Radiometry and Photometry

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Materials Covered

- Radiometry
  - Radiant Flux
  - Radiant Intensity
  - Irradiance
  - Radiance
- Photometry
  - luminous Flux
  - luminous Intensity
  - Illuminance
  - luminance

Conversion from radiometric and photometric

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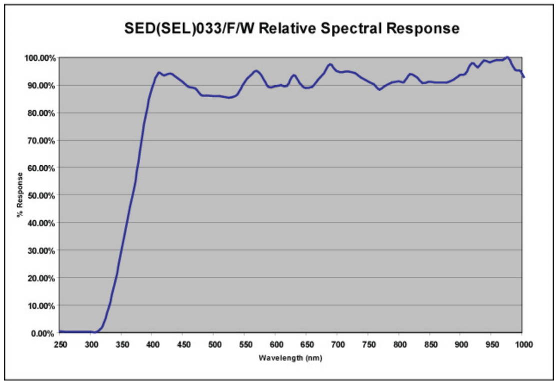
Radiometry

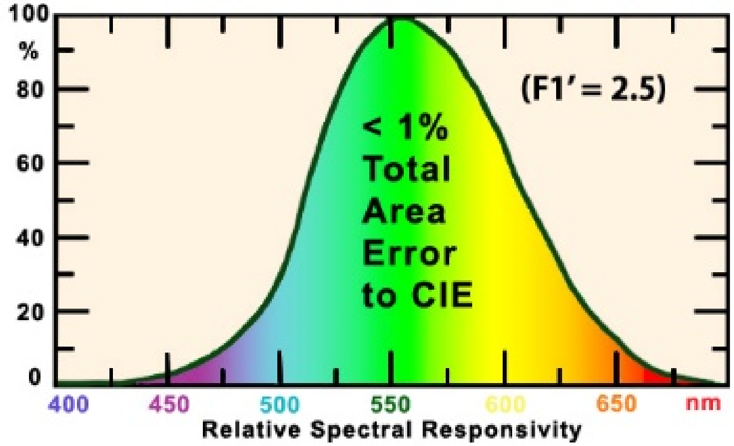
Radiometry is the detection and measurement of light waves in the optical portion of the electromagnetic spectrum which is further divided into ultraviolet, visible, and infrared light.



Example of a typical radiometer

Photometry

All light measurement is considered radiometry with photometry being a special subset of radiometry weighted for a typical human eye response.



Example of a typical photometer

Human Eyes

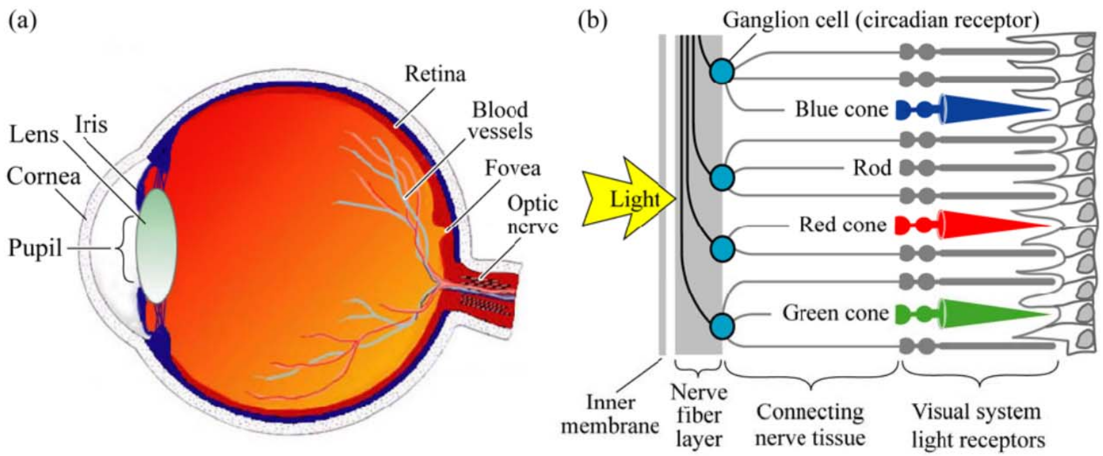


Figure shows a schematic illustration of the human eye (Encyclopedia Britannica, 1994).

The inside of the eyeball is clad by the retina, which is the light-sensitive part of the eye. The illustration also shows the fovea, a cone-rich central region of the retina which affords the high acuteness of central vision. Figure also shows the cell structure of the retina including the light-sensitive rod cells and cone cells. Also shown are the ganglion cells and nerve fibers that transmit the visual information to the brain. Rod cells are more abundant and more light sensitive than cone cells. Rods are sensitive over the entire visible spectrum.

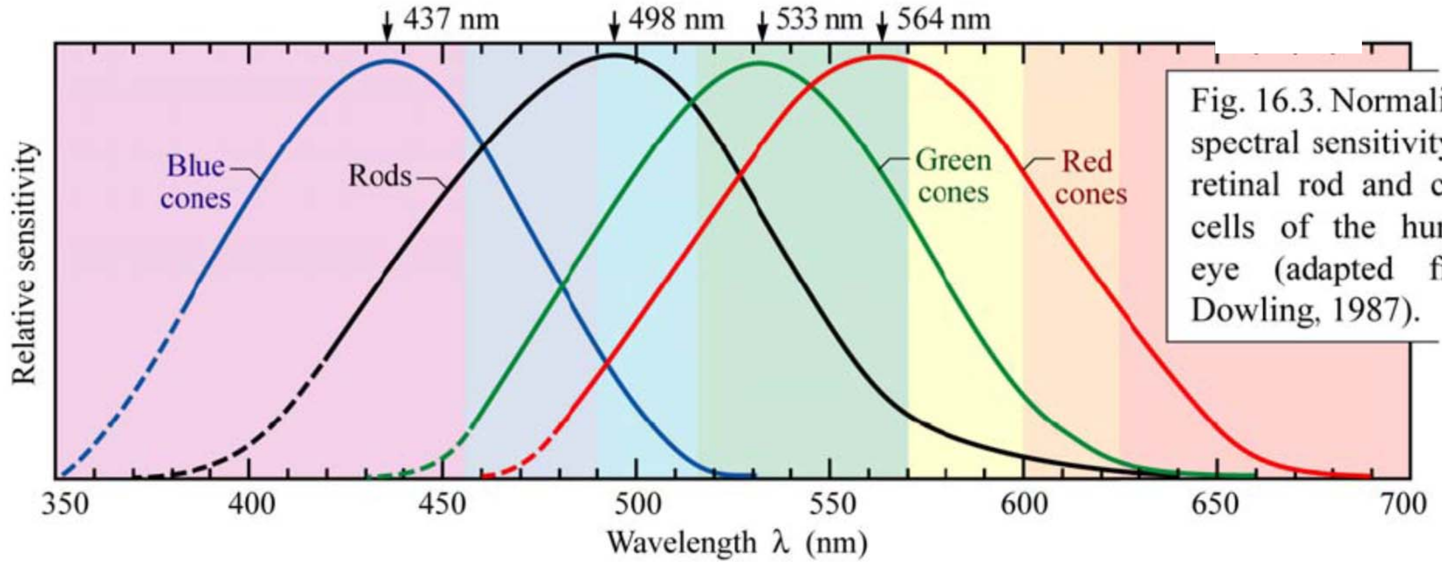
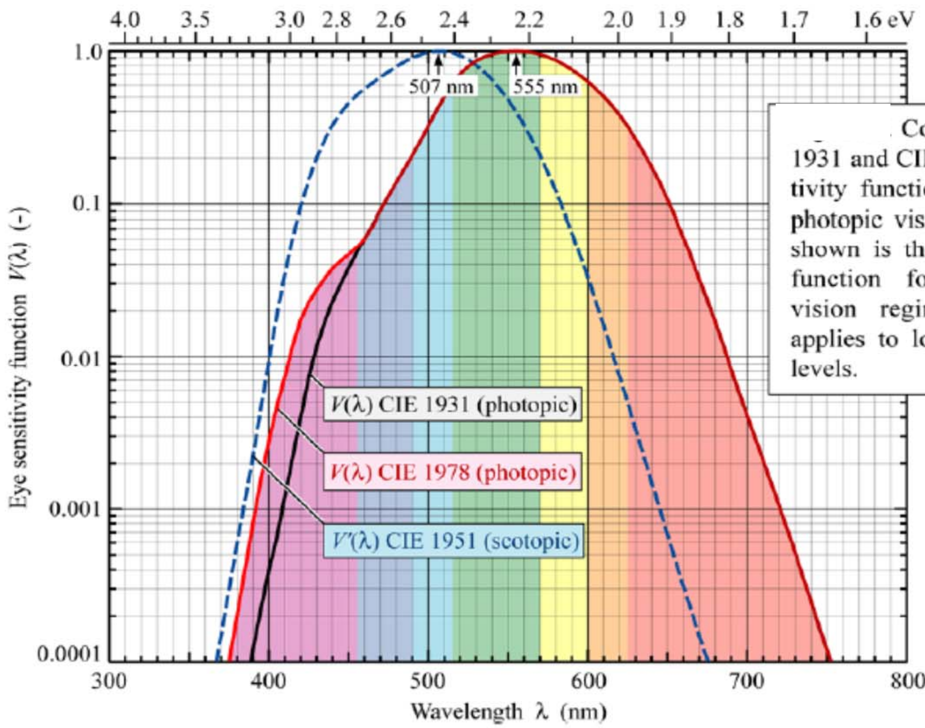


Fig. 16.3. Normalized spectral sensitivity of retinal rod and cone cells of the human eye (adapted from Dowling, 1987).

