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RADIOMETRY AND PHOTOMETRY: UNITS AND CONVERSIONS

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36.1 GLOSSARY†

A	area, m^2
A_{proj}	projected area, m^2
E, E_e	radiant incidance (irradiance), W m^{-2}
E_p, E_q	photon incidance, s^{-1} m^{-2}
E_v	illuminance, lm m^{-2} [lux (lx)]
I, I_e	radiant intensity, W sr^{-1}
I_p, I_q	photon intensity, s^{-1} sr^{-1}
I_v	luminous intensity, candela (cd)
K_m	absolute luminous efficiency at λ_p for photopic vision, 683 lm/W
K'_m	absolute luminous efficiency at λ_p for scotopic vision, 1700 lm/W
$K(\lambda)$	absolute spectral luminous efficiency, photopic vision, lm/W
$K'(\lambda)$	absolute spectral luminous efficiency, scotopic vision, lm/W
L, L_e	radiance, W m^{-2} sr^{-1}
L_p, L_q	photon radiance (photonance), s^{-1} m^{-2} sr^{-1}
L_v	luminance, cd sr^{-1}
M, M_e	radiant exitance, W m^{-2}
M_p, M_q	photon exitance, s^{-1} m^{-2}
Q, Q_e	radiant energy, joule (J)
Q_p, Q_q	photon energy, J or eV
Q_v	luminous energy, lm s^{-1}

*Deceased.
†*Note.* The subscripts are used as follows: *e* (energy) for radiometric, *v* (visual) for photometric, and *q* (or *p*) for photonic. The subscript *e* is usually omitted; the other subscripts may also be omitted if the context is unambiguous.

$\mathfrak{R}(\lambda)$	spectral responsivity, A/W or V/W
$V(\lambda)$	relative spectral luminous efficiency, photopic vision
$V'(\lambda)$	relative spectral luminous efficiency, scotopic vision
$V_q(\lambda)$	relative spectral luminous efficiency for photons
λ	wavelength, nm or μm
λ_p	wavelength at peak of function, nm or μm
Φ, Φ_e	radiant power (radiant flux), watt (W)
Φ_p, Φ_q	photon flux, s^{-1}
Φ_v	luminous power (luminous flux), lumen (lm)
ω	solid angle, steradian (sr)
Ω	projected solid angle, sr

36.2 INTRODUCTION AND BACKGROUND

After more than a century of turmoil, the symbols, units, and nomenclature (SUN) for radiometry and photometry seem somewhat stable at present. There are still small, isolated pockets of debate and even resistance; by and large, though, the community has settled on the International System of Units (SI) and the recommendations of the International Organization for Standardization (ISO)[1] and the International Union of Pure and Applied Physics (IUPAP).[2]

The seed of the SI was planted in 1799 with the deposition of two prototype standards, the meter and the kilogram, into the Archives de la République in Paris. Noted physicists Gauss, Weber, Maxwell, and Thompson made significant contributions to measurement science over the next 75 years. Their efforts culminated in the Convention of the Meter, a diplomatic treaty originally signed by representatives of 17 nations in 1875 (currently there are 48 member nations). The Convention grants authority to the General Conference on Weights and Measures (CGPM), the International Committee for Weights and Measures (CIPM), and the International Bureau of Weights and Measures (BIPM). The CIPM, along with a number of subcommittees, suggests modifications to the CGPM. In our arena, the subcommittee is the Consultative Committee on Photometry and Radiometry (CCPR). The BIPM, the international metrology institute, is the physical facility that is responsible for realization, maintenance, and dissemination of standards.

The SI was adopted by the CGPM in 1960 and is the official system in the 48 member states. It currently consists of seven base units and a much larger number of derived units. The base units are a choice of seven well-defined units that, by convention, are regarded as independent. The seven base units are as follows:

1. Meter
2. Kilogram
3. Second
4. Ampere
5. Kelvin
6. Mole
7. Candela

The derived units are those that are formed by various combinations of the base units.

International organizations involved in the promulgation of SUN include the International Commission on Illumination (CIE), the IUPAP, and the ISO. In the United States, the American National Standards Institute (ANSI) is the primary documentary (protocol) standards organization. Many other scientific and technical organizations publish recommendations concerning the use of SUN for their scholarly journals. Several examples are the Illuminating Engineering Society

TABLE 1 Projected Areas of Common Shapes

Shape	Area	Projected area
Flat rectangle	$A = L \times W$	$A_{proj} = L \times W \cos\beta$
Circular disc	$A = \pi r^2 = \pi d^2/4$	$A_{proj} = \pi r^2 \cos\beta = (\pi d^2 \cos\beta)/4$
Sphere	$A = 4\pi r^2 = \pi d^2$	$A_{proj} = A/4 = \pi r^2$

(IESNA), the International Astronomical Union (IAU), the Institute for Electrical and Electronic Engineering (IEEE), and the American Institute of Physics (AIP).

The terminology employed in radiometry and photometry consists principally of two parts: (1) an adjective distinguishing between a radiometric, photonic, or photometric entity, and (2) a noun describing the underlying geometric or spatial concept. In some instances, the two parts are replaced by a single term (e.g., radiance).

There are some background concepts and terminology that are needed before proceeding further.

Projected area is defined as the rectilinear projection of a surface of any shape onto a plane normal to the unit vector. The differential form is $dA_{proj} = \cos(\beta)dA$, where β is the angle between the local surface normal and the line of sight. Integrate over the (observable) surface area to get

$$A_{proj} = \int_A \cos\beta \, dA \tag{1}$$

Some common examples are shown in Table 1.

Plane angle and solid angle are both derived units in the SI system. The following definitions are from National Institute of Standards and Technology (NIST) SP811.[3]

> The radian is the plane angle between two radii of a circle that cuts off on the circumference an arc equal in length to the radius.

The abbreviation for the radian is *rad.* Since there are 2π rad in a circle, the conversion between degrees and radians is 1 rad = $(180/\pi)$ degrees. (See Fig. 1.)

A solid angle is the same concept that is extended to three dimensions.

> One steradian (sr) is the solid angle that, having its vertex in the center of a sphere, cuts off an area on the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

The solid angle is the ratio of the spherical area (A_{proj}) to the square of the radius, *r.* The spherical area is a projection of the object of interest onto a unit sphere, and the solid angle is the surface area of that projection, as shown in Fig. 2. Divide the surface area of a sphere by the square of its radius to find that there are 4π sr of solid angle in a sphere. One hemisphere has 2π sr. The accepted symbols

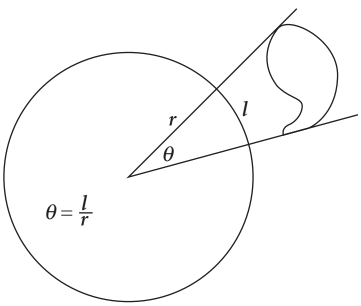

FIGURE 1 Plane angle.

