

1.2 Photometric units

Before starting to describe photomultiplier tubes and their characteristics, this section briefly discusses photometric units commonly used to measure the quantity of light. This section also explains the wavelength regions of light (spectral range) and the units to denote them, as well as the unit systems used to express light intensity. Since information included here is just an overview of major photometric units, please refer to specialty books for more details.

1.2.1 Spectral regions and units

Electromagnetic waves cover a very wide range from gamma rays up to millimeter waves. So-called "light" is a very narrow range of these electromagnetic waves.

Table 1-1 shows designated spectral regions when light is classified by wavelength, along with the conversion diagram for light units. In general, what we usually refer to as light covers a range from 10^2 to 10^6 nanometers (nm) in wavelength. The spectral region between 350 and 700nm shown in the table is usually known as the visible region. The region with wavelengths shorter than the visible region is divided into near UV (shorter than 350nm), vacuum UV (shorter than 200nm) where air is absorbed, and extreme UV (shorter than 100nm). Even shorter wavelengths span into the region called soft X-rays (shorter than 10nm) and X-rays. In contrast, longer wavelengths beyond the visible region extend from near IR (750nm or up) to the infrared (several micrometers or up) and far IR (several tens of micrometers) regions.

Wavelength	Spectral Range	Frequency	Energy
nm		(Hz)	(eV)
	X-ray Soft X-ray		
10	Extreme UV region	10^{16}	10^2
10^2			10
200	Vacuum UV region	10^{15}	1
350	Ultraviolet region		
750	Visible region		
10^3	Near infrared region	10^{14}	10^{-1}
10^4	Infrared region		
10^5	Far infrared region	10^{13}	10^{-2}
10^6		10^{12}	10^{-3}

Table 1-1: Spectral regions and unit conversions

Light energy E (eV) is given by the following equation (Eq. 1-1).

$$E = h\nu = h \cdot \frac{c}{\lambda} = ch\bar{\nu} \dots\dots\dots \text{(Eq. 1-1)}$$

- h: Planck's constant 6.626×10⁻³⁴(J·S)
- ν: Frequency of light (Hz)
- $\bar{\nu}$: Wave number (cm⁻¹)
- c: Velocity of light 3×10⁸m/s

Here, velocity of light has relation to frequency ν and wavelength λ as follow:

$$c = \nu\lambda.$$

When E is expressed in eV (electron volts) and λ in nm, the relation between eV and λ is given as follows:

$$E \text{ (eV)} = \frac{1240}{\lambda} \dots\dots\dots \text{(Eq. 1-2)}$$

From Eq. 1-2, it can be seen that light energy increases in proportion to the reciprocal of wavelength. This equation is helpful when discussing the relation between light energy (eV) and wavelength (nm), so remembering it is suggested.

1. 2. 2 Units of light intensity

This section explains the units used to represent light intensity and their definitions.

The radiant quantity of light or radiant flux is a pure physical quantity expressed in units of watts (W). In contrast, the photometric quantity of light or luminous flux is represented in lumens which correlate to the visual sensation of light.

The "watt (W)" is the basic unit of radiated light when it is measured as analog quantity, and the photon is the minimum unit of radiated light. The energy of one photon is given by the equation below.

$$P = h\nu = hc/\lambda \dots\dots\dots \text{(Eq. 1-3)}$$

From the relation W=J/sec., the following calculation can be made by substituting specific values for the above equation.

$$1 \text{ watt} = 5.05 \lambda \text{ (}\mu\text{m)} \times 10^{18} \text{ photons/sec.}$$

This equation gives the number of photons (per second) from the radiant flux (W) measured, and will be helpful if you remember it.

Table 1-2 shows comparisons of radiant units with photometric units are listed. (Each unit is detailed in subsequent sections.)

