# Optical Radiation Terminology and Units

There are many systems of units for optical radiation. In this tutorial, we try to adhere to the internationally agreed CIE system. The CIE system fits well with the SI system of units. We work mostly with the units familiar to those working in the UV to near IR. We have limited the first part of this discussion to steady state conditions, essentially neglecting dependence on time. We explicitly discuss time dependence at the end of the section; please see Pulsed Radiation for a brief tutorial on pulsed radiation.

## Radiometric, Photometric and Photon Quantities

The emphasis is on radiometric quantities. These are purely physical. How the human eye records optical radiation is often more relevant than the absolute physical values. This evaluation is described in photometric units and is limited to the small part of the spectrum called the visible. Photon quantities are important for many physical processes. Table 1 lists radiometric, photometric and photon quantities.

Table 1 Commonly Used Radiometric, Photometric and Photon Quantities

| Radiometric | | | Photometric | | | Photon | | |
|---|---|---|---|---|---|---|---|---|
| **Quantity** | **Usual Symbol** | **Units** | **Quantity** | **Usual Symbol** | **Units** | **Quantity** | **Usual Symbol** | **Units** |
| Radiant Energy | $Q_e$ | J | Luminous Energy | $Q_v$ | lm s | Photon Energy | $N_p$ | * |
| Radiant Power or Flux | $\varphi_e$ | W | Luminous Flux | $\varphi_v$ | lm | Photon Flux | $\Phi_P = \frac{dN_P}{dt}$ | $s^{-1}$ |
| Radiant Exitance or Emittance | $M_e$ | W $m^{-2}$ | Luminous Exitance or Emittance | $M_v$ | lm $m^{-2}$ | Photon Exitance | $m_p$ | $s^{-1}m^{-2}$ |
| Irradiance | $E_e$ | W $m^{-2}$ | Illuminance | $E_v$ | lx | Photon Irradiance | $E_p$ | $s^{-1}m^{-2}$ |
| Radiant Intensity | $I_e$ | W $sr^{-1}$ | Luminous Intensity | $I_v$ | cd | Photon Intensity | $I_p$ | $s^{-1}sr^{-1}$ |
| Radiance | $L_e$ | W $sr^{-1}m^{-2}$ | Luminance | $L_v$ | cd $m^{-2}$ | Photon Radiance | $L_p$ | $s^{-1}sr^{-1}m^{-2}$ |

* Photon quantities are expressed in number of photons, followed by the units, e.g. photon flux (number of photons) $s^{-1}$. The unit for photon energy is number of photons. The subscripts e,v, and p designate radiometric, photometric, and photon quantities respectively. They are usually omitted when working with only one type of quantity.

Symbols Key:

| | |
|---|---|
| J: Joule | lm: lumen |
| W: watts | S: seconds |
| m: meter | cd: candela |
| sr: steradian | lx: lux, lumen $m^{-2}$ |

Table 2 Samples of Units Still in Common Use

| Units | Equivalent | Quantity |
|---|---|---|
| Talbot | lm s | Luminous Energy |
| Footcandle | lm $ft^{-2}$ | Illuminance |
| Footlambert | cd $ft^{-2}$ | Luminance |
| lambert | cd $cm^{-2}$ | Luminance |

Sometimes “sterance”, “areance”, and “pointance” are used to supplement or replace the terms above.

- Sterance, means, related to the solid angle, so radiance may be described by **radiant sterance**.
- Areance, related to an area, gives radiant areance instead of **radiant exitance**.
- Pointance, related to a point, leads to **radiant** pointance instead of radiant intensity.

## Spectral Distribution

"Spectral" used before the tabulated radiometric quantities implies consideration of the wavelength dependence of the quantity. The measurement wavelength should be given when a spectral radiometric value is quoted.
The variation of spectral radiant exitance ($M_{e\lambda}$), or irradiance ($E_{e\lambda}$) with wavelength is often shown in a spectral distribution curve.
We use mW $m^{-2}nm^{-1}$as our preferred units for spectral irradiance. Conversion to other units, such as mW $m^{-2}$ $\mu m^{-1}$, is straightforward.
For example:
The spectral irradiance at 0.5 m from our 6333 100 watt QTH lamp is 12.2 mW $m^{-2}$ $nm^{-1}$at 480 nm. This is:

0.0122 W $m^{-2}$ $nm^{-1}$
1.22 W $m^{-2}$ $\mu m^{-1}$
1.22 $\mu$W $cm^{-2}$ $nm^{-1}$

all at 0.48 µm and 0.5 m distance.
With all spectral irradiance data or plots, the measurement parameters, particularly the source-measurement plane distance, must be specified. Values cited in this tutorial for lamps imply the direction of maximum radiance and at the specified distance.