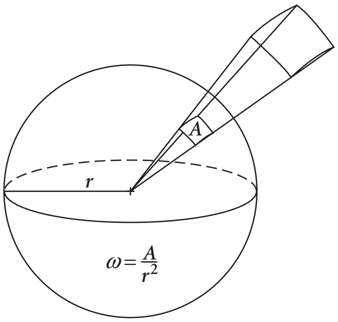

FIGURE 2 Solid angle.

for solid angle are either lowercase Greek omega (ω) or uppercase Greek omega (Ω). I recommend using ω exclusively for solid angle, and reserving Ω for the advanced concept of projected solid angle ($\omega \cos \theta$). The equation for solid angle is $d\omega = dA_{proj}/r^2$. For a right circular cone, $\omega = 2\pi(1 - \cos \theta)$, where θ is the half-angle of the cone.

Both plane angles and solid angles are dimensionless quantities, and they can lead to confusion when attempting dimensional analysis. For example, the simple inverse square law, $E = I/d^2$ appears dimensionally inconsistent. The left side has units W m^{-2} while the right side has W sr^{-1} m^{-2}. It has been suggested that this equation be written $E = I\Omega_0/d^2$, where Ω_0 is the unit solid angle, 1 sr. Inclusion of the term Ω_0 will render the equation dimensionally correct, but will far too often be considered a free variable rather than a constant equal to 1, leading to erroneous results.

Isotropic and lambertian both carry the meaning "the same in all directions" and, regrettably, are used interchangeably.

Isotropic implies a spherical source that radiates the same amount in all directions [i.e., the intensity (W/sr or cd) is independent of direction]. The term *isotropic point source* is often heard. No such entity can exist, for the energy density would necessarily be infinite. A small, uniform sphere comes very close. Small in this context means that the size of the sphere is much less than the distance from the sphere to the plane of observation, such that the inverse square law is applicable. An example is a globular tungsten lamp with a milky white diffuse envelope some 10 cm in diameter, as viewed from a distance greater than 1 m. From our vantage point, a distant star is considered an isotropic point source.

Lambertian implies a flat radiating surface. It can be an active emitter or a passive, reflective surface. The intensity decreases with the cosine of the observation angle with respect to the surface normal (Lambert's law). The radiance (W m^2 sr^{-1}) or luminance (cd m^{-2}) is independent of direction. A good approximation is a surface painted with a quality matte, or flat, white paint. The intensity is the product of the radiance, L, or luminance, L_v, and the projected area A_{proj}. If the surface is uniformly illuminated, it appears equally bright from whatever direction it is viewed. Note that the flat radiating surface can be used as an elemental area of a curved surface.

The ratio of the radiant exitance (power per unit area, W m^{-2}) to the radiance (power per unit projected area per unit solid angle, W m^2 sr^{-1}) of a lambertian surface is a factor of π and not 2π. This result is not intuitive, as, by definition, there are 2π sr in a hemisphere. The factor of π comes from the influence of the $\cos\theta$ term while integrating over a hemisphere.

A sphere with a lambertian surface illuminated by a distant point source will display a radiance that is maximum at the point where the local normal coincides with the incoming beam. The radiance will fall off with a cosine dependence to zero at the terminator. If the intensity (integrated radiance over area) is unity when viewing from the direction of the source, then the intensity when viewing from the side is $1/\pi$. Think about this and ponder whether our Moon has a lambertian surface.

36.3 SYMBOLS, UNITS, AND NOMENCLATURE IN RADIOMETRY

Radiometry is the measurement of optical radiation, defined as electromagnetic radiation within the frequency range from 3×10^{11} to 3×10^{16} hertz (Hz). This range corresponds to wavelengths between 0.01 and 1000 micrometers (μm) and includes the regions commonly called *ultraviolet, visible,* and *infrared.*

Radiometric units can be divided into two conceptual areas: (1) those having to do with power or energy, and (2) those that are geometric in nature. In the first category are:

Energy is an SI-derived unit, measured in joules (J). The recommended symbol for energy is Q. An acceptable alternate is W.

Power (also called *radiant flux*) is another SI-derived unit. It is the derivative of energy with respect to time, dQ/dt, and the unit is the watt (W). The recommended symbol for power is uppercase Greek phi (Φ). An accepted alternate is P.

Energy is the integral of power over time, and it is commonly used with integrating detectors and pulsed sources. Power is used for continuous sources and nonintegrating detectors. The radiometric quantity power can now be combined with the geometric spatial quantities area and solid angle.

Irradiance (also referred to *as flux density* or *radiant incidance*) is an SI-derived unit and is measured in W m^{-2}. Irradiance is power per unit area *incident* from all directions within a hemisphere onto a surface that coincides with the base of that hemisphere. A related quantity is *radiant exitance,* which is power per unit area *leaving* a surface into a hemisphere whose base is that surface. The symbol for irradiance is E, and the symbol for radiant exitance is M. Irradiance (or radiant exitance) is the derivative of power with respect to area, $d\Phi/dA$. The integral of irradiance or radiant exitance over area is power. There is no compelling reason to have two quantities carrying the same units, but it is convenient.

Radiant intensity is an SI-derived unit and is measured in W sr^{-1}. Intensity is power per unit of solid angle. The symbol is I. *Intensity* is the derivative of power with respect to solid angle, $d\Phi/dA$ The integral of radiant intensity over solid angle is power.

A great deal of confusion surrounds the use and misuse of the term *intensity.* Some use it for W sr^{-1}*;* some use it for W m^{-2}; others use it for W m^{-2} sr^{-1}. It is quite clearly defined in the SI system, in the definition of the base unit of luminous intensity—the candela. Attempts are often made to justify these different uses of intensity by adding adjectives like *optical* or *field* (used for W m^{-2}) or *specific* (used for W m^{-2} sr^{-1}). In the SI system, the underlying geometric concept for intensity is quantity per unit solid angle. For more discussion, see Palmer.[4]

Radiance is an SI-derived unit and is measured in W m^{-2} sr^{-1}. Radiance is a directional quantity, power per unit projected area per unit solid angle. The symbol is L. Radiance is the derivative of power with respect to solid angle and projected area, $d\Phi/d\omega\, dA \cos\theta$, where θ is the angle between the surface normal and the specified direction. The integral of radiance over area and solid angle is power.

Photon quantities are also common. They are related to the radiometric quantities by the relationship $Q_p = hc/\lambda$, where Q_p is the energy of a photon at wavelength λ, h is Planck's constant, and c is the velocity of light. At a wavelength of 1 μm, there are approximately 5×10^{18} photons per second in a watt. Conversely, one photon has an energy of about 2×10^{-19} J (W/s) at 1 μm.

36.4 SYMBOLS, UNITS, AND NOMENCLATURE IN PHOTOMETRY

Photometry is the measurement of light, electromagnetic radiation detectable by the human eye. It is thus restricted to the wavelength range from about 360 to 830 nanometers (nm; 1000 nm = 1 μm). Photometry is identical to radiometry *except* that everything is weighted by the spectral response of the nominal human eye. *Visual photometry* uses the eye as a comparison detector, while *physical photometry* uses either optical radiation detectors constructed to mimic the spectral response of the nominal eye, or spectroradiometry coupled with appropriate calculations to do the eye response weighting.