Quantity	Unit Name	Symbol
Radiant flux [Luminous flux]	watts [lumens]	W [lm]
Radiant energy [Quantity of light]	joules [lumen· sec.]	J [lm·s]
Irradiance [Illuminance]	watts per square meter [lux]	W/m ² [lx]
Radiant emittance [Luminous emittance]	watts per square meter [lumens per square meter]	W/m ² [lm/m ²]
Radiant intensity [Luminous intensity]	watts per steradian [candelas]	W/sr [cd]
Radiance [Luminance]	watts per steradia· square meter [candelas per square meter]	W/sr·m ² [cd/m ²]

Table 1-2: Comparisons of radiant units with photometric units (shown in brackets [])

1. Radiant flux [luminous flux]

Radiant flux is a unit to express radiant quantity, while luminous flux shown in brackets [] in Table 1-2 and the subhead just above is a unit to represent luminous quantity. (Units are shown this way in the rest of this chapter.) Radiant flux (Φ_e) is the flow of radiant energy (Q_e) past a given point in a unit time period, and is defined as follows:

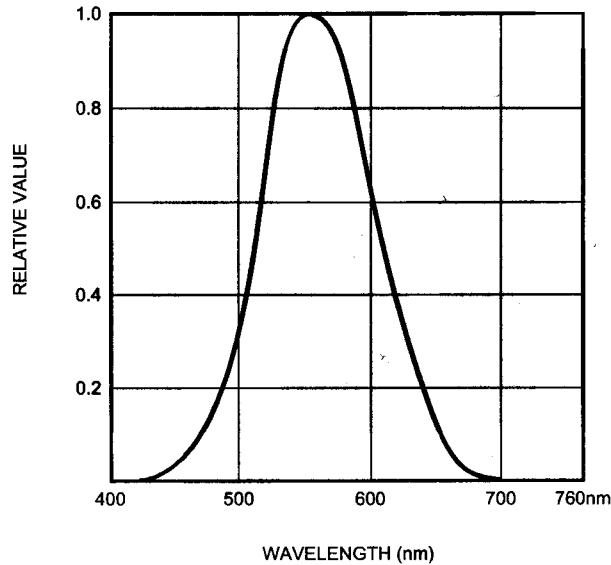
$$\Phi_e = dQ_e/dt \text{ (joules per sec. ; watts) } \dots\dots\dots \text{ (Eq. 1-4)}$$

On the other hand, luminous flux (Φ) is measured in lumens and defined as follows:

$$\Phi = km \int \Phi_e(\lambda) v(\lambda) d\lambda \dots\dots\dots \text{ (Eq. 1-5)}$$

- where $\Phi_e(\lambda)$: Spectral radiant density of a radiant flux, or spectral radiant flux
- km : Maximum sensitivity of the human eye (~~638 lumens/watt~~) 683 lumens/watt
- $v(\lambda)$: Typical sensitivity of the human eye

The maximum sensitivity of the eye (km) is a conversion coefficient used to link the radiant quantity and luminous quantity. Here, $v(\lambda)$ indicates the typical spectral response of the human eye, internationally established as spectral luminous efficiency. A typical plot of spectral luminous efficiency versus wavelength (also called the luminosity curve) and relative spectral luminous efficiency at each wavelength are shown in Figure 1-1 and Table 1-3, respectively.



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Figure 1-1: Spectral luminous efficiency distribution

Wavelength (nm)	Luminous Efficiency	Wavelength (nm)	Luminous Efficiency
400	0.0004	600	0.631
10	0.0012	10	0.503
20	0.0040	20	0.381
30	0.0116	30	0.265
40	0.023	40	0.175
450	0.038	650	0.107
60	0.060	60	0.061
70	0.091	70	0.032
80	0.139	80	0.017
90	0.208	90	0.0082
500	0.323	700	0.0041
10	0.503	10	0.0021
20	0.710	20	0.00105
30	0.862	30	0.00052
40	0.954	40	0.00025
550	0.995	750	0.00012
555	1.0	60	0.00006
60	0.995		
70	0.952		
80	0.870		
90	0.757		