There are three types of cone cells, namely cone cells sensitive in the red, green, and blue spectral range. The approximate spectral sensitivity functions of the rods and three types or cones are shown in the figure above

Eye sensitivity function

The conversion between radiometric and photometric units is provided by the ***luminous efficiency function*** or ***eye sensitivity function***, *V*(λ). The CIE 1978 V(λ) function, which can be considered the most accurate description of the eye sensitivity in the photopic vision regime



Comparison of CIE 1931 and CIE 1978 eye sensitivity functions *V*(λ) for the photopic vision regime. Also shown is the eye sensitivity function for the scotopic vision regime, *V'*(λ), that applies to low ambient light levels.

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Scotopic and Photopic filter

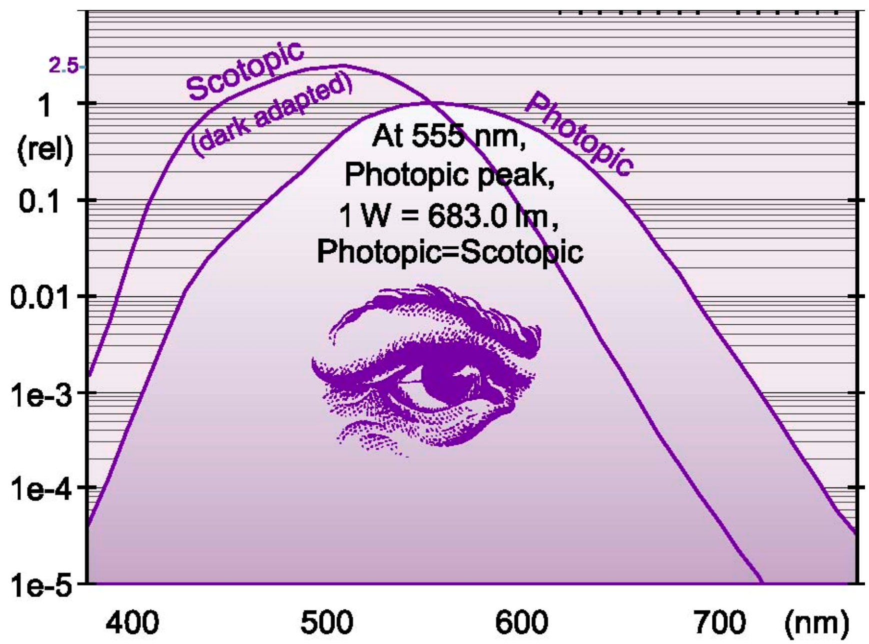

Fig. 2.3 CIE Photopic and Scotopic sensitivity curves.

Use of a photopic correction filter is important when measuring the perceived brightness of a source to a human. The filter weights incoming light in proportion to the effect it would produce in the human eye. Regardless of the color or spectral distribution of the source, the photopic detector can deliver accurate illuminance and luminance measurements in a single reading. Scotopic vision refers to the eye's dark-adapted sensitivity (night vision).

Definitions, Units and Symbols

- **Radiometry** – deals with the detection and measurement of electromagnetic radiation across the total spectrum
- **Photometry** – subfield of radiometry; radiometric power scaled by the spectral response of the human eye

Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m^2	Illuminance	E_v	lm/m^2
Radiance	L_e	W/m^2-sr	Luminance	L_v	lm/m^2-sr

"e" = "energetic"

"v" = "visual"

The table summarizes the most common radiometric and photometric quantities.

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Conversion

To convert between radiometric and photometric units, one needs to know the photopic spectral luminous efficiency curve V(λ), which gives the spectral response of the human eye to various wavelengths of light. The original curve, which is shown earlier, was adopted by the Commission on Illumination (CIE) as the standard in 1924 and is still used today even though modifications have been suggested. Empirical data shows that the curve has a maximum value of unity at 555nm, which is the wavelength of light at which the human eye is most sensitive, and trails off to levels below 10^{-5} for wavelengths below 370nm and above 780nm.

The lumen (lm) is the photometric equivalent of the watt, weighted to match the eye response of the “standard observer”. Yellowish-green light receives the greatest weight because it stimulates the eye more than blue or red light of equal radiometric power:

1 watt at 555 nm = 683.0 lumens

QUANTITY	RADIOMETRIC	PHOTOMETRIC
Power	W	Lumen (lm) = cd·sr
Power Per Unit Area	W/m²	Lux (lx) = cd·sr/m² = lm/m²
Power Per Unit Solid Angle	W/sr	Candela (cd) Power
Per Unit Area Per Unit Solid Angle	W/m²·sr	cd/m² = lm/m²·sr = nit

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Conversion

The conversion between photometric units which take into account human physiology and straight radiometric units is given by the following:(photometric unit) = (radiometric unit) x (683) x V(λ)where V(λ) is the 'Photopic Response,' shown earlier and basically tells us how efficiently the eye picks up certain wavelengths of light. The Photopic response is a function of the wavelength of light and so to convert from radiometric units to photometric units first requires knowledge of the light source. If the source is specified as having a certain color temperature we can assume that its spectral radiance emittance is the same as a perfect black body radiator and use Planck's law.

Conversion

A non-linear regression fit to the experimental data yields the approximation,

$$V(\lambda) = 1.019e^{-285.4(\lambda - 0.559)^2},$$

where the wavelength is in micrometers.
According to the definition for a candela, there are 683 lumens per watt for 555nm light that is propagating in a vacuum. Hence, for a monochromatic light source, it is fairly simple to convert from watts to lumens; simply multiply the power in watts by the appropriate V(λ) value, and use the conversion factor from the definition for a candela.

For example, the photometric power of a 5mW red (= 650nm) laser pointer, which corresponds to V(λ) = 0.096, is 0.096 x 0.005W x 683lm/W = 0.33lm, whereas the value for a 5mW green (= 532nm) laser pointer is 0.828 x 0.005W x 683lm/W = 2.83lm. Thus, although both laser pointers have the exact same radiant flux, the green laser pointer will appear approximately 8.5 times brighter than the red one assuming both have the same beam diameter.

Conversion

Conversion from radiometric to photometric units becomes more complex if the light source is not monochromatic. In this case, the mathematical quantity of interest is

$$\Phi_V = K_m \int_{\lambda=380}^{\lambda=830} \Phi_E(\lambda)\, V(\lambda)\, \delta\lambda$$

where Φ_v is the luminous flux in lumens, K_m is a scaling factor equal to 683 lumens per watt, $E(\lambda)$ is the spectral power in watts per nanometer, and $V(\lambda)$ is the photopic spectral luminous efficiency function. Note that the integration is only carried out over the wavelengths for which $V(\lambda)$ is non-zero (i.e. λ= 380 - 830nm). Since $V(\lambda)$ is given by a table of empirical values, it is best to do the integration numerically.

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Converting to Photometric Units

- Power (Watts) is converted to luminous flux (lumens) via the relation:

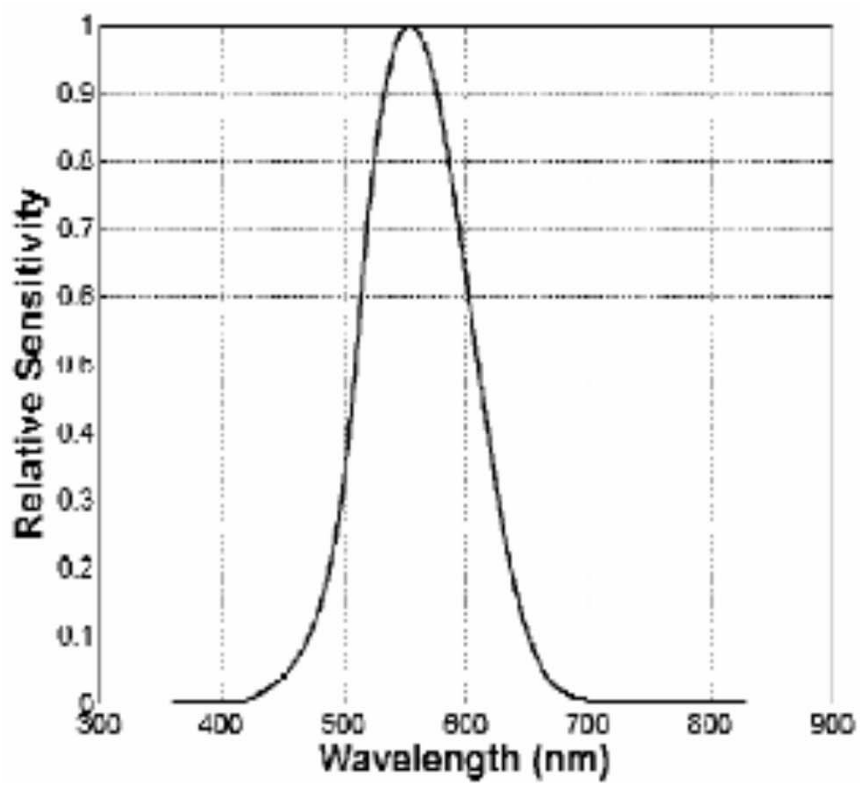
$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

Φ_v = flux (lumens)

P_e = Power

V = photopic response function of the human eye

K = constant (683 lm/W for photopic)



Radiometric power is converted to luminous flux via the integral equation. V(λ) is the spectral response of the human eye in daylight, otherwise known as the photopic curve. The unit of luminous flux is the lumen.