Photometric units are basically the same as the radiometric units, except that they are weighted for the spectral response of the human eye and have strange names. A few additional units have been introduced to deal with the amount of light that is reflected from diffuse (matte) surfaces. The symbols used are identical to the geometrically equivalent radiometric symbols, except that a subscript v is added to denote *visual.* Table 2 compares radiometric and photometric units.

The SI unit for light is the *candela* (unit of luminous intensity). It is one of the seven base units of the SI system. The candela is defined as follows:[5]

> The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

The candela is abbreviated as *cd,* and its symbol is I_v. This definition was adopted by the 16th CGPM in 1979. The candela was formerly defined as the luminous intensity, in the perpendicular direction,

TABLE 2 Comparison of Radiometric and Photometric Units

Quantity	Radiometric	Photometric
Power	Φ: watt (W)	Φ_v: lumen (lm)
Power per area	E, M: W m^{-2}	E_v: lm m^{-2} = lux (1x)
Power per solid angle	I: W sr^{-1}	I_v: lm sr^{-1} = candela (cd)
Power per area per solid angle	L: W m^{-2} sr^{-1}	L_v: lm m^{-2}sr^{-1} = cd m^{-2} = nit

of a surface of 1/600,000 m^2 of a blackbody at the temperature of freezing platinum under a pressure of 101,325 newtons per square meter (N m^{-2}). This earlier definition was initially adopted in 1948 and later modified by the 13th CGPM in 1968. It was abrogated in 1979 and replaced by the current definition.

The 1979 definition was adopted for several reasons.[6–10] First, the realization of the candela using a platinum blackbody was extraordinarily difficult—only several were ever built, and there were large variations between the units realized by different national laboratories based upon the state of platinum at its freezing point. The difficulty in fabricating and operating the platinum point blackbody created an unacceptable uncertainty in the value of the candela. For example, if the platinum blackbody temperature is slightly off, possibly because of temperature gradients in the ceramic crucible or contamination of the platinum, the freezing point may change or the temperature of the cavity may differ. The sensitivity of the candela to a slight change in temperature is significant. At a wavelength of 555 nm, a change in temperature of only 1 K results in a luminance change approaching 1 percent. Second, the unit of the candela was realized on the specific broadband radiation, whose spectral power distribution was not known with satisfactory accuracy (because the platinum fix point temperature was not precisely known), thus there were large uncertainties in determining photometric quantities of various other practical light sources from their spectral power distributions. Third, recent advances in radiometry based on absolute radiometers offered new possibilities for realization of the candela using a much simpler device with much lower uncertainties if the candela is defined in relation to watt. In 1977, through an international comparison among several national laboratories, the Comité International des Poids et Mesures (CIPM) determined the numerical relationship (683 lm/W at 555 nm) to be recommended for the new standard for candela so that the magnitude of the unit was kept consistent with the previous unit of the candela.

The value of 683 lm/W was selected based upon the best measurements with existing platinum freezing point blackbodies at several national standards laboratories. It has varied over time from 620 to nearly 700 lm/W, depending largely upon the assigned value of the freezing point of platinum. The value of 1/600,000 m^2 was chosen to maintain consistency with prior standards. Note that neither the old nor the new definition of the candela say anything about the spectral responsivity of the human eye. There are additional definitions that include the characteristics of the eye, but the base unit (candela) and those SI units derived from it are "eyeless."

Note also that in the definition of the candela, there is no specification for the spatial distribution of intensity. Luminous intensity, while often associated with an isotropic point (i.e., small) source, is a valid specification for characterizing any highly directional light source, such as a spotlight or an LED.

One other issue: since the candela is no longer independent but is now defined in terms of other SI-derived quantities, there is really no need to retain it as an SI base quantity. It remains so for reasons of history and continuity and perhaps some politics.

The *lumen* is an SI-derived unit for luminous flux (power). The abbreviation is *lm*, and the symbol is Φ_v. The lumen is derived from the candela and is the luminous flux that is emitted into unit solid angle (1 sr) by an isotropic point source having a luminous intensity of 1 cd. The lumen is the product of luminous intensity and solid angle (cd sr). It is analogous to the unit of radiant flux (watt), differing only in the eye response weighting. If a light source is isotropic, the relationship between lumens and candelas is 1 cd = 4π lm. In other words, an isotropic source that has a luminous intensity of 1 cd emits 4π lm into space, which is 4π sr. Also, 1 cd = 1 lm sr^{-1}, which is analogous to the equivalent radiometric definition.

If a source is not isotropic, the relationship between candelas and lumens is empirical. A fundamental method used to determine the total flux (lumens) is to measure the luminous intensity (candelas) in many directions using a goniophotometer, and then numerically integrate over the entire sphere. Later on, this "calibrated" lamp can be used as a reference in an integrating sphere for routine measurements of luminous flux.

The SI-derived unit of luminous flux density, or illuminance, has a special name: *lux*. It is lumens per square meter (lm m^{-2}), and the symbol is E_v. Most light meters measure this quantity, as it is of great importance in illuminating engineering. The IESNA's *Lighting Handbook*[11] has some 16 pages of recommended illuminances for various activities and locales, ranging from morgues to museums. Typical values range from 100,000 lx for direct sunlight to between 20 and 50 lx for hospital corridors at night.

Luminance should probably be included on the list of SI-derived units, but it is not. Luminance is analogous to radiance, giving the spatial and directional dependences. It also has a special name, *nit*, and is candelas per square meter (cd m^{-2}) or lumens per square meter per steradian (lm m^{-2} sr^{-1}). The symbol is L_v. Luminance is most often used to characterize the "brightness" of flat-emitting or -reflecting surfaces. A common use is the luminance of a laptop computer screen. They typically have between 100 and 250 nits, and the sunlight-readable ones have more than 1000 nits. Typical CRT monitors have luminances between 50 and 125 nits.

Other Photometric Units

There are other photometric units, largely historical. The literature is filled with now obsolete terminology, and it is important to be able to properly interpret these terms. Here are several terms for illuminance that have been used in the past.

1 meter-candle = 1 lx

1 phot (ph) = 1 lm cm^{-2} = 10^4 lx

1 footcandle (fc) = 1 lm ft^{-2} = 10.76 lx

1 milliphot = 10 lx

Table 3 is useful to convert from one unit to another. Start with the unit in the leftmost column and multiply it by the factor in the table to arrive at the unit in the top row.

There are two classes of units that are used for luminance. The first is conventional, directly related to the SI unit, the cd m^{-2} (nit).

1 stilb = 1 cd cm^{-2} = 10^4 cd m^{-2} = 10^4 nit

1 cd ft^{-2} = 10.76 cd m^{-2} = 10.76 nit

The second class was designed to "simplify" characterization of light that is reflected from diffuse surfaces by incorporating within the definition the concept of a perfect diffuse reflector (lambertian, reflectance $\rho = 1$). If 1 unit of illuminance falls upon this ideal reflector, then 1 unit of luminance is reflected. The perfect diffuse reflector emits $1/\pi$ units of luminance per unit of illuminance. If the reflectance is ρ, then the luminance is ρ/π times the illuminance. Consequently, these units all incorporate a factor of $1/\pi$.