Table 1-3: Relative spectral luminous efficiency at each wavelength

2. Radiant energy (Quantity of light)

Radiant energy (Q_e) is the integral of radiant flux over a duration of time. Similarly, the quantity of light (Q) is defined as the integral of luminous flux over a duration of time. Each term is respectively given by Eq. 1-6 and Eq. 1-7.

$$Q_e = \int \Phi_e dt \text{ (watt}\cdot\text{sec.)} \dots\dots\dots \text{(Eq. 1-6)}$$

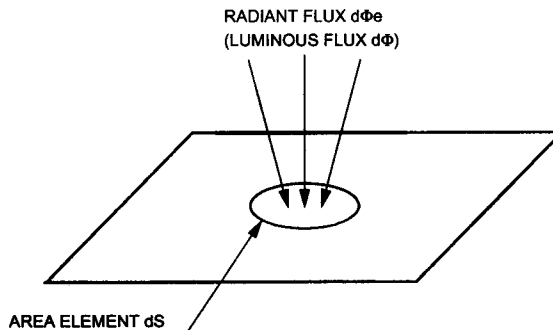
$$Q = \int \Phi dt \text{ (lumen}\cdot\text{sec.)} \dots\dots\dots \text{(Eq. 1-7)}$$

3. Irradiance (Illuminance)

Irradiance (E_e) is the radiant flux incident per unit area of a surface, and is also called radiant flux density. (See Figure 1-2.) Likewise, illuminance (E) is the luminous flux incident per unit area of a surface. Each term is respectively given by Eq. 1-8 and Eq. 1-9.

$$\text{Irradiance } E_e = d\Phi_e/ds \text{ (watts per square meter; } W/m^2) \dots\dots\dots \text{(Eq. 1-8)}$$

$$\text{Illuminance } E = d\Phi/ds \text{ (lumen per square meter; } lm/m^2 \text{ or lux)} \dots\dots\dots \text{(Eq. 1-9)}$$



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Figure 1-2: Irradiance (Illuminance)

4. Radiant emittance (Luminous emittance)

Radiant emittance (M_e) is the radiant flux emitted per unit area of a surface. (See Figure 1-3.) Likewise, Luminous emittance (M) is the luminous flux emitted per unit area of a surface. Each term is respectively expressed by Eq. 1-10 and Eq. 1-11.

$$\text{Radiant emittance } M_e = d\Phi_e/ds \text{ (watt per square meter; } W/m^2) \text{ (Eq. 1-10)}$$

$$\text{Luminous emittance } M = d\Phi/ds \text{ (lumen per square meter; } lm/m^2) \text{ (Eq. 1-11)}$$

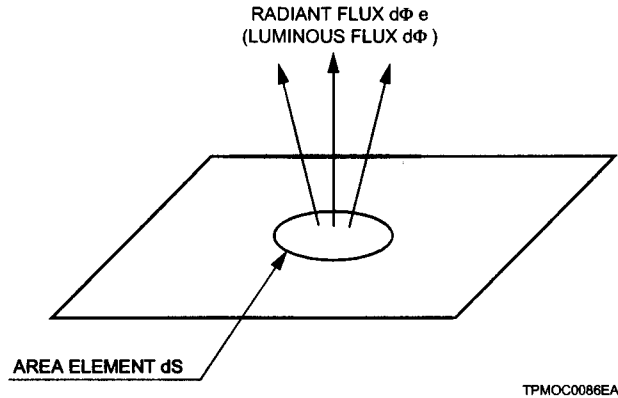


Figure 1-3: Radiant emittance (Luminous emittance)

5. Radiant intensity (Luminous intensity)

Radiant intensity (I_e) is the radiant flux emerging from a point source, divided by the unit solid angle. (See Figure 1-4.) Likewise, luminous intensity (I) is the luminous flux emerging from a point source, divided by the unit solid angle. These terms are respectively expressed by Eq. 1-12 and Eq. 1-13.