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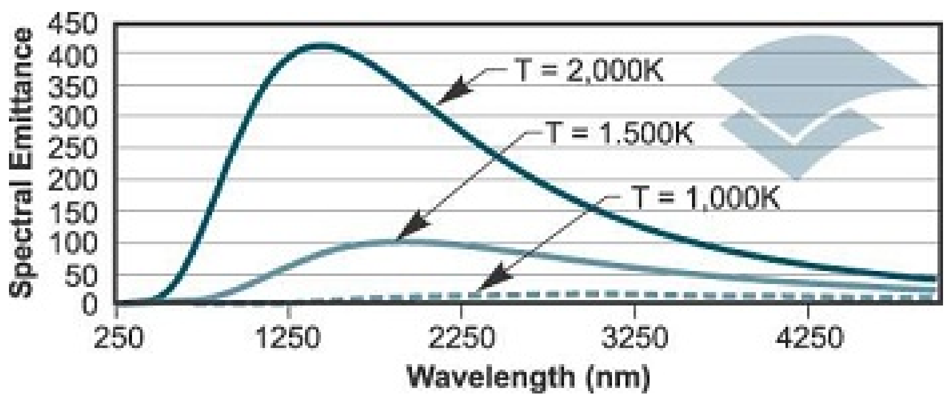
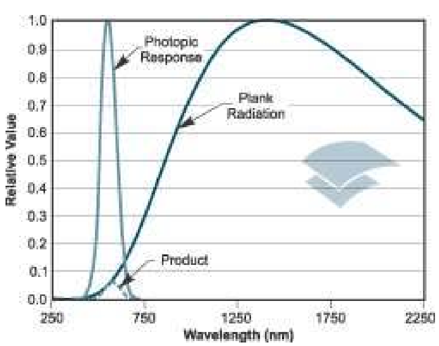
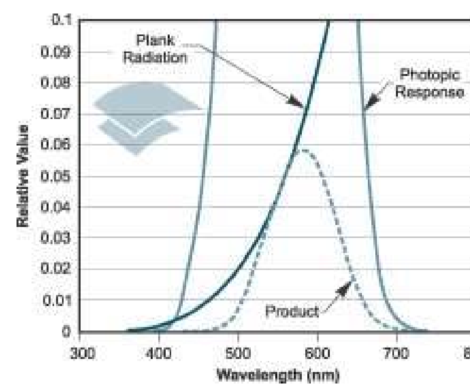
Example

Artificial sources in general do not have the same spectral distribution as a perfect black body but for our purposes we shall consider them equal. The graph above depicts the spectral radiance of several black body radiators. If we consider the Photopic evaluation of a black body radiation at a temperature of T=2045K.



Integration of the product of the light emittance by the Photopic function provides the conversion from a Radiometric signal to a Photometric.





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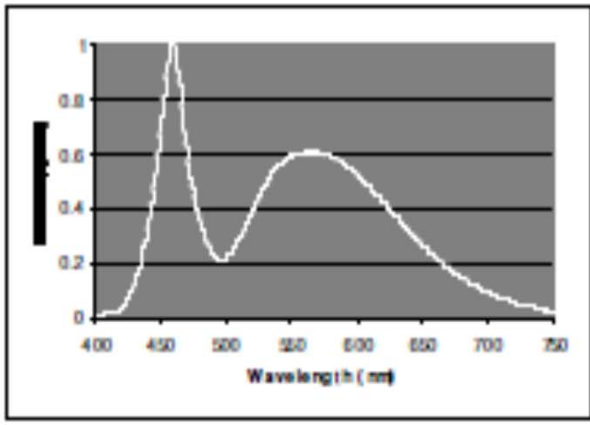
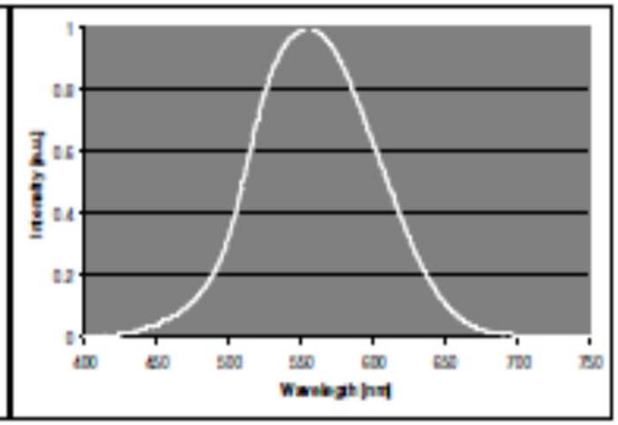
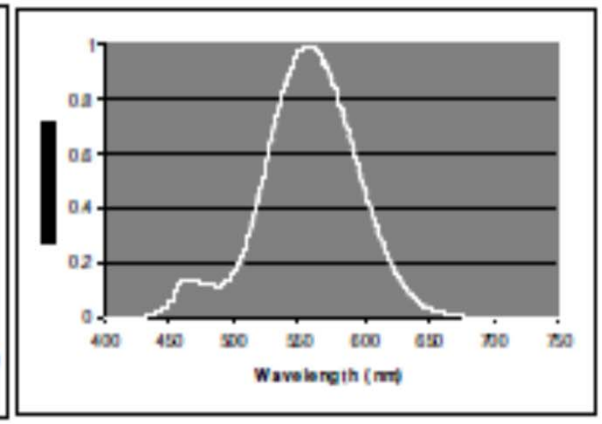
Convert Radiometric to Photometric

$P_e(\lambda)$ $V(\lambda)$ → $\Phi_v(\lambda)$







$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

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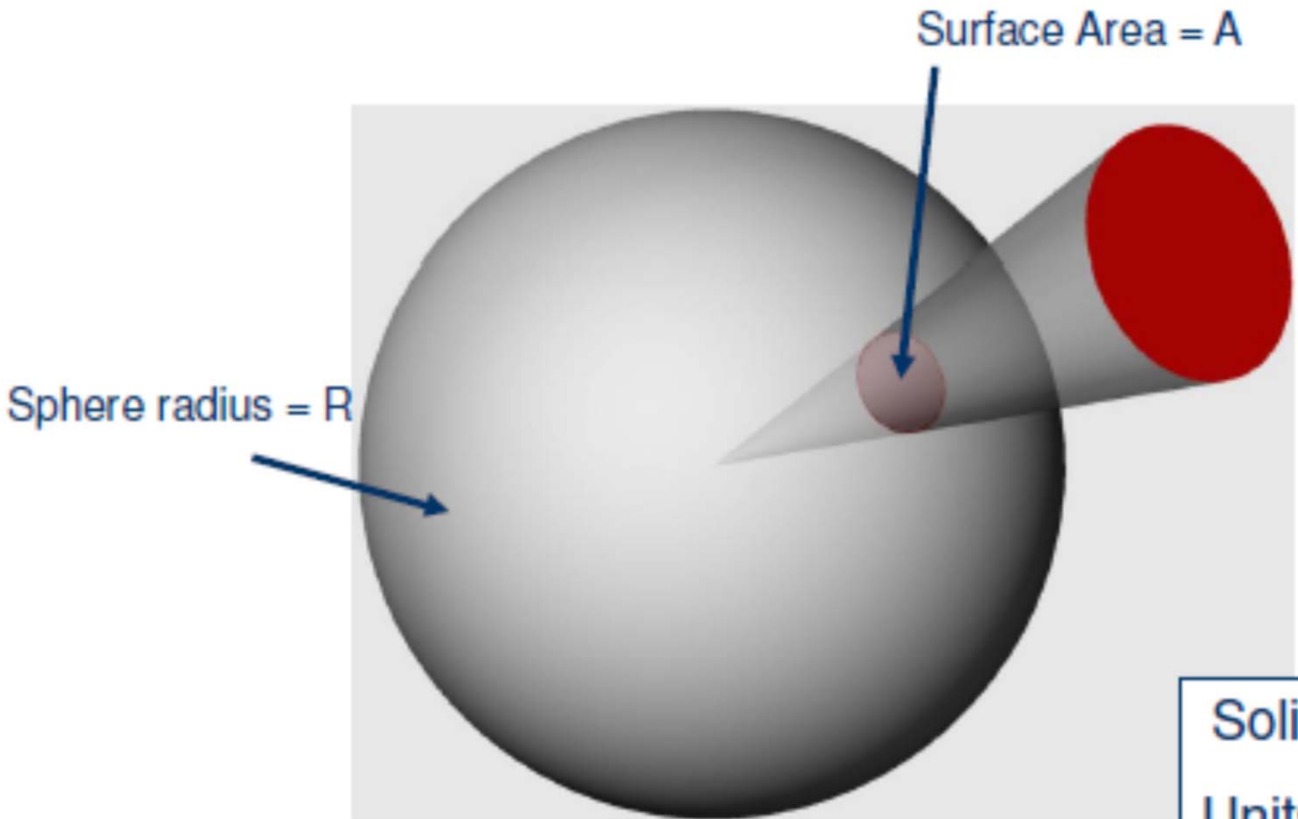
Radiant Intensity and luminous Intensity

Solid Angle



Solid Angle $\Omega = A/R^2$

Units: Steradians (sr)

Solid angle is the 3 dimensional analog of an ordinary angle. In the figure, the edge of a circular disk, the bright red circle, is projected to the center of a sphere. The projection intersects the sphere and forms a surface area A. Solid angle is the area A on the surface of a sphere of radius R divided by the radius squared. The units of solid angle are steradians. Note that it is a dimensionless quantity.