1 lambert (L) = $(1/\pi)$ cd cm^{-2} = $(10^4/\pi)$ cd m^2 = $(10^4/\pi)$ nit

1 apostilb = $(1/\pi)$ cd m^{-2} = $(1/\pi)$ nit

1 foot-lambert (ft-lambert) = $(1/\pi)$ cd ft^{-2} = 3.426 cd m^{-2} = 3.426 nit

1 millilambert = $(10/\pi)$ cd m^{-2} = $(10/\pi)$ nit

1 skot = 1 milliblondel = $(10^{-3}/\pi)$ cd m^{-2} = $10^{-3}/\pi$ nit

TABLE 3 Illuminance Unit Conversions

	fc	lx	phot	milliphot
1 fc (lm/ft^2) =	1	10.764	0.0010764	1.0764
1 lx (lm/m^2) =	0.0929	1	0.0001	0.1
1 phot(lm/cm^2) =	929	10,000	1	0.001
1 milliphot =	0.929	10	0.1	1

TABLE 4 Illuminance Unit Conversions*

	nit	stilb	cd/ft^2	apostilb	lambert	ft-lambert
1 nit(cd/m^2) =	1	10^{-4}	0.0929	π	π/10000	0.0929π
1 stilb (cd/cm^2) =	10,000	1	929	$10^4\pi$	π	929π
1 cd/ft^2 =	10.764	1.0764×10^{-3}	1	10.764π	π/929	π
1 apostilb =	1/π	$10^4/\pi$	0.0929/π	1	10^{-4}	0.0929
1 lambert =	$10^4/\pi$	1/π	929/π	10^4	1	929
1 ft·lambert =	10.76/π	1/(929π)	1/π	10.764	1.076×10^4	1

**Note:* Photometric quantities are the result of an integration over wavelength. It therefore makes no sense to speak of spectral luminance or the like.

Table 4 is useful to convert from one unit to another. Start with the unit in the leftmost column and multiply it by the factor in the table to arrive at the unit in the top row.

Human Eye The SI base unit and units derived therefrom have a strictly physical basis; they have been defined monochromatically at a wavelength of 555 nm. But the eye does not see all wavelengths equally. For other wavelengths or for band or continuous-source spectral distributions, the spectral properties of the human eye must be considered. The eye has two general classes of photosensors: *cones* and *rods.*

Cones The cones are responsible for light-adapted vision; they respond to color and have high resolution in the central foveal region. The light-adapted relative spectral response of the eye is called the *spectral luminous efficiency function for photopic vision*, $V(\lambda)$, and is published in tabular form.[12] This empirical curve, shown in Fig. 3, was first adopted by the CIE in 1924. It has a peak that is normalized to unity at 555 nm, and it decreases to levels below 10^{-5} at about 370 and 785 nm. The 50 percent points are near 510 and 610 nm, indicating that the curve is slightly skewed. A logarithmic representation is shown in Fig. 4.

More recent measurements have shown that the 1924 curve may not best represent typical human vision. It appears to underestimate the response at wavelengths shorter than 460 nm. Judd,[13] Vos,[14] and Stockman and Sharpe[15] have made incremental advances in our knowledge of the photopic response.

Rods The rods are responsible for dark-adapted vision, with no color information and poor resolution when compared with the foveal cones. The dark-adapted relative spectral response of the

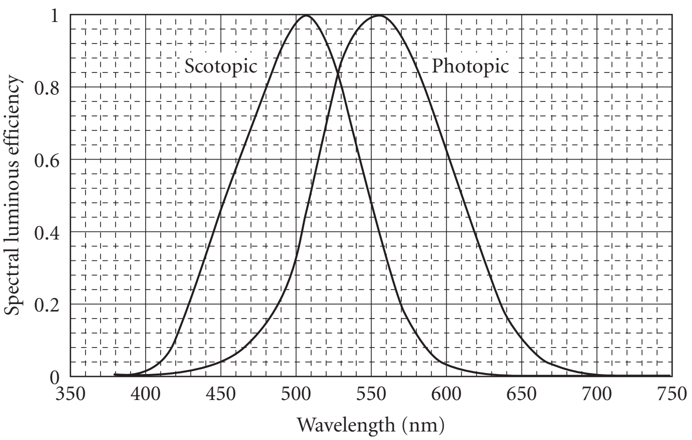

FIGURE 3 Spectral luminous efficiency for photopic and scotopic vision.

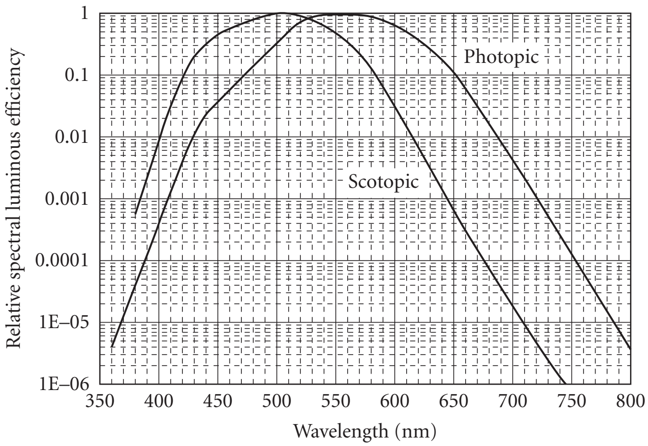

FIGURE 4 Spectral luminous efficiency for photopic and scotopic vision (log scale).

eye is called the *spectral luminous efficiency function for scotopic vision*, $V(\lambda)$, also published in tabular form.[12] Figures 3 and 4 also show this empirical curve, which was adopted by the CIE in 1951. It is defined between 380 and 780 nm. The $V(\lambda)$ curve has a peak of unity at 507 nm, and it decreases to levels below 10^{-3} at about 380 and 645 nm. The 50 percent points are near 455 and 550 nm.

Photopic (light-adapted cone) vision is active for luminances that are greater than 3 cd m^{-2}. Scotopic (dark-adapted rod) vision is active for luminances that are lower than 0.01 cd m^{-2}. In between, both rods and cones contribute in varying amounts, and in this range the vision is called *mesopic*. There have been efforts to characterize the composite spectral response in the mesopic range for vision research at intermediate luminance levels. Definitive values at 1-nm intervals for both photopic and scotopic spectral luminous efficiency functions may be found in CIE.[12] Values at 5-nm intervals are given by Zalewski.[16]

The relative spectral luminous efficiency functions can be converted for use with photon flux (s^{-1}) by multiplying by the spectrally dependent conversion from watts to photons per second. The results are shown in Fig. 5. The curves are similar to the spectral luminous efficiency curves, with the peaks shifted to slightly shorter wavelengths, and the skewness of the curves is different. This function

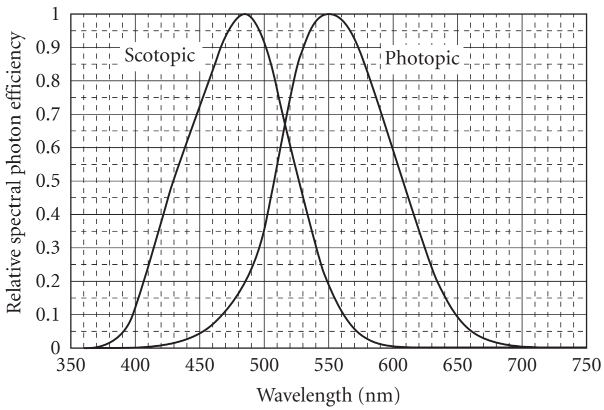

FIGURE 5 Spectral photon efficiency for scotopic and photopic vision.

