Part III: Light measurement

This is the final installment of a series on the terminology of light. It will cover radiometric quantities and units as well as conversion between lumens and watts.

For years the necessity for a complete understanding of light for the production of good TV scenes has been a "given." As the importance of fiber optics in communications increases, the corollary importance of light and its measurement in that field follows. Over the many years of the study of light, a jungle of often bewildering technology developed. The lack of uniqueness, in addition to everyday connotations of much visual terminology, often confuses the reader not familiar with the subject.

It is further confusing because light measurement has two different generic approaches. From a physicist's viewpoint light is radiant energy and thus can be measured in watts—radiometry. Over the course of time, the measurement of light as we see it and photograph with it, for use by human observers, has produced light measurement units (lumens) in photometry. The formulas for various radiometric quantities are analogous to the ones for the corresponding photometric quantities. If watts are substituted for lumens, the units (in the international MKS unit system) in the radiometric quantities are the same as those of the corresponding photometric quantities.

Customarily, photometric measurements are used in general illumination and photography (film and TV), whereas radiometric measurements are widely used in scientific applications, e.g., microwave/satellite RF, fiber optics, etc.

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The symbols, names, definitions and units of radiometric quantities are summarized in Table 1, while Table 2 shows the radiometric quantities and units with the corresponding photometric quantities and units.

Conversion from lumens to watts and watts to lumens

Photometry refers to the measurement of light as perceived by the human eye. Radiometric quantities and units are those that actually exist in nature. Analogous units exist for photometric quantities, all evaluated re the human eye response. Radiant flux is power (watts); the unit of photometric flux is the lumen. Since the response of the human eye varies with wavelength, the conversion from watts to lumens (or lumens to watts) is wavelength dependent. The conversion factor, K (λ), between watts and lumens is shown in Figure 1. The K (λ) curve labeled photopic refers to high light-level human vision and the curve labeled scotopic refers to low light-level vision. The "photopic curve" has been suggested by the CIE (*Commission Internationale de L'Eclairage.*) The range of definition of K (λ) extends from 390 to 760 nanometers. The maximum value of K (λ) for photopic vision occurs at 555 nm and has a value of 683 lumen/watt. The reciprocal of K $(\lambda)_{max}$ has been called the "mechanical light equivalent M":

$$M = 1/K(\lambda)_{max} = 1.464 \times 10^{-3} \text{ watts/lumen}$$

Summary of terminology

In concept, both radiometry and photometry are quite straightforward; however, both have been cursed with a jungle of often bewildering terminology. Radiometry deals with radiant energy (i.e., electromagnetic radiation) of any wavelength. Photometry is restricted to radiation in the visible region of the spectrum. The basic unit of power (i.e., rate of transfer of energy) in radiometry is the watt; in photometry the corresponding unit is the lumen, which is simply radiant power as modified by the relative spectral sensitivity of the eye. Note that watts and lumens have the same dimensions, namely energy per time.

The principles of radiometry and photometry are readily understood when one thinks in terms of the basic units involved, rather than the special terminology which is conventionally used.

Photometry deals with luminous radiation; that is, radiation that the human eye can detect. The basic photometric unit of radiant power is the lumen, which is defined as the luminous flux emitted into a solid angle of one steradian by a point source whose intensity is 1/60 of that of one square centimeter of a black body at the solidification temperature of platinum (2042°K).

The unit of luminous intensity is called the *can-*

Figure 1: Absolute photometric radiation equivalents, K (λ) and K' (λ), as a function of wavelength λ, $K_m(\lambda)$ = 683 lumens/watt at 555 nm