## Wavelength, Wavenumber, Frequency and Photon Energy

This tutorial uses “wavelength" as the spectral parameter. Wavelength is inversely proportional to the photon energy; i.e. shorter wavelength photons are more energetic photons. Wavenumber and frequency increase with photon energy.
The units of wavelength we use are nanometers (nm) and micrometers (µm) (or the common, but incorrect version, microns).

1 nm = $10^{-9}$ m = $10^{-3}$ µm
1 µm = $10^{-6}$ m = 1000 nm
1 Angstom unit (Å) = $10^{-10}$ m = $10^{-1}$ nm

Fig. 1 shows the solar spectrum and 5800K blackbody spectral distributions against energy (and wavenumber), in contrast with the familiar representation shown in Fig. 4. Table 2 helps you to convert from one spectral parameter to another. The conversions use the approximation 3 x $10^8$ m $s^{-1}$ for the speed of light. For accurate work, you must use the actual speed of light in medium. The speed in air depends on wavelength, humidity and pressure, but the variance is only important for interferometry and high-resolution spectroscopy.

## Converting From Radiometric to Photon Quantities

Expressing radiation in photon quantities is important when the results of irradiation are described in terms of cross section, number of molecules excited or for many detector and energy conversion systems, quantum efficiency.

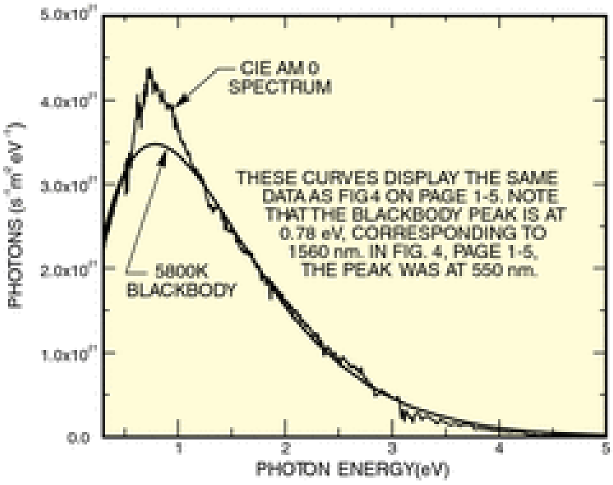


Fig. 1 Unconventional display of solar irradiance on the outer atmosphere
and the spectral distribution of a 5800K blackbody with the same total radiant flux.

## Monochromatic Radiation

Calculating the number of photons in a joule of monochromatic light of wavelength λ is straightforward since the energy in each photon is given by:
$E = hc/\lambda$ joules

Where:
h = Planck’s constant (6.626 x $10^{-34}$ J s)
c = Speed of light (2.998 x $10^8$ m $s^{-1}$)
λ = Wavelength in m

So the number of photons per joule is:
$N_{p\lambda} = \lambda \times 5.03 \times 10^{15}$ where λ is in nm⁺
Since a watt is a joule per second, one Watt of monochromatic radiation at λ corresponds to $N_{p\lambda}$ photons per second. The general expression is:

$\frac{dN_{p\lambda}}{dt} = P_\lambda \times \lambda \times 5.03 \times 10^{15}$ where $P_\lambda$ is in watts, λ is in nm

Similarly, you can easily calculate photon irradiance by dividing by the beam impact area.
**+ We have changed from a fundamental expression where quantities are in base SI units, to the derived expression for everyday use.**

## Tech Note

Irradiance and most other radiometric quantities have values defined at a point, even though the units, mW $m^{-2}$ $nm^{-1}$, imply a large area. The full description requires the spatial map of the irradiance. Often average values over a defined area are most useful. Peak levels can greatly exceed average values.

### Table 3 Spectral Parameter Conversion Factors

| Symbol (units) | Wavelength λ (nm) | Wavenumber* υ ($cm^{-1}$) | Frequency ν (Hz) | Photon Energy** $E_p$ (eV) |
|---|---|---|---|---|
| Conversion Factors | λ | $10^7$/ λ | 3 x $10^{17}$/λ | 1,240/λ |
| | $10^7$/υ | υ | 3 x $10^{10}$υ | 1.24 x $10^{-4}$υ |
| | 3 x $10^{17}$/ν | 3.33 x $10^{-11}$ν | ν | 4.1 x $10^{-15}$ν |
| | 1,240/Ep | 8,056 x Ep | 2.42 x $10^{14}$Ep | Ep |
| Conversion Examples | 200 | 5 x $10^4$ | 1.5 x $10^{15}$ | 6.20 |
| | 500 | 2 x $10^4$ | 6 x $10^{14}$ | 2.48 |
| | 1000 | $10^4$ | 3 x $10^{14}$ | 1.24 |

When you use this table, remember that applicable wavelength units are nm, wavenumber units are $cm^{-1}$, etc.
* The S.I. unit is the $m^{-1}$. Most users, primarily individuals working in infrared analysis, adhere to the $cm^{-1}$.
** Photon energy is usually expressed in electron volts to relate to chemical bond strengths. The units are also more convenient than photon energy expressed in joules as the energy of a 500 nm photon is 3.98 x $10^{-19}$ J = 2.48 eV.