can be called $V_q(\lambda)$ for photopic response or $V'_q(\lambda)$ for scotopic response. The conversion to an absolute curve is made by multiplying by the response at the peak wavelength. For photopic vision ($\lambda = 550$ nm), $K_{mp} = 2.45 \times 10^{-16}$ lm/photon s^{-1}. There are, therefore, 4.082×10^{15} photon s^{-1} lm^{-1} at 550 nm, and more at all other wavelengths. For scotopic vision ($\lambda_p = 504$ nm), $K'_{mp} = 6.68 \times 10^{-16}$ lm/photon s^{-1}. There are 1.497×10^{15} photon s^{-1} lm^{-1} at 504 nm, and more at all other wavelengths.

Approximations The $V(\lambda)$ curve appears similar to a Gaussian (normal) function. A nonlinear regression technique was used to fit the Gaussian shown in Eq. (2) to the $V(\lambda)$ data

$$V(\lambda) \cong 1.019e^{-285.4(\lambda-0.559)^2} \tag{2}$$

The scotopic curve can also be fit with a Gaussian, although the fit is not quite as good as the photopic curve. My best fit is

$$V'(\lambda) \cong 0.992e^{-321.0(\lambda-0.503)^2} \tag{3}$$

The results of the curve fitting are shown in Figs. 6 and 7. These approximations are satisfactory for application with continuous spectral distributions, such as sunlight, daylight, and incandescent sources. Calculations have demonstrated errors of less than 1 percent with blackbody sources from 1500 K to more than 20,000 K. The equations must be used with caution for narrowband or line sources, particularly in those spectral regions where the response is low and the fit is poor.

Usage The SI definition of the candela was chosen in strictly physical terms at a single wavelength. The intent of photometry, however, is to correlate a photometric observation to the visual perception of a human observer. The CIE introduced the two standard spectral luminous efficiency functions $V(\lambda)$ (photopic) and $V'(\lambda)$ (scotopic) as spectral weighting functions, and they have been approved by the CIPM for use with light sources at other wavelengths. Another useful function is the CIE $V_M(\lambda)$ Judd-Vos modified $V(\lambda)$ function,[14] which has increased response at wavelengths that are shorter than 460 nm. It is identical to the $V(\lambda)$ function for wavelengths that are longer than 460 nm. This function, while not approved by CIPM, represents more realistically the spectral responsivity of the eye. More recently, studies on cone responses have led to the proposal of a new, improved luminous spectral efficiency curve, with the suggested designation $V_2^*(\lambda)$.[15]

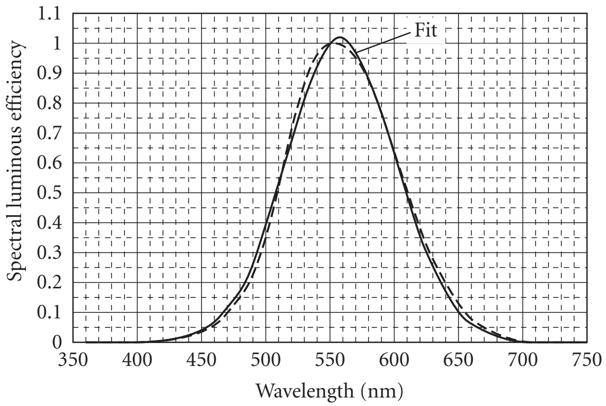

FIGURE 6 Gaussian fit to photopic relative spectral efficiency curve.

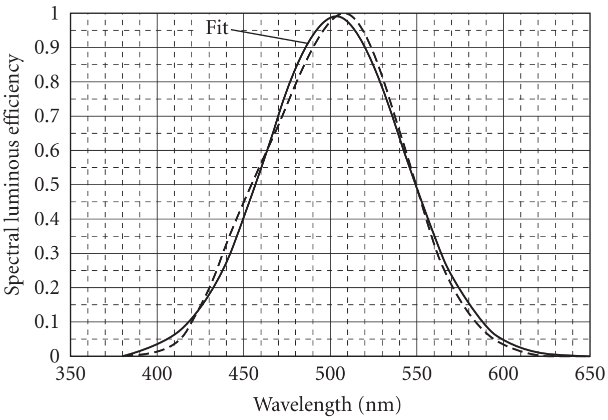

FIGURE 7 Gaussian fit to scotopic relative spectral efficiency curve.

36.5 CONVERSION OF RADIOMETRIC QUANTITIES TO PHOTOMETRIC QUANTITIES

The definition of the candela states that there are 683 lm W^{-1} at a frequency of 540 terahertz (THz), which is very nearly 555 nm (vacuum or air), the wavelength that corresponds to the maximum spectral responsivity of the photopic (light-adapted) human eye. The value 683 lm W^{-1} is K_m, the absolute luminous efficiency at λ_p for photopic vision. The conversion from watts to lumens at any other wavelength involves the product of the power (watts), K_m, and the $V(\lambda)$ value at the wavelength of interest. For example, a 5-mW laser pointer has 0.005 W × 0.032 × 683 lm W^{-1} = 0.11 lm. $V(\lambda)$ is 0.032 at 670 nm. At 635 nm, $V(\lambda)$ is 0.217, and a 5-mW laser pointer has 0.005 W × 0.217 × 683 lm W^{-1} = 0.74 lm. The shorter-wavelength laser pointer will create a spot that has nearly seven times the luminous power as the longer-wavelength laser.

Similar calculations can be done in terms of photon flux at a single wavelength. As was shown previously, there are 2.45×10^{-16} lm in 1 photon s^{-1} at 550 nm, the wavelength that corresponds to the maximum spectral responsivity of the light-adapted human eye to photon flux. The conversion from lumens to photons per second at any other wavelength involves the product of the photon flux (s^{-1}) and the $V_p(\lambda)$ value at the wavelength of interest. For example, again compare laser pointers at 670 and 635 nm. As shown before, a 5-mW laser at 670 nm [$V_p(\lambda) = 0.0264$] has a luminous power of 0.11 lm. The conversion is $0.11 \times 4.082 \times 10^{15}/0.0264 = 1.68 \times 10^{16}$ photon s^{-1}. At 635 nm [$V_p(\lambda) = 0.189$], the 5-mW laser has a luminous power of 0.74 lm. The conversion is $0.74 \times 4.082 \times 10^{15}/0.189 = 1.6 \times 10^{16}$ photon s^{-1}. The 635-nm laser delivers just 5 percent more photons per second.