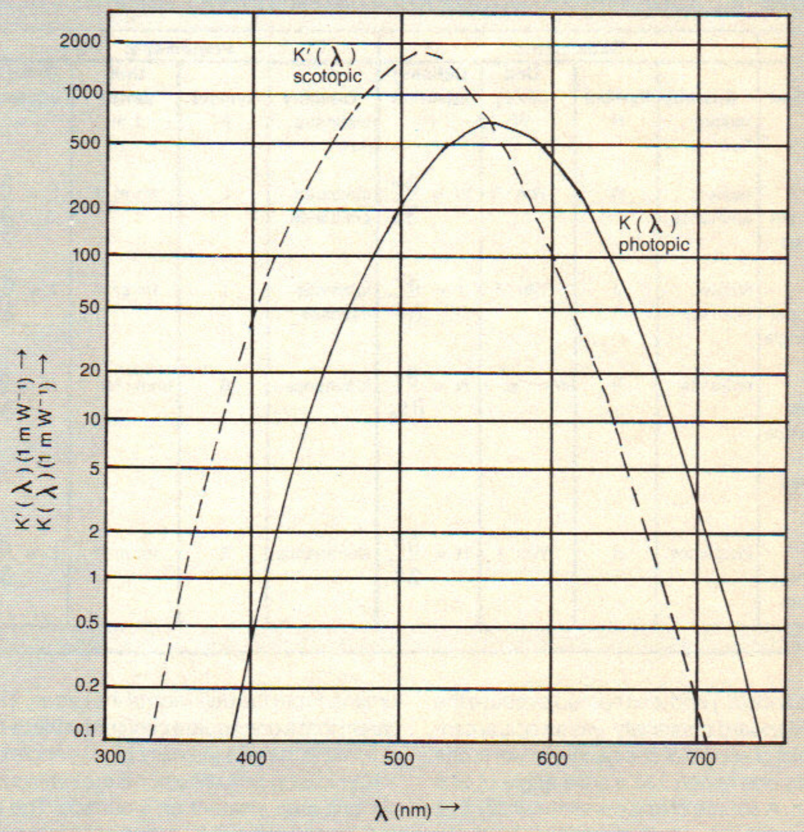


Table 1: Radiometric quantities and units

Symbol	Name	Description	Units
S, S_p	Area	Area, projected area	m^2
Ω	Solid angle	—	sr
ν	Frequency	—	Hz
λ	Wavelength	—	μm
U	Radiant energy	—	J
P	Radiant power	Rate of transfer of radiant energy $\frac{\partial U}{\partial t}$	W
W	Radiant emittance	Radiant power per unit area emitted from a surface $\frac{\partial P}{\partial S}$	Wm^{-2}
H	Irradiance	Radiant power per unit area incident upon a surface $\frac{\partial P}{\partial S}$	Wm^{-2}
J	Radiant intensity	Radiant power per unit solid angle from a point source $\frac{\partial P}{\partial \Omega}$	Wsr^{-1}
N	Radiance*	Radiant power per unit solid angle per unit projected area $\frac{\partial^2 P}{\partial \Omega \, \partial S_P}$	$Wm^{-2}sr^{-1}$
P_λ	Spectral radiant power	Radiant power per unit wavelength interval $\frac{\partial P}{\partial \lambda}$	$W\mu m^{-1}$
P_ν	Spectral radiant power	Radiant power per unit frequency interval $\frac{\partial P}{\partial \nu}$	Ws or WHz^{-1}
W_λ	Spectral radiant emittance	Radiant emittance per unit wavelength interval $\frac{\partial W}{\partial \lambda}$	$Wm^{-2}\mu m^{-1}$
H_λ	Spectral irradiance	Irradiance per unit wavelength interval $\frac{\partial H}{\partial \lambda}$	$Wm^{-2}\mu m^{-1}$
J_λ	Spectral radiant intensity	Radiant intensity per unit wavelength interval $\frac{\partial J}{\partial \lambda}$	$Wsr^{-1}\mu m^{-1}$
N_λ	Spectral radiance	Radiance per unit wavelength interval $\frac{\partial N}{\partial \lambda}$	$Wm^{-2}sr^{-1}\mu m^{-1}$

* Some authors define radiance in terms of actual surface area rather than projected area; hence, they include a factor cos θ in their formulas, θ being the angle from normal incidence.

Table 2: Radiometric and photometric quantities and units

	Radiometric				Photometric			
Definition	Quantity	Symbol	Unit (MKS)	Defining equation	Quantity	Symbol	Unit (MKS)	Defining equation
Power	radiant flux	P	W	—	luminous flux	F	1 m	—
Power output per unit area	radiant emittance	W	Wm^{-2}	$W = \frac{\partial P}{\partial S}$	luminous emittance	L	$1m\ m^{-2}$	$L = \frac{\partial F}{\partial S}$
Power output per solid angle	radiant intensity	J	Wsr^{-1}	$J = \frac{\partial P}{\partial \Omega}$	luminous intensity	I	$1m\ sr^{-1}$	$I = \frac{\partial F}{\partial \Omega}$
Power per unit solid angle per unit projected area	radiance	N	$Wm^{-2}sr^{-1}$	$N = \frac{\partial J}{\partial S_p}$	luminance	B	$1mm^{-2}sr^{-1}$	$B = \frac{\partial I}{\partial S_p}$
Power input per unit area	irradiance	H	Wm^{-2}	$H = \frac{\partial P}{\partial S}$	illuminance	E	$1m\ m^{-2}$	$E = \frac{\partial F}{\partial S}$

