuser is essentially imaged onto the sensor, the diffuser's area, not the sensor's, represents the measurement surface.

Luminous Exitance

Luminous exitance is an intrinsic property of a light source. It is calculated by measuring luminous flux (lumens), and dividing by the surface area of the source. This measurement is also expressed in lumens per square meter, but is not to be confused with illuminance measurements or lux. The area referred to in luminous exitance is that of the light source, not the illuminated surface. This measurement is most applicable to emitters with flat surfaces.

Luminous Intensity

Luminous intensity is also a source property, but one where the source's direction and divergence come into play. Defined as the quantity of luminous flux emitted uniformly into a solid angle, the basic unit of luminous intensity is the candela, equal to one lumen per steradian.

Several things are suggested by this definition. One, this measurement is not applicable to collimated light sources. Two, it is inaccurate for non-uniform emitters.

Important Terms

PHOTOMETRY

To calculate luminous intensity, the detector's area (or the area prescribed by the aperture in front of it), and its distance from the light source must be known. From these, the solid angle can be calculated, and then divided into the flux reading.

Luminance

Also known as photometric brightness, luminance is a measure of the flux reflected by, or emitted from, a relatively flat and uniform surface. The technique takes into account the area of the surface measured, and the angle subtended by an observer looking at it.

Luminance may be thought of as luminous intensity per unit area, and so in metric terms is expressed as candelas per square meter. But a host of other terms are used for this measurement, some to describe a circular measurement area rather than a square one (see Photometric Quantities and Units chart).

To measure luminance, the detector field-of-view must be restricted, and its angle calculated. Usually, a lens or baffle is used to achieve this. In fact, the human eye, with its lens and aperture, functions as a luminance meter.

Note that so long as the detector's field-of-view is filled, this measurement is independent of the distance between the detector and measurement planes. That's because field size and source intensity vary in direct proportion to one another as a function of distance.

Luminous Energy

Luminous energy is a measure of the rate of flow of flux, and so is expressed in lumen-seconds. Generally, it is applied to flashed or pulsed sources.

It is also possible to measure any photometric quantity on a time-dependent basis. For instance, the illuminance of a rotating beacon in one direction could be integrated over time to yield footcandle-seconds.

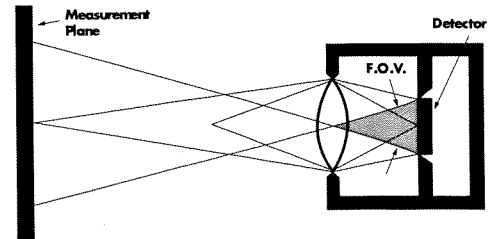
How To Specify A Photometer System

Specifying a photometer system is best approached in three steps. First, evaluate the source to determine which measurement technique best applies. Then, select a detector and optical system (detector head) that suit the measurement. And finally, match the detector head to the particular electronics which provide the most effective user interface for the application.

Consider the Source

Common sense goes a long way in determining the right measurement for an application. After all, photometry is concerned with the relation of light to the human eye. So, the first question is: how will people be affected by the source to be measured?

For instance, measurements of ambient or environmental lighting are concerned with people's ability to read print or safely see objects in an area. It is not the power of a particular source that is of concern, but



One luminance measurement technique involves fixing the detector's field-of-view through use of a lens.