In order to convert a source with nonmonochromatic spectral distribution to a luminous quantity, the situation is decidedly more complex. The spectral nature of the source must be known, as it is used in an equation of the form

$$X_v = K_m \int_0^\infty X_\lambda V(\lambda) d\lambda \tag{4}$$

where X_v is a luminous term, X_λ is the corresponding spectral radiant term, and $V(\lambda)$ is the photopic spectral luminous efficiency function. For X, luminous flux (lm) may be paired with spectral power (W nm^{-1}), luminous intensity (cd) with spectral radiant intensity (W sr^{-1} nm^{-1}), illuminance (lx) with spectral irradiance (W m^{-2} nm^{-1}), or luminance (cd m^{-2}) with spectral radiance (W m^{-2} sr^{-1} nm^{-1}). This equation represents a weighting, wavelength by wavelength, of the radiant spectral term

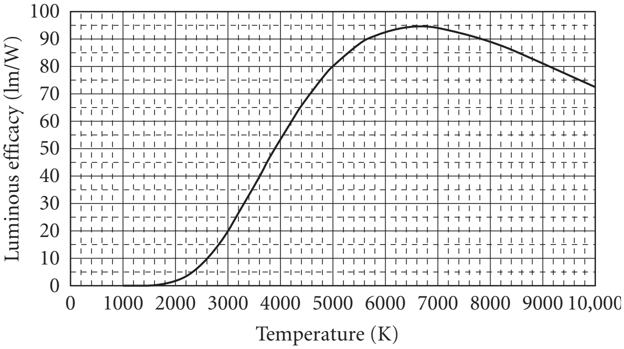

FIGURE 8 Luminous efficacy of blackbody radiation versus temperature (K).

by the visual response at that wavelength. The constant K_m is the maximum spectral luminous efficiency for photopic vision, 683 lm W^{-1}. The wavelength limits can be set to restrict the integration to only those wavelengths where the product of the spectral term X_λ and $V(\lambda)$ is nonzero. Practically, the limits of integration need only extend from 360 to 830 nm, limits specified by the CIE $V(\lambda)$ function. Since this $V(\lambda)$ function is defined by a table of empirical values,[12] it is best to do the integration numerically. Use of the Gaussian equation [Eq. (2)] is only an approximation.

For source spectral distributions that are blackbody-like (thermal source, spectral emissivity constant between 360 and 830 nm) and of known source temperature, it is straightforward to convert from power to luminous flux and vice versa. Equation (4) is used to determine a scale factor for the source term X_λ. Figure 8 shows the relationship between total power and luminous flux for blackbody (and graybody) radiation as a function of blackbody temperature. The most efficient temperature for the production of luminous flux is near 6630 K.

There is nothing in the SI definitions of the base or derived units concerning the eye response, so there is some flexibility in the choice of the weighting function. The choice can be made to use a different spectral luminous efficiency curve, perhaps one of the newer ones. The equivalent curve for scotopic (dark-adapted) vision can also be used for work at lower light levels. The $V'(\lambda)$ curve has its own constant, K'_m, the maximum spectral luminous efficiency for scotopic vision. K'_m is defined as 1700 lm/W at the peak wavelength for scotopic vision (507 nm). This value was deliberately chosen such that the absolute value of the scotopic curve at 555 nm coincides with the photopic curve, 683 lm/W at 555 nm. Some researchers are referring to "scotopic lumens," a term that should be discouraged because of the potential for misunderstanding. In the future, expect to see spectral weighting to represent the mesopic region as well.

The CGPM has approved the use of the CIE $V(\lambda)$ and $V'(\lambda)$ curves for determination of the value of photometric quantities of luminous sources.

36.6 CONVERSION OF PHOTOMETRIC QUANTITIES TO RADIOMETRIC QUANTITIES

The conversion from watts to lumens in the previous section required only that the spectral function, X_λ, of the radiation be known over the spectral range from 360 to 830 nm, where $V(\lambda)$ is nonzero. Attempts to go in the other direction, from lumens to watts, are far more difficult. Since the desired quantity was inside of an integral, weighted by a sensor spectral responsivity function, the spectral function, X_λ, of the radiation must be known over the entire spectral range where the source emits, not just the visible.

For a monochromatic source in the visible spectrum (between the wavelengths of 380 and 860 nm), if the photometric quantity (e.g., lux) is known, apply the conversion $K_m \times V(\lambda)$ and determine the radiometric quantity (e.g., W m^{-2}). In practice, the results that one obtains are governed by the quality of the $V(\lambda)$ correction of the photometer and the knowledge of the wavelength of the source. Both of these factors are of extreme importance at wavelengths where the $V(\lambda)$ curve is steep (i.e., other than very close to the peak of the $V(\lambda)$ curve).

Narrowband sources, such as LEDs, cause major problems. Typical LEDs have spectral bandwidths ranging from 10- to 40-nm full width at half-maximum (FWHM). It is intuitive that in those spectral regions where the $V(\lambda)$ curve is steep, the luminous output will be greater than that predicted using the $V(\lambda)$ curve at the peak LED wavelength. This expected result increases with wider-bandwidth LEDs. Similarly, it is also intuitive that the luminous output is less than that predicted by using the $V(\lambda)$ curve when the peak LED wavelength is in the vicinity of the peak of the $V(\lambda)$ curve. Therefore, there must be two wavelengths where the conversion ratio (lm/W) is largely independent of LED bandwidth. An analysis of this conversion ratio was done using a Gaussian equation to represent the spectral power distribution of an LED and applying Eq. (4). Indeed, two null wavelengths were identified (513 and 604 nm) where the conversion between radiometric and photometric quantities is constant (independent of LED bandwidth) to within 0.2 percent up to an LED bandwidth of 40 nm. These wavelengths correspond (approximately) to the wavelengths where the two maxima of the first derivative of the $V(\lambda)$ curve are located.

At wavelengths between these two null wavelengths (513 and 604 nm), the conversion ratio (lm/W) decreases slightly with increasing bandwidth. The worst case occurs when the peak wavelength of the LED corresponds with the peak of $V(\lambda)$. It is about 5 percent lower for bandwidths up to 30 nm, increasing to nearly 10 percent for 40-nm bandwidth. At wavelengths outside of the null wavelengths, the conversion (lm/W) increases with increasing bandwidth, and the increase is greater when the wavelength approaches the limits of the $V(\lambda)$ curve. Figure 9 shows that factor by which a conversion ratio (lm/W) should be multiplied as a function of LED bandwidth, with the peak LED wavelength as the parameter. Note that the peak wavelength of the LED is specified as the radiometric peak and not as the dominant wavelength (a color specification). The dominant wavelength shifts with respect to the radiometric peak, the difference increasing with bandwidth.

Most often, LEDs are specified in luminous intensity [cd or millicandela (mcd)]. The corresponding radiometric unit is watts per steradian (W/sr). In order to determine the radiometric power (watts), the details of the spatial distribution of the radiant intensity must be known prior to integration.