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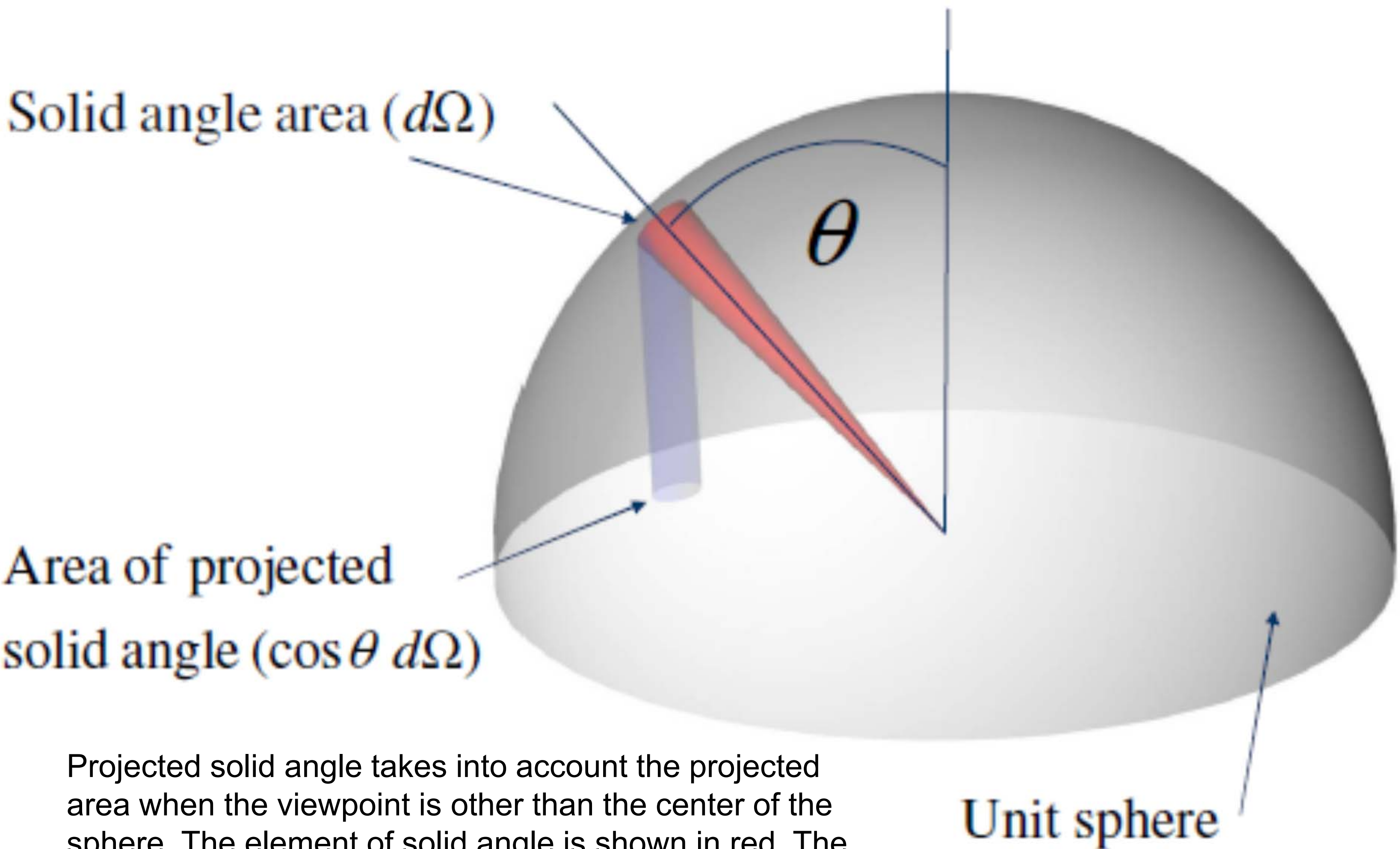
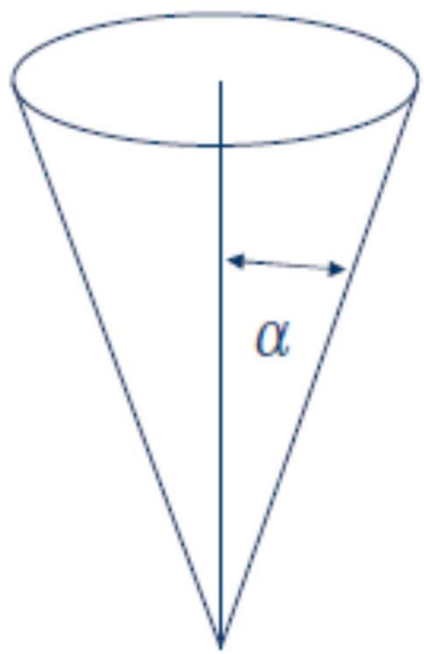
Projected Solid Angle



Projected solid angle takes into account the projected area when the viewpoint is other than the center of the sphere. The element of solid angle is shown in red. The area of projected solid angle is shown in blue.

Projected Solid Angle



$$d\Omega = \sin\theta \, d\theta \, d\phi$$

$$d\Omega_{proj} = \cos\theta \, d\Omega$$

$$\Omega_{proj} = \int_0^{2\pi} \int_0^{\alpha} \cos\theta \sin\theta \, d\theta \, d\phi$$

$$\Omega_{proj} = \pi \sin^2 \alpha$$

As an example, the projected solid angle for a cone of half angle alpha is calculated.

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Lambertian Source LED Example

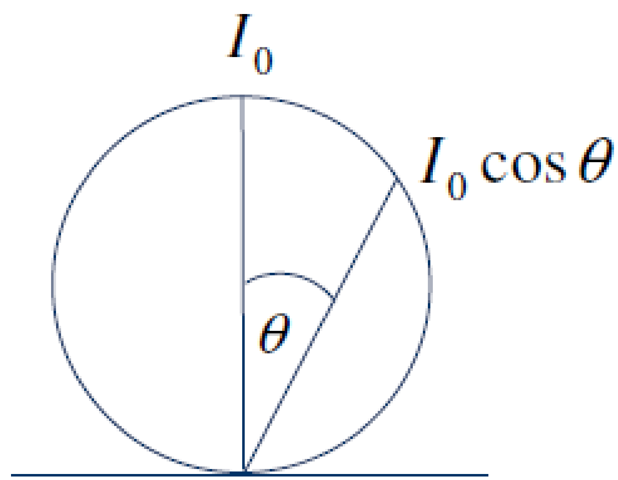
- Brightness (luminance) is independent of angle

$$L(\theta) = L(0)$$

- Intensity falls off as cos θ

$$I(\theta) = I_0 \cos\theta$$

- Many LEDs are very nearly Lambertian sources



A Lambertian source is defined as one in which the brightness (or luminance) is independent of angle, in other words the off-axis luminance is the same as on-axis. Such a source has an intensity vs. angle profile that falls off as the cosine of the angle. Historically, many LED sources have had nearly Lambertian beam distributions, simplifying certain calculations.

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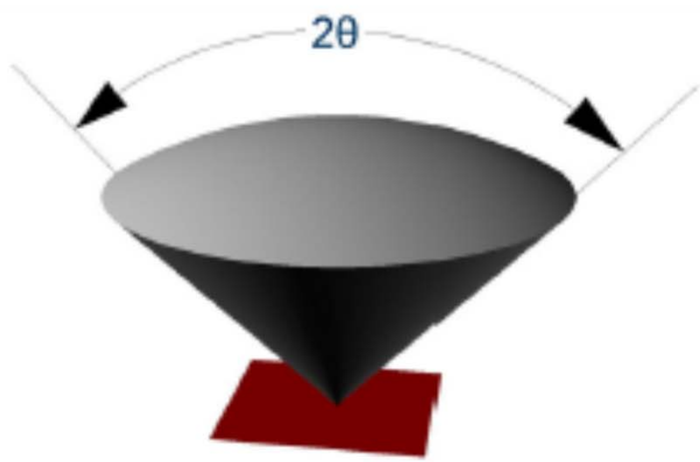
Lambertian Source

LED Example



Total flux in a 2 θ cone:

$$\Phi = 2\pi\int_0^{\theta} I(\theta')\sin\theta'\,d\theta'$$

$$\Phi = 2\pi\int_0^{\theta} I_0\cos\theta'\sin\theta'\,d\theta'$$

$$\Phi = I_0\pi\sin^2\theta$$

Take the example of calculating the luminous flux within a certain cone angle. Substituting the intensity distribution of a Lambertian source into the equation makes the integration simple. For a so-called Lambertian LED, the total lumens is about 3 times the on-axis intensity.