## Example 1

What is the output of a 2 mW (632.8 nm) HeNe laser in photons per second?

$$\begin{aligned} 2\text{ mW} &= 2 \times 10^{-3}\text{ W} \\ \phi_p &= 2 \times 10^{-3} \times 632.8 \times 5.03 \times 10^{15} \\ &= 6.37 \times 10^{15}\text{ photons/second} \end{aligned}$$

## Broadband Radiation

To convert from radiometric to photon quantities, you need to know the spectral distribution of the radiation. For irradiance you need to know the dependence of $E_{e\lambda}$ on λ. You then obtain the photon flux curve by converting the irradiance at each wavelength as shown in Example 1. The curves will have different shapes as shown in Fig. 2.

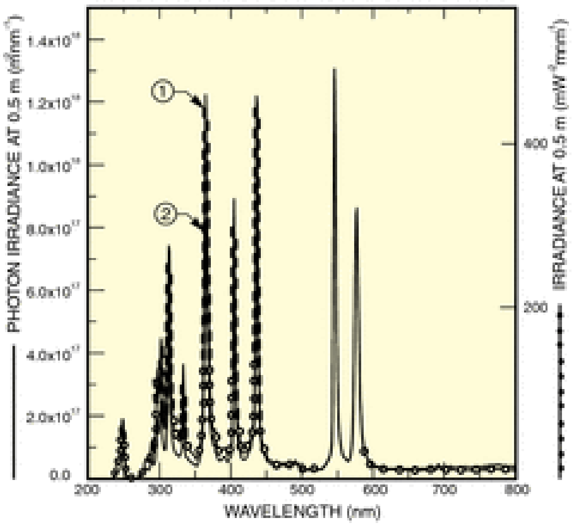


Fig. 2 The wavelength dependence of the irradiance produced by the 6283 200 W mercury lamp at 0.5 m.
(1) shown conventionally in mW $m^{-2}$ $nm^{-1}$ and (2) as photon flux.

## Converting from Radiometric to Photometric Values

You can convert from radiometric terms to the matching photometric quantity (Table 1). The photometric measure depends on how the source appears to the human eye. This means that the variation of eye response with wavelength, and the spectrum of the radiation, determines the photometric value. Invisible sources have no luminance, so a very intense ultraviolet or infrared source registers no reading on a photometer. The response of the "standard" light adapted eye (photopic vision) is denoted by the normalized function V (λ). See Fig. 3 and Table 4. Your eye response may be significantly different!

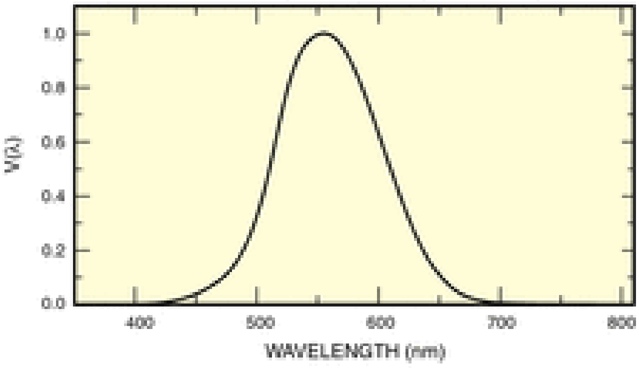


Fig. 3 The normalized response of the “standard” light adapted eye.

Table 4 Photopic Response

| Wavelength (nm) | Photopic Luminous Efficiency V(λ) | Wavelength (nm) | Photopic Luminous Efficiency V(λ) |
|---|---|---|---|
| 380 | 0.00004 | 580 | 0.870 |
| 390 | 0.00012 | 590 | 0.757 |
| 400 | 0.0004 | 600 | 0.631 |
| 410 | 0.0012 | 610 | 0.503 |
| 420 | 0.0040 | 620 | 0.381 |
| 430 | 0.0116 | 630 | 0.265 |
| 440 | 0.023 | 640 | 0.175 |
| 450 | 0.038 