For broadband sources, a photometric quantity cannot in general be converted to a radiometric quantity unless the radiometric source function, Φ_λ, is known over all wavelengths. However, if the source spectral distribution is blackbody-like (thermal source, spectral emissivity constant between 360 and 830 nm), and the source temperature is also known, then an illuminance can be converted to a spectral irradiance curve over that wavelength range. Again, use Eq. (4) to determine a scale factor

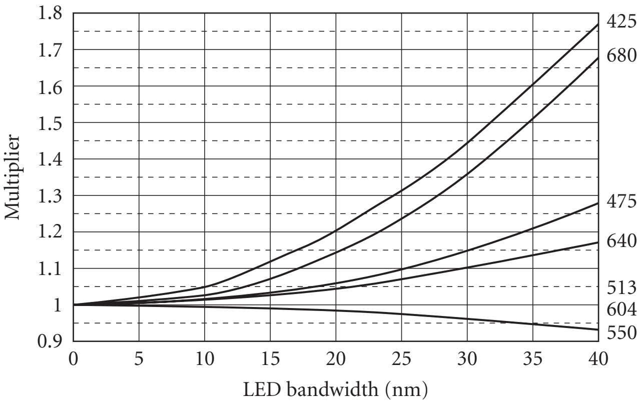

FIGURE 9 Multiplier for converting LED luminous intensity to radiant intensity.

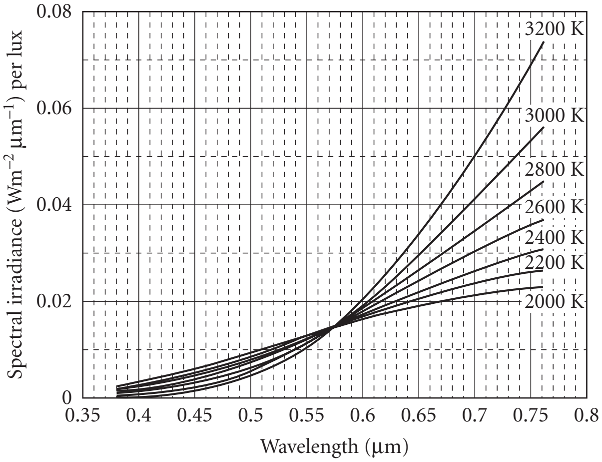

FIGURE 10 Spectral irradiance versus wavelength of blackbody radiation versus temperature.

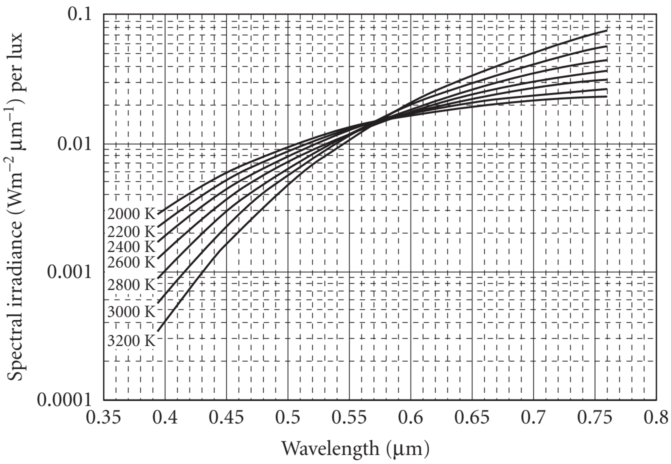

FIGURE 11 Spectral irradiance versus wavelength of blackbody radiation versus temperature.

for the source term, X_λ. Figures 10 and 11 show the calculated spectral irradiance versus wavelength for blackbody radiation with source temperature as the parameter.

36.7 RADIOMETRIC/PHOTOMETRIC NORMALIZATION

In radiometry and photometry, there are two mathematical activities that fall into the category called *normalization*. The first is bandwidth normalization. The second doesn't have an official title but involves a conversion between photometric and radiometric quantities, used to convert detector responsivities from amperes per lumen to amperes per watt.

The measurement equation relates the output signal from a sensor to its spectral responsivity and the spectral power that is incident upon it:

$$S = \int_0^\infty \Phi_\lambda \mathfrak{R}(\lambda) \mathrm{d}\lambda \tag{5}$$

An extended discourse on bandwidth normalization[17] showed that the spectral responsivity of a sensor (or detector) can be manipulated to yield more source information than is immediately apparent from the measurement equation. The sensor weights the input spectral power according to its spectral responsivity, $\mathfrak{R}(\lambda)$, such that only a limited amount of information about the source can be deduced. If either the source or the sensor has a sufficiently small bandwidth such that the spectral function of the other term does not change significantly over the passband, the equation simplifies to

$$S = \Phi_\lambda \cdot \mathfrak{R}(\lambda) \cdot \Delta\lambda \tag{6}$$

where $\Delta\lambda$ is the passband. Spectroradiometry and multifilter radiometry, using narrow-bandpass filters, take advantage of this simplified equation. For those cases where the passband is larger, the techniques of bandwidth normalization can be used. The idea is to substitute for $\mathfrak{R}(\lambda)$ an equivalent response that has a uniform spectral responsivity, $\mathfrak{R}_n$, between wavelength limits λ_1 and λ_2 and zero response elsewhere. Then, the signal is given by

$$S = \mathfrak{R}_n \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \mathrm{d}\lambda \tag{7}$$

and now the integrated power between wavelengths λ_1 and λ_2 is determined. There are many ways of assigning values for λ_1 λ_2, and $\mathfrak{R}_n$ for a sensor. Some of the more popular methods were described by Nicodemus[17] and Palmer.[18] An effective choice is known as the *moments method*,[19] an analysis of the zeroth, first, and second moments of the sensor spectral responsivity curve. The derivation of this normalization scheme involves the assumption that the source function is exactly represented by a second-degree polynomial. If this condition is met, the moments method of determining sensor parameters yields exact results for the source integral. In addition, the results are completely independent of the source function. The errors encountered are related to deviation of the source function from the said second-degree polynomial.

Moments normalization has been applied to the photopic spectral luminous efficiency function, $V(\lambda)$, and the results are given in Table 5 and shown in Fig. 12. These values indicate the skewed nature of the photopic and scotopic curves as the deviation from the centroid and the peak wavelengths. The results can be applied to most continuous sources, like blackbody and tungsten radiation, which are both continuous across the visible spectrum. To demonstrate the effectiveness of moments normalization, the blackbody curve was multiplied by the $V(\lambda)$ curve for temperatures ranging from 1000 to 20,000 K to determine a photometric function [e.g., lumens per square meter (or lux)]. Then, the blackbody curve was integrated over the wavelength interval between λ_1 and λ_2 to determine the equivalent (integrated between λ_1 and λ_2) radiometric

TABLE 5 Bandwidth Normalization on Spectral Luminous Efficiency

	Photopic	Scotopic
Peak wavelength (λ_p)	555 nm	507 nm
Centroid wavelength (λ_C)	560.19 nm	502.40 nm
Short wavelength (λ_1)	487.57 nm	436.88 nm
Long wavelength (λ_2)	632.81 nm	567.93 nm
Moments bandwidth	145.24 nm	131.05 nm
Normalized $\mathfrak{R}_n$	0.7357	0.7407
Absolute $\mathfrak{R}_n$	502.4 lm/W	1260 lm/W