dle (or "candela") and is so named because the original standard of intensity was an actual candle. A point of source of one candle power is one that emits one lumen into a solid angle of one steradian. A source of one candle intensity that radiates uniformly in all directions emits 4π lumens. From the definition of the lumen, it is apparent that a one square centimeter black body at 2,042°K has an intensity of 60 candles.

Illumination or illuminance is the luminous flux per unit area incident on a surface. The most widely used unit of illumination is the foot-candle. One foot-candle is one lumen incident per square foot. The misleading name foot-candle resulted from the fact that it is the illumination produced on a surface one foot away from a source of one candle intensity. The photometric term illuminance corresponds to irradiance in radiometry.

The term *brightness* or *luminance* corresponds to the term *radiance*. Brightness is the luminous flux emitted from a surface per unit solid angle per unit of area (projected on a plane normal to the line of sight). There are several commonly used units of brightness. The candle per square centimeter is equal to one lumen emitted per steradian per square centimeter. The lambert is equal to $1/\pi$ candles per square centimeter. The foot-lambert is equal to $1/\pi$ candles per square foot. The foot-lambert is a convenient unit for illuminating engineering work, since it is the brightness that results from one foot-candle of illumination falling on a "perfect" diffusing surface.

Since one lumen is incident on the one square foot area under an illumination of one foot-candle, the total flux radiated into a hemisphere of 2π steradian from a perfectly diffuse (Lambertian) surface is just one lumen. The brightness of a number of sources is shown in Figure 2.

The terminology of photometry has grown through engineering usage and is thus far from orderly. Special terms have derived from special usages and many such terms have survived. A tabulation of photometric units is given in Table 3.

If lumens are substituted for watts in all the expressions, the computations are straightforward. When the starting and final data must be expressed in the special terminology of photometry (as opposed to what one might term the rational units of lumens, steradians and square centimeters), then conversion factors may be necessary for each relationship. A very simple way of avoiding this difficulty is to convert the starting data to lumens, steradians and cm^2, complete the calculation and then convert the results into the desired units.

For convenience, the basic relationships are presented here:

a) *Intensity*

$$I = \frac{F}{\Omega}$$

where:
I = luminous intensity
F = the luminous flux emitted into solid angle Ω

b) *Illumination* (illuminance)