$$\text{Radiant intensity } I_e = d\Phi_e/dw \text{ (watts per steradian; } W/sr) \text{ (Eq. 1-12)}$$

Where

Φ_e : radiant flux (watts)

w : solid angle (steradians)

$$\text{Luminous intensity } I = d\Phi/dw \text{ (candelas: cd) (Eq. 1-13)}$$

Where

Φ : luminous flux (lumens)

w : solid angle (steradians)

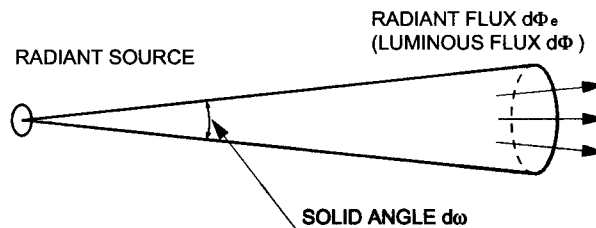


Figure 1-4: Radiant intensity (Luminous intensity)

6. Radiance (Luminance)

Radiance (L_e) is the radiant intensity emitted in a certain direction from a radiant source, divided by unit area of an orthographically projected surface. (See Figure 1-5.) Likewise, luminance (L) is the luminous flux emitted from a light source, divided by the unit area of an orthographically projected surface. Each term is respectively given by Eq. 1-14 and Eq. 1-15.

$$\text{Radiance } L_e = dI_e/ds \times \cos\theta \text{ (watts per steradian}\cdot\text{m}^2) \text{ (Eq. 1-14)}$$

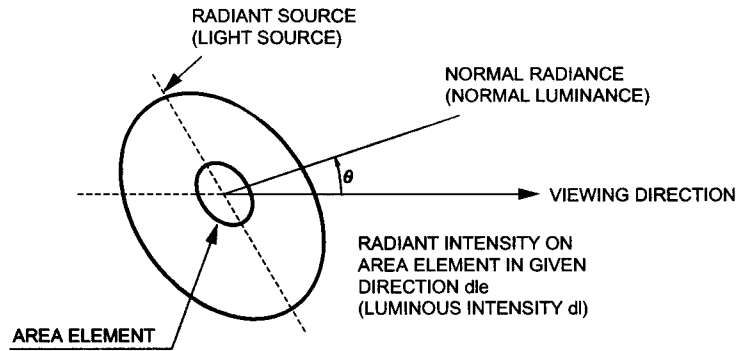
Where

- le: radiant intensity
- s : area
- θ : angle between viewing direction and small area surface

$$\text{Luminance } L = dI/ds \times \cos\theta \text{ (candelas/m}^2) \text{ (Eq. 1-15)}$$

Where

- I: luminous intensity (candelas)



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Figure 1-5: Radiant intensity (Luminous intensity)

In the above sections, we discussed basic photometric units which are internationally specified as SI units for quantitative measurements of light. However in some cases, units other than SI units are used.

Tables 1-4 and 1-5 show conversion tables for SI units and non-SI units, with respect to luminance and illuminance. Refer to these conversion tables as necessary.

	Unit Name	Symbol	Conversion Fomula
SI Unit	nit	nt	1nt = 1cd/m ²
	stilb	sb	1sb = 1cd/cm ² = 10 ⁴ cd/m ²
	apostilb	asb	1asb = 1/π cd/m ²
	lambert	L	1L = 1/π cd/cm ² = 10 ⁴ /π cd/m ²
Non SI Unit	foot lambert	fL	1fL = 1/π cd/ft ² = 3.426 cd/m ²

Table 1-4: Luminance units

	Unit Name	Symbol	Conversion Fomula
SI Unit	photo	ph	1ph = 1 lm/cm ² = 10 ⁴ lx
Non SI Unit	food candle	fc	1fc = 1 lm/ft ² = 10.764 lx

Table 1-5: Illuminance units