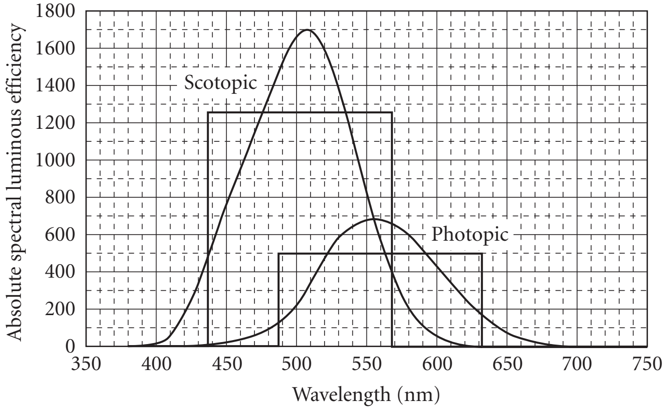

FIGURE 12 Absolute spectral luminous efficiency functions and equivalent normalized bandwidths

function (e.g., in-band watts per square meter). The ratio of lux to watt per square meter is 502.4 ± 1.0 (3σ) over the temperature range from 1600 to more than 20,000 K. This means that the in-band (487.6 to 632.8 nm) irradiance for a continuous blackbody-like source can be determined using a photometer that is properly calibrated in lux and that is well corrected for $V(\lambda)$. Simply divide the reading in lux by 502.4 to get the in-band irradiance in watts per square meter between 487.6 and 632.8 nm.

If a photometer is available with a $V'(\lambda)$ correction, calibrated for lux (scotopic) with K'_m of 1700 lm/W, a similar procedure is effective. The integration takes place over the wavelength range from 436.9 to 567.9 nm. The ratio of lux (scotopic) to watts per square meter is 1260 ± 2 (3σ) over the temperature range from 1800 K to more than 20,000 K. This means that the in-band (436.9 to 567.9 nm) irradiance for a continuous blackbody-like source can be determined using a $V'(\lambda)$-corrected photometer that is properly calibrated in lux (scotopic). Simply divide the reading in lux (scotopic) by 1260; the result is the in-band irradiance in watts per square meter between 436.9 and 567.9 nm.

A common problem is the interpretation of specifications for photodetectors, which are given in photometric units. An example is a photomultiplier with an S-20 photocathode, which has a typical responsivity of 200 μA/lm. Given this specification and a curve of the relative spectral responsivity, the problem is to determine the output when exposed to a known power from an arbitrary source.

Photosensitive devices, in particular vacuum photodiodes and photomultiplier tubes, are characterized using CIE Illuminant A, a tungsten source at 2854 K color temperature. The illuminance is measured using a photoptically corrected photometer, and this illuminance is applied to the device under scrutiny. This technique is satisfactory only if the source being used is spectrally comparable to Illuminant A. If a source with a different spectral distribution is used, a photometric normalization must be done. Eberhart[20] generated a series of conversion factors for various sources and standardized detector spectral responsivities (S-1, S-11, S-20, etc.).

The luminous flux from any source is given by

$$\Phi_v = K_m \int_{360}^{830} \Phi_\lambda V(\lambda) d\lambda \tag{8}$$

and the output of a detector when exposed to the said luminous flux is

$$S = \int_0^\infty \Phi_\lambda \Re(\lambda) d\lambda \tag{9}$$

where Φ_λ is spectral radiant flux, $V(\lambda)$ is the spectral luminous efficiency of the photopic eye, $\mathfrak{R}(\lambda)$ is the absolute spectral responsivity of the photodetector, and S is the photodetector signal. The luminous responsivity of the detector when exposed to this source is

$$\mathfrak{R} = \frac{\int_0^\infty \Phi_\lambda \mathfrak{R}(\lambda) d\lambda}{K_m \int_{360}^{830} \Phi_\lambda V(\lambda) d\lambda} \text{A/lm} \tag{10}$$

This luminous responsivity is specific to the source that is used to make the measurement, and it cannot be applied to other sources with differing spectral distributions.

36.8 OTHER WEIGHTING FUNCTIONS AND CONVERSIONS

The general principles that are outlined here can be applied to action spectra other than those already defined for the human eye (photopic and scotopic). Some action spectra take the form of defined spectral regions, such as UVA (315–400 nm), UVB (280–315 nm), UVC (100–280 nm), IR-A (770–1400 nm), IR-B (1400–3000 nm), and IR-C (3000–10^6 nm). Others are more specific. $A(\lambda)$ is for aphakic hazard, $B(\lambda)$ is for photochemical blue-light hazard, $R(\lambda)$ is for retinal thermal hazard, and $S(\lambda)$ is an actinic ultraviolet action spectrum.[21] PPF (a.k.a. PhAR) is a general action spectrum for plant growth. Many others have been defined, including those for erythema (sunburn), skin cancer, psoriasis treatment, mammalian and insect vision, and other generalized chemical and biological photoeffects. Various conversion factors from one action spectrum to another are scattered throughout the popular and archival literature. Ideally, they have been derived via integration over the appropriate spectral regions.

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36.10 FURTHER READING

Books, Documentary Standards, Significant Journal Articles

American National Standard Nomenclature and Definitions for Illuminating Engineering, ANSI Standard ANSI/IESNA RP-16 96.

W R. Blevin and B. Steiner, "Redefinition of the Candela and the Lumen," *Metrologia* **11**:97 (1975).

C. DeCusatis, *Handbook of Applied Photometry,* AIP Press, 1997. (Authoritative, with pertinent chapters written by technical experts at BIPM, CIE, and NIST. Skip chapter 4!)

J. W. T. Walsh, *Photometry,* Constable, London, 1958. (The classic!)

Publications Available on the World Wide Web

All you ever wanted to know about the SI is contained at BIPM and at NIST. Available publications (highly recommended) include the following:

"The International System of Units (SI)," 7th ed. (1998), direct from BIPM. This is the English translation of the official document, which is in French. Available in PDF format at *www.bipm.fr/*.

NIST Special Publication SP330, "The International System of Units (SI)." The U.S. edition (meter rather than metre) of the above BIPM publication. Available in PDF format from *http://physics.nist.gov/cuu/*.

NIST Special Publication SP811, "Guide for the Use of the International System of Units (SI)," Available in PDF format from *http://physics.nist.gov/cuu/*.

Papers published in recent issues of the NIST Journal of Research are also available on the Web in PDF format from *nvl.nist.gov/pub/nistpubs/jres/jres.htm.* Of particular relevance is "The NIST Detector-Based Luminous Intensity Scale," vol. 101, p. 109 (1996).

Useful Web Sites

AIP (American Institute of Physics): *www.aip.org*

ANSI (American National Standards Institute): *www.ansi.org/*

BIPM (International Bureau of Weights and Measures): *www.bipm.fr/*

CIE (International Commission on Illumination): *www.de.co.at/cie/*

Color Vision Lab at UCSD: *cvision.uscd.edu/*

CORM (Council for Optical Radiation Measurements): *www.corm.org*

IESNA (Illuminating Engineering Society of North America): *www.iesna.org/*

ISO (International Standards Organization): *www.iso.ch/*

IUPAP (International Union of Pure and Applied Physics): *www.physics.umanitoba.ca/iupap/*

NIST (National Institute of Standards and Technology): *physics.nist.gov/*

OSA (Optical Society of America): *www.osa.org*

SPIE (International Society for Optical Engineering): *www.spie.org*