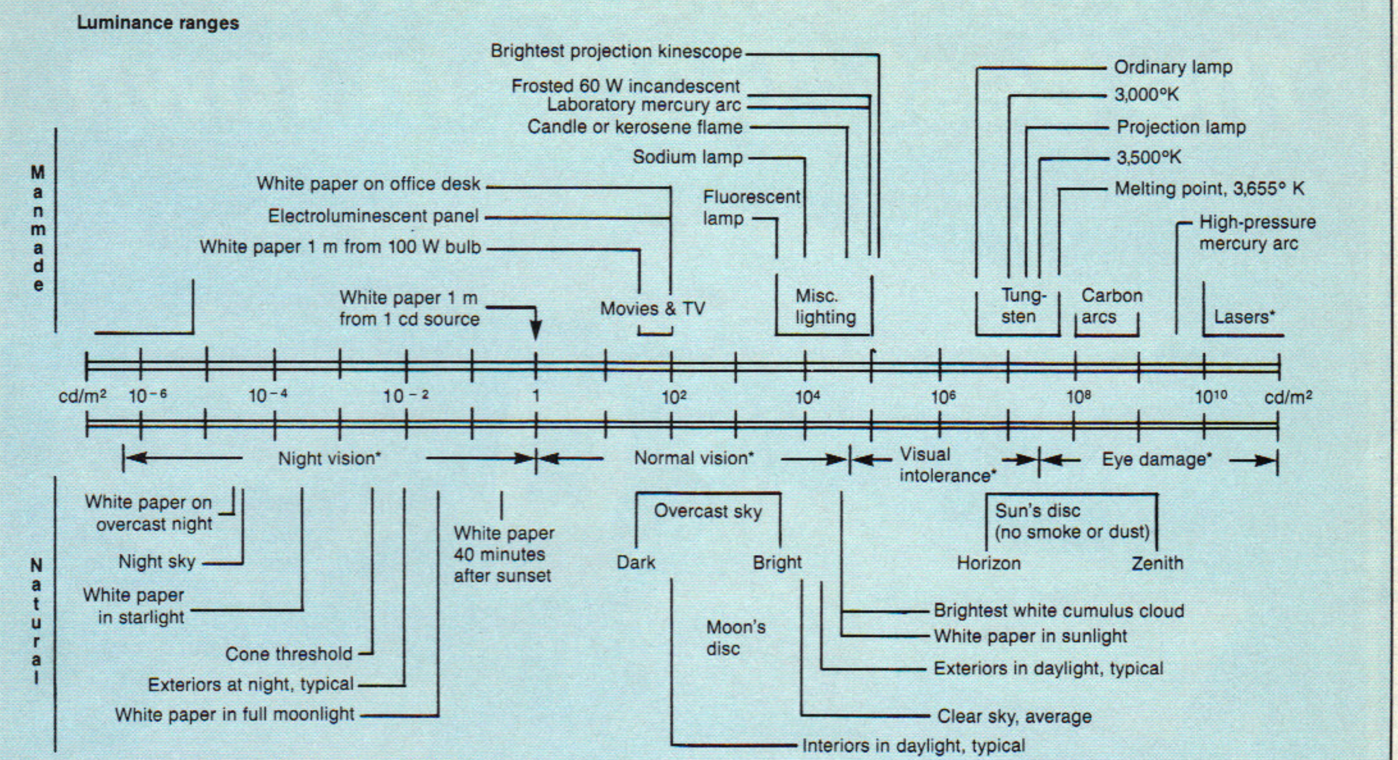
$$E = \frac{I}{S^2} = I\Omega$$

where:
E is the illumination incident on a surface a distance S from a point source of intensity I. Ω is the solid angle subtended by a unit area of the surface from the source.

$$E = \pi B \sin^2\theta$$

where:
E is the illumination produced by a diffuse cir-

Figure 2: Light-level brightness values of common objects



*Actual ranges depend on spectral makeup of radiation

Table 3: Photometric quantities

Flux (Symbol: F)	
lumen	defined in text
Intensity (Symbol: I)	
candle (candela)	one lumen per steradian emitted from a point source. 1/60 of the intensity of one sq. cm. of a black body at 2,042° K
carcel	9.6 candles
hefner	0.9 candles
"old candle"	1.02 candles (candela)
Illumination (Symbol: E) (Also called *illuminance*)	
foot-candle	one lumen per square foot incident on a surface
phot	one lumen per square centimeter
lux	one lumen per square meter
meter-candle	one lumen per square meter
Brightness (Symbol: B) (Also called *luminance*)	
candle per sq. cm.	one lumen emitted per steradian per sq. cm. area projected normal to direction
stilb	one candle per square centimeter
lambert	$1/\pi$ candles per square centimeter
foot-lambert	$1/\pi$ candles per square foot

cular source of brightness (luminance) B at a point from which the source diameters subtends 2θ.

$$E = B\omega$$

where:
E is the illumination produced by a diffuse source of brightness B at a point from which the area of the source subtends the solid angle ω.

$$E = T\pi B \sin^2\theta$$
$$(E = TB\omega)$$

where:
E is the illumination at an image formed by an optical system of transmission T whose exit pupil diameter (area) subtends an angle 2θ (solid angle ω) from the image point when the objective brightness is B.

c) *Brightness* (luminance)

$$B = \frac{F}{\pi A}$$

where:
B is the brightness of a diffuse source of area A that emits luminous flux F into a hemisphere of 2π steradians.

The two generic approaches to the definition and measurement of light (photometry and radiometry) have been described and units defined. The relation of photometric units and radiometric units and the method of conversion of one to the other have been presented. Customarily, photometric measurements are used in general illumination and photography (film and TV), whereas radiometric measurements are widely used in scientific applications and, most importantly, extensively in fiber systems.

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