The total flux of a Lambertian source of 1 cd is π lumens.

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Radiant Flux (ϕ)

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. 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.

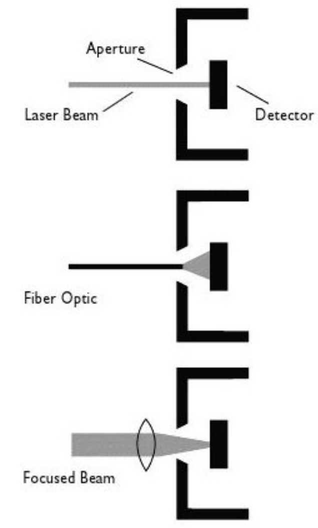

Figure 2

Radiant Intensity ($I = d\phi/d\Omega$)

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.

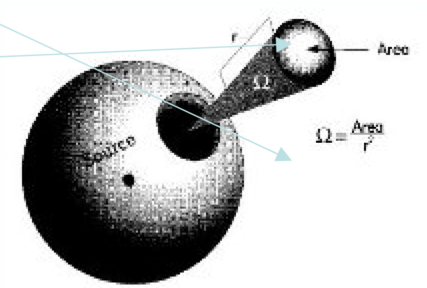

Figure 4

Irradiance ($E=\phi/A = 4\pi I/4\pi r^2 = I/r^2$)

Irradiance is the amount of radiant flux incident on a known surface area. Its international unit of measure is watt/m^2. However, because many sensor heads have a 1-cm^2 detector area, it is simpler to use watt/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 does not completely fill the detector, an aperture is the only reliable method of controlling detector area.

Radiance ($L= dI/ dA\cos\theta$)

Radiance is the radiant intensity emitted from a known unit area of a source. Units of radiance are used to describe extended light sources, such as a CRT or an EL/O Panel 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. This is usually simulated using an aperture and a positive lens in front of the detector. It is expressed as watts/cm^2·ster.

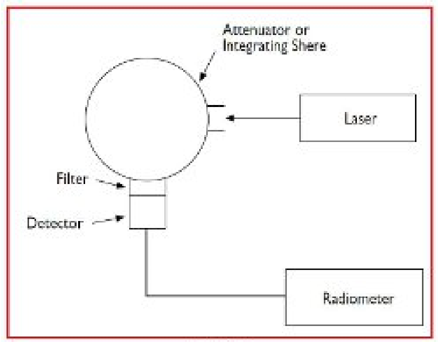

Figure 6

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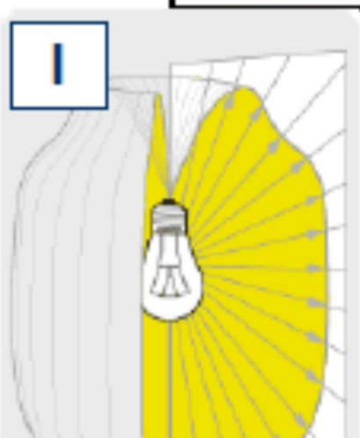
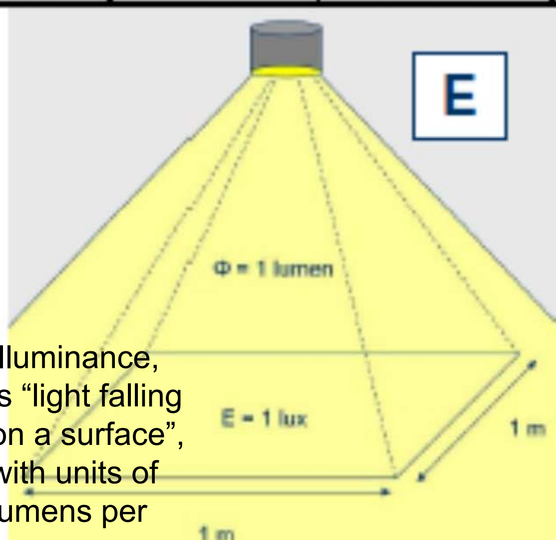
Photometric Units and Symbols

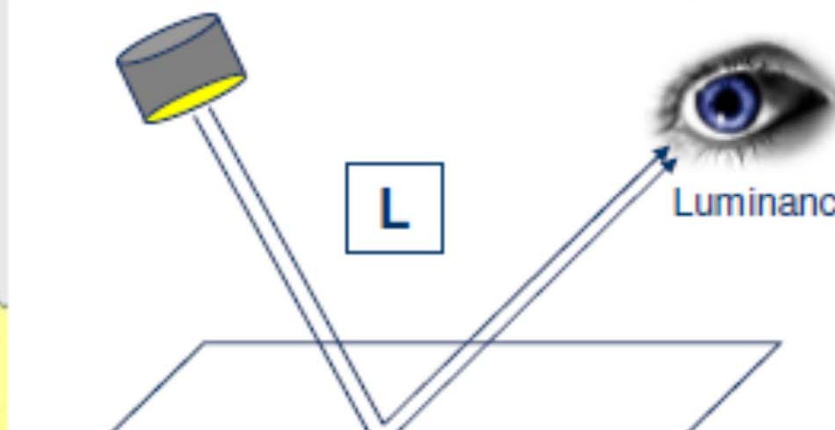
Photometric Units					
Quantity	**Symbol**	**Metric Units**	**Name**	**English Units**	**Name**
Luminous Flux	Φ	lumens (lm)	lumens		
Luminous Intensity	I	lm/sr	candela (cd) or candlepower		
Illuminance	E	lm/m^2	lux (lx)	lm/ft^2	Ft-candle
Luminance	L	cd/m^2	nits	$cd/\pi*ft^2$	Ft-Lambert



of intensity are lumens per solid angle, or steradians



Illuminance, is “light falling on a surface”, with units of lumens per area



Luminance is “light from a surface in a direction”. The units are lumens per area per solid angle; it is the perceived brightness.

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Quantity		Unit		Dimension	Notes
Name	Symbol[nb 1]	Name	Symbol	Symbol	
Radiant energy	Q_e[nb 2]	joule	J	$\mathbf{M}\cdot\mathbf{L}^2\cdot\mathbf{T}^{-2}$	Energy of electromagnetic radiation.
Radiant energy density	w_e	joule per cubic metre	J/m^3	$\mathbf{M}\cdot\mathbf{L}^{-1}\cdot\mathbf{T}^{-2}$	Radiant energy per unit volume.
Radiant flux	Φ_e[nb 2]	watt	W *or* J/s	$\mathbf{M}\cdot\mathbf{L}^2\cdot\mathbf{T}^{-3}$	Radiant energy emitted, reflected, transmitted or received, per unit time. This is sometimes also called "radiant power".
Spectral flux	$\Phi_{e,\nu}$[nb 3] or $\Phi_{e,\lambda}$[nb 4]	watt per hertz *or* watt per metre	W/Hz *or* W/m	$\mathbf{M}\cdot\mathbf{L}^2\cdot\mathbf{T}^{-2}$ *or* $\mathbf{M}\cdot\mathbf{L}\cdot\mathbf{T}^{-3}$	Radiant flux per unit frequency or wavelength. The latter is commonly measured in $W\cdot sr^{-1}\cdot m^{-2}\cdot nm^{-1}$.

Radiant intensity	$I_{e,\Omega}$[nb 5]	watt per steradian	W/sr	$\mathbf{M} \cdot \mathbf{L}^{2} \cdot \mathbf{T}^{-3}$	Radiant flux emitted, reflected, transmitted or received, per unit solid angle. This is a *directional* quantity.
Spectral intensity	$I_{e,\Omega,\nu}$[nb 3] or $I_{e,\Omega,\lambda}$[nb 4]	watt per steradian per hertz *or* watt per steradian per metre	$W \cdot sr^{-1} \cdot Hz^{-1}$ *or* $W \cdot sr^{-1} \cdot m^{-1}$	$\mathbf{M} \cdot \mathbf{L}^{2} \cdot \mathbf{T}^{-2}$ *or* $\mathbf{M} \cdot \mathbf{L} \cdot \mathbf{T}^{-3}$	Radiant intensity per unit frequency or wavelength. The latter is commonly measured in $W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$. This is a *directional* quantity.
Radiance	$L_{e,\Omega}$[nb 5]	watt per steradian per square metre	$W \cdot sr^{-1} \cdot m^{-2}$	$\mathbf{M} \cdot \mathbf{T}^{-3}$	Radiant flux emitted, reflected, transmitted or received by a *surface*, per unit solid angle per unit projected area. This is a *directional* quantity. This is sometimes also confusingly called "intensity".
Spectral radiance	$L_{e,\Omega,\nu}$[nb 3] or $L_{e,\Omega,\lambda}$[nb 4]	watt per steradian per square metre per hertz *or* watt per steradian per square metre, per metre	$W \cdot sr^{-1} \cdot m^{-2} \cdot Hz^{-1}$ *or* $W \cdot sr^{-1} \cdot m^{-3}$	$\mathbf{M} \cdot \mathbf{T}^{-2}$ *or* $\mathbf{M} \cdot \mathbf{L}^{-1} \cdot \mathbf{T}^{-3}$	Radiance of a *surface* per unit frequency or wavelength. The latter is commonly measured in $W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$. This is a *directional*

Irradiance	E_e[nb 2]	watt per square metre	W/m^2	$\mathbf{M}\cdot\mathbf{T}^{-3}$	Radiant flux *received* by a *surface* per unit area. This is sometimes also confusingly called "intensity".
Spectral irradiance	$E_{e,\nu}$[nb 3] or $E_{e,\lambda}$[nb 4]	watt per square metre per hertz *or* watt per square metre, per metre	$W\cdot m^{-2}\cdot Hz^{-1}$ *or* W/m^3	$\mathbf{M}\cdot\mathbf{T}^{-2}$ *or* $\mathbf{M}\cdot\mathbf{L}^{-1}\cdot\mathbf{T}^{-3}$	Irradiance of a *surface* per unit frequency or wavelength. The terms spectral flux density or more confusingly "spectral intensity" are also used. Non-SI units of spectral irradiance include Jansky = 10^{-26} $W\cdot m^{-2}\cdot Hz^{-1}$ and solar flux unit (1SFU = 10^{-22} $W\cdot m^{-2}\cdot Hz^{-1}$).
Radiosity	J_e[nb 2]	watt per square metre	W/m^2	$\mathbf{M}\cdot\mathbf{T}^{-3}$	Radiant flux *leaving* (emitted, reflected and transmitted by) a *surface* per unit area. This is sometimes also confusingly called "intensity".
Spectral radiosity	$J_{e,\nu}$[nb 3] or $J_{e,\lambda}$[nb 4]	watt per square metre per hertz *or* watt per square metre, per metre	$W\cdot m^{-2}\cdot Hz^{-1}$ *or* W/m^3	$\mathbf{M}\cdot\mathbf{T}^{-2}$ *or* $\mathbf{M}\cdot\mathbf{L}^{-1}\cdot\mathbf{T}^{-3}$	Radiosity of a *surface* per unit frequency or wavelength. The latter is commonly measured in $W\cdot m^{-2}\cdot nm^{-1}$. This is sometimes also confusingly called "spectral intensity".

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Radiant exitance	M_e [nb 2]	watt per square metre	W/m^2	$\mathbf{M}\cdot\mathbf{T}^{-3}$	Radiant flux *emitted* by a *surface* per unit area. This is the emitted component of radiosity. "Radiant emittance" is an old term for this quantity. This is sometimes also confusingly called "intensity".
Spectral exitance	$M_{e,\nu}$ [nb 3] or $M_{e,\lambda}$ [nb 4]	watt per square metre per hertz *or* watt per square metre, per metre	$W\cdot m^{-2}\cdot Hz^{-1}$ *or* W/m^3	$\mathbf{M}\cdot\mathbf{T}^{-2}$ *or* $\mathbf{M}\cdot\mathbf{L}^{-1}\cdot\mathbf{T}^{-3}$	Radiant exitance of a *surface* per unit frequency or wavelength. The latter is commonly measured in $W\cdot m^{-2}\cdot nm^{-1}$. "Spectral emittance" is an old term for this quantity. This is sometimes also confusingly called "spectral intensity".
Radiant exposure	H_e	joule per square metre	J/m^2	$\mathbf{M}\cdot\mathbf{T}^{-2}$	Radiant energy received by a *surface* per unit area, or equivalently irradiance of a *surface* integrated over time of irradiation. This is sometimes also called "radiant fluence".
Spectral exposure	$H_{e,\nu}$ [nb 3] or $H_{e,\lambda}$ [nb 4]	joule per square metre per hertz *or* joule per square metre, per metre	$J\cdot m^{-2}\cdot Hz^{-1}$ *or* J/m^3	$\mathbf{M}\cdot\mathbf{T}^{-1}$ *or* $\mathbf{M}\cdot\mathbf{L}^{-1}\cdot\mathbf{T}^{-2}$	Radiant exposure of a *surface* per unit frequency or wavelength. The latter is commonly measured in $J\cdot m^{-2}\cdot nm^{-1}$. This is sometimes also called "spectral fluence".

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Hemispherical emissivity	ε	1	Radiant exitance of a *surface*, divided by that of a *black body* at the same temperature as that surface.
Spectral hemispherical emissivity	ε_{ν} or ε_{λ}	1	Spectral exitance of a *surface*, divided by that of a *black body* at the same temperature as that surface.
Directional emissivity	ε_{Ω}	1	Radiance *emitted* by a *surface*, divided by that emitted by a *black body* at the same temperature as that surface.
Spectral directional emissivity	$\varepsilon_{\Omega,\nu}$ or $\varepsilon_{\Omega,\lambda}$	1	Spectral radiance *emitted* by a *surface*, divided by that of a *black body* at the same temperature as that surface.

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Hemispherical absorptance	A	1	Radiant flux *absorbed* by a *surface*, divided by that received by that surface. This should not be confused with "absorbance".
Spectral hemispherical absorptance	A_{ν} or A_{λ}	1	Spectral flux *absorbed* by a *surface*, divided by that received by that surface. This should not be confused with "spectral absorbance".
Directional absorptance	A_{Ω}	1	Radiance *absorbed* by a *surface*, divided by the radiance incident onto that surface. This should not be confused with "absorbance".
Spectral directional absorptance	$A_{\Omega,\nu}$ or $A_{\Omega,\lambda}$	1	Spectral radiance *absorbed* by a *surface*, divided by the spectral radiance incident onto that surface. This should not be confused with "spectral absorbance".

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Hemispherical reflectance	*R*	1	Radiant flux *reflected* by a *surface*, divided by that received by that surface.
Spectral hemispherical reflectance	R_ν or R_λ	1	Spectral flux *reflected* by a *surface*, divided by that received by that surface.
Directional reflectance	R_Ω	1	Radiance *reflected* by a *surface*, divided by that received by that surface.
Spectral directional reflectance	$R_{\Omega,\nu}$ or $R_{\Omega,\lambda}$	1	Spectral radiance *reflected* by a *surface*, divided by that received by that surface.

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Hemispherical transmittance	T	1	Radiant flux *transmitted* by a *surface*, divided by that received by that surface.
Spectral hemispherical transmittance	T_{ν} or T_{λ}	1	Spectral flux *transmitted* by a *surface*, divided by that received by that surface.
Directional transmittance	T_{Ω}	1	Radiance *transmitted* by a *surface*, divided by that received by that surface.
Spectral directional transmittance	$T_{\Omega,\nu}$ or $T_{\Omega,\lambda}$	1	Spectral radiance *transmitted* by a *surface*, divided by that received by that surface.

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Hemispherical attenuation coefficient	μ	reciprocal metre	m^{-1}	$\mathbf{L}^{-1}$	Radiant flux *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.
Spectral hemispherical attenuation coefficient	μ_{ν} or μ_{λ}	reciprocal metre	m^{-1}	$\mathbf{L}^{-1}$	Spectral radiant flux *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.
Directional attenuation coefficient	μ_{Ω}	reciprocal metre	m^{-1}	$\mathbf{L}^{-1}$	Radiance *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.
Spectral directional attenuation coefficient	$\mu_{\Omega,\nu}$ or $\mu_{\Omega,\lambda}$	reciprocal metre	m^{-1}	$\mathbf{L}^{-1}$	Spectral radiance *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.

W. Wang

1. **^** Standards organizations recommend that radiometric quantities should be denoted with suffix "e" (for "energetic") to avoid confusion with photometric or photon quantities.
2. ^ Jump up to: *a* *b* *c* *d* *e* Alternative symbols sometimes seen: *W* or *E* for radiant energy, *P* or *F* for radiant flux, *I* for irradiance, *W* for radiant exitance.
3. ^ Jump up to: *a* *b* *c* *d* *e* *f* *g* Spectral quantities given per unit frequency are denoted with suffix "ν" (Greek)—not to be confused with suffix "v" (for "visual") indicating a photometric quantity.
4. ^ Jump up to: *a* *b* *c* *d* *e* *f* *g* Spectral quantities given per unit wavelength are denoted with suffix "λ" (Greek).
5. ^ Jump up to: *a* *b* Directional quantities are denoted with suffix "Ω" (Greek).

Quantity		Unit		Dimension	Notes
Name	Symbol [nb 1]	Name	Symbol	Symbol	
Luminous energy	Q_v [nb 2]	lumen second	lm·s	**T·J** [nb 3]	Units are sometimes called *talbots*.
Luminous flux / luminous power	Φ_v [nb 2]	lumen (= cd·sr)	lm	**J** [nb 3]	Luminous energy per unit time.
Luminous intensity	I_v	candela (= lm/sr)	cd	**J** [nb 3]	Luminous power per unit solid angle.
Luminance	L_v	candela per square metre	cd/m^2	$\mathbf{L}^{-2}\cdot\mathbf{J}$	Luminous power per unit solid angle per unit *projected* source area. Units are sometimes called *nits*.
Illuminance	E_v	lux (= lm/m^2)	lx	$\mathbf{L}^{-2}\cdot\mathbf{J}$	Luminous power *incident* on a surface.
Luminous exitance / luminous emittance	M_v	lux	lx	$\mathbf{L}^{-2}\cdot\mathbf{J}$	Luminous power *emitted* from a surface.
Luminous exposure	H_v	lux second	lx·s	$\mathbf{L}^{-2}\cdot\mathbf{T}\cdot\mathbf{J}$	
Luminous energy density	ω_v	lumen second per cubic metre	lm·s·m^{-3}	$\mathbf{L}^{-3}\cdot\mathbf{T}\cdot\mathbf{J}$	
Luminous efficacy	η [nb 2]	lumen per watt	lm/W	$\mathbf{M}^{-1}\cdot\mathbf{L}^{-2}\cdot\mathbf{T}^{3}\cdot\mathbf{J}$	Ratio of luminous flux to radiant flux or power consumption, depending on context.
Luminous efficiency / luminous coefficient	V			1	

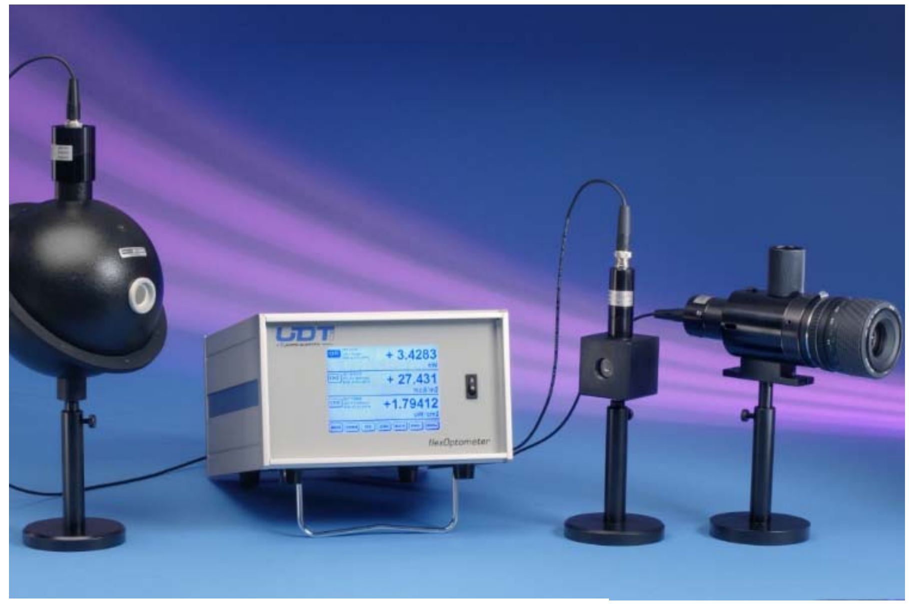
W. Wang

Radiometric Measurement

•**Radiant Flux Measurements** (in units of watts) are performed with an instrument known as a flux meter or optical power meter. This type of testing is typically used for characterizing the total output of sources such as:Lasers, LEDs, Lamps and Fiber-Optic Systems
•**Radiant Intensity Measurements** (in units of W/sr) are performed with an instrument that may be described as an optical intensity meter. This type of testing is typically used for characterizing the output of a relatively small source in a particular direction. Typical devices under test include: LEDs, UV Lamps and IR Lamps
•**Irradiance Measurements** (in units of W/m2) are performed with an irradiance meter. This involves the measurement of the radiant flux incident upon a surface, per unit area. Such measurements are important in the following fields: Medical, Biological and Remote Sensing
•**Radiance Measurements** (in units of W/m2sr) are performed with a radiance meter. This involves measuring the light emitted in a particular direction by a given spot on the surface of an extended source. Such measurements are important in fields such as: Remote Sensing, Avionics and Night Vision

Radiometers

Radiometers. Radiometers are used to measure the amount of electromagnetic energy present within a specific wavelength range. The measurement is expressed in Watts (W) which is a unit of measurement for power. Radiometers are usually used to detect and measure the amount of energy outside the visible light spectrum and are used to measure ultraviolet (UV) light or infrared (IR). A typical use for a UV meter is in the museum lighting world where the presence of UV is can be very troublesome. UV energy hastens the ageing process due to its higher energy content so any energy below 400nm needs to be filtered out or eliminated. Another application for a radiometer is in the detection and measurement of infrared or IR. It is used to detect and measure heat on a surface. Technicians use them to safely detect and repair overheating motors or shorted out wiring. Radiometers can measure very quickly because they are simple meters that use only one sensor with a filter designed to just measure the wavelength range they were intended for.



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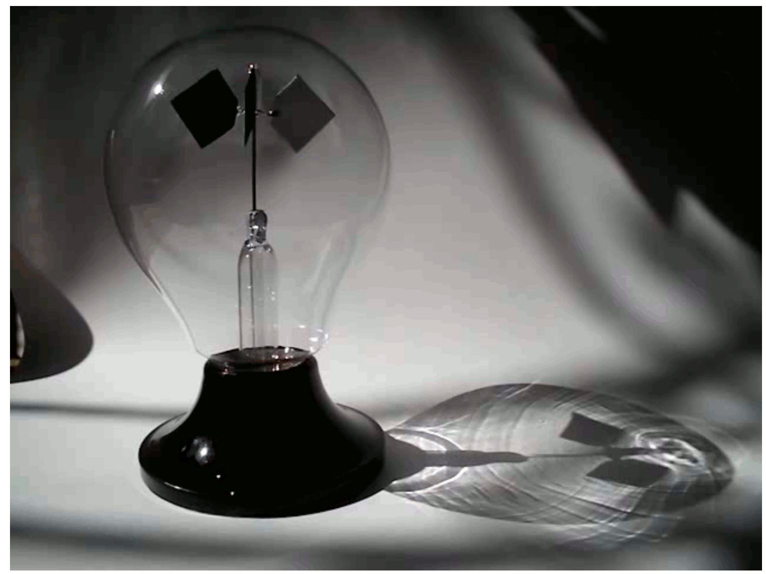
First Radiometer

The radiometer is made from a glass bulb from which much of the air has been removed to form a partial vacuum. Inside the bulb, on a low friction spindle, is a rotor with several (usually four) vertical lightweight metal vanes spaced equally around the axis. The vanes are polished or white on one side and black on the other.



When exposed to sunlight, artificial light, or infrared radiation (even the heat of a hand nearby can be enough), the vanes turn with no apparent motive power, the dark sides retreating from the radiation source and the light sides advancing.

Cooling the radiometer causes rotation in the opposite direction.

Photometric Measurement

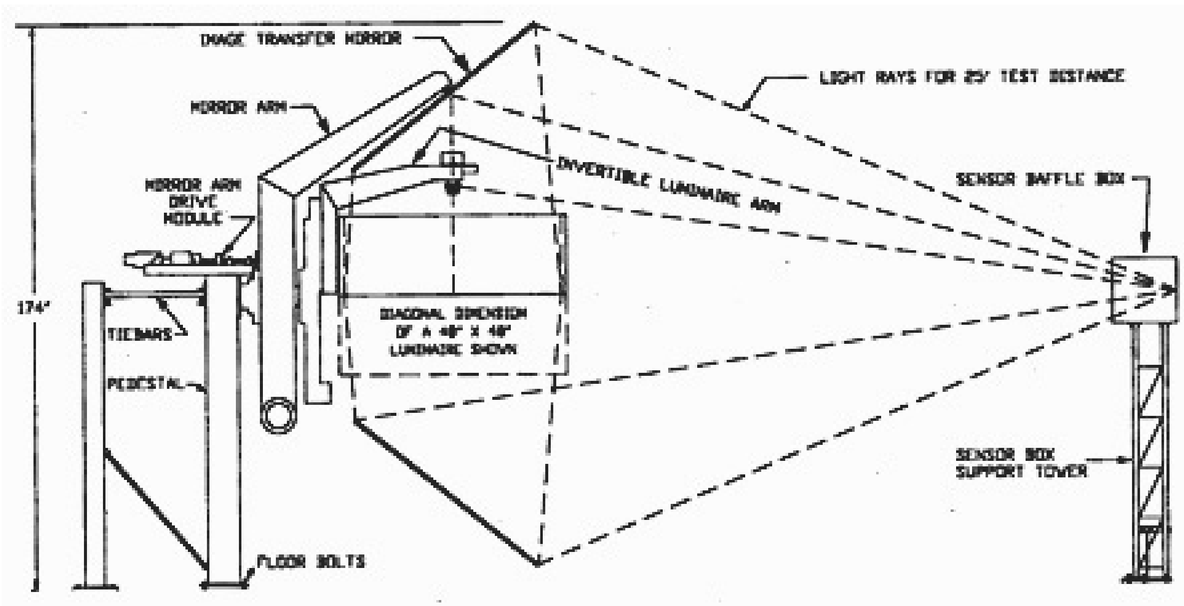
Photometric measurement is based on photodetectors, devices (of several types) that produce an electric signal when exposed to light. Simple applications of this technology include switching luminaires on and off based on ambient light conditions, and light meters, used to measure the total amount of light incident on a point.

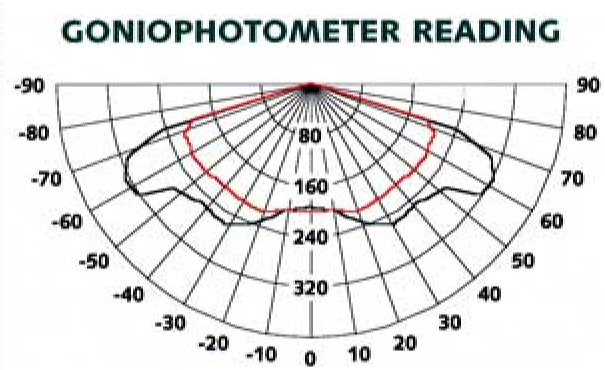
More complex forms of photometric measurement are used frequently within the lighting industry. Spherical photometers can be used to measure the directional luminous flux produced by lamps, and consist of a large-diameter globe with a lamp mounted at its center. A photocell rotates about the lamp in three axes, measuring the output of the lamp from all sides.

Lamps and lighting fixtures are tested using goniophotometers and rotating mirror photometers, which keep the photocell stationary at a sufficient distance that the luminaire can be considered a point source. Rotating mirror photometers use a motorized system of mirrors to reflect light emanating from the luminaire in all directions to the distant photocell; goniophotometers use a rotating 2-axis table to change the orientation of the luminaire with respect to the photocell. In either case, luminous intensity is tabulated from this data and used in lighting design.

Goniophotometers

A Goniophotometer is a device used for measurement of the light emitted from an object at different angles.[1] The use of goniophotometers has been increasing in recent years with the introduction of LED-light sources, which are mostly directed light sources, where the spatial distribution of light is not homogeneous.[2] If a light source is homogeneous in its distribution of light, it is called a Lambertian source.[3] Due to strict regulations, the spatial distribution of light is of high importance to automotive lighting and its design.





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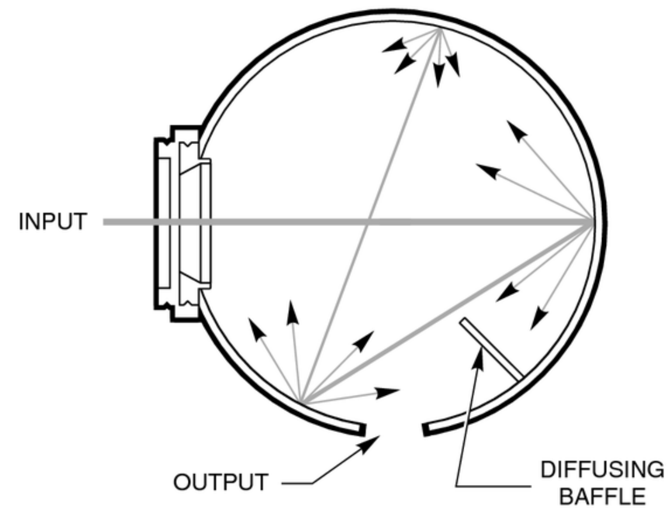
Spherical photometers

Luminous flux measurement is to determine the total visible energy emitted by a light source. An integrating sphere is often used to converge all the power emitted by the source to the detector head.



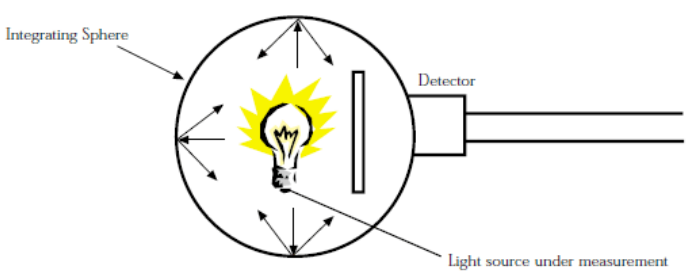


Fig. 3.2.3.3 - Total luminous flux measurement using an integrating sphere

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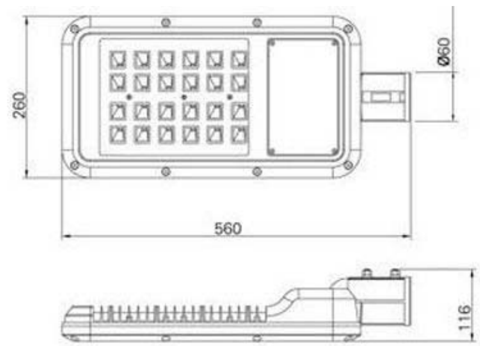
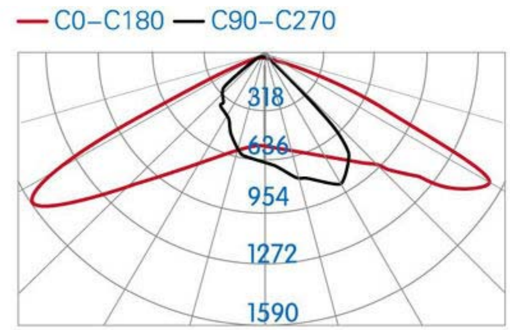
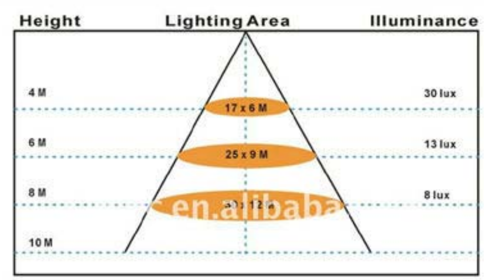
Handheld Photometer

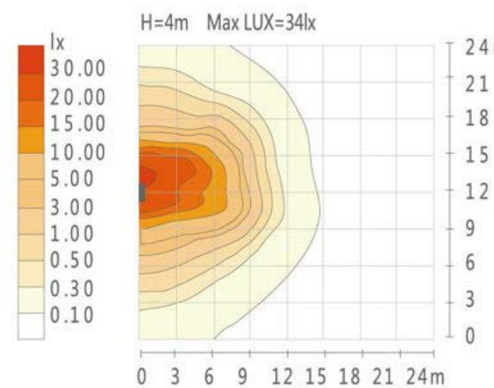


product dimensions



Distribution Curve Flux





Led Street Lamp Varies With Distance Illuminance

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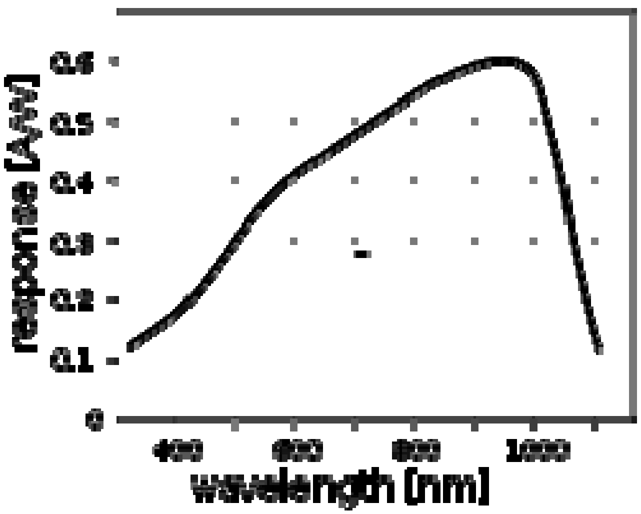
Silicon Detector with Flat Response Filter



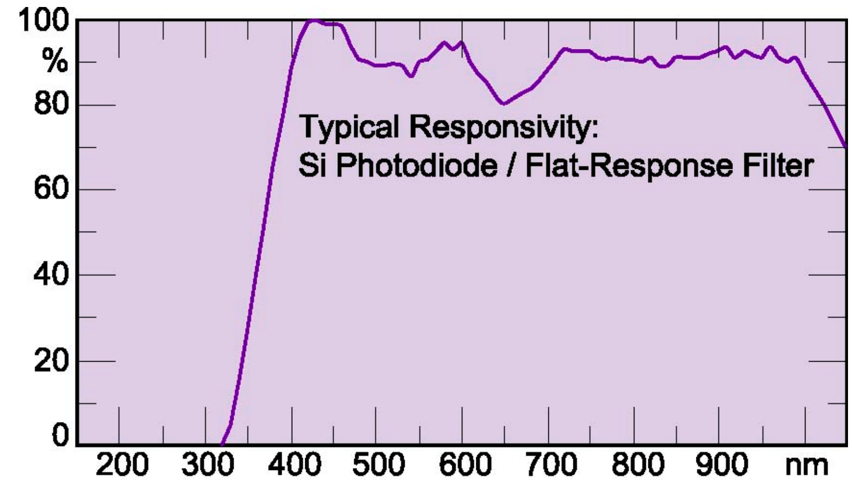


Fig. 2.2 Relative spectral responsivity of a flat response detector.

Since silicon photodiodes are more sensitive to light at the red end of the spectrum than to light at the blue end, radiometric detectors filter the incoming light to even out the responsivity, producing a "flat response". This is important for accurate radiometric measurements, because the spectrum of a light source may be unknown, or may be dependent on operating conditions such as input voltage.

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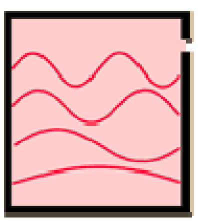
Blackbody Radiation

Blackbody radiation" or "cavity radiation" refers to an object or system which absorbs all radiation incident upon it and re-radiates energy which is characteristic of this radiating system only, not dependent upon the type of radiation which is incident upon it. The radiated energy can be considered to be produced by standing wave or resonant modes of the cavity which is radiating

Radiation modes in a hot cavity provide a test of quantum theory



	#Modes per unit frequency per unit volume	Probability of occupying modes	Average energy per mode
CLASSICAL	$\frac{8\pi\nu^2}{c^3}$	Equal for all modes	kT
QUANTUM	$\frac{8\pi\nu^2}{c^3}$	Quantized modes: require $h\nu$ energy to excite upper modes, less probable	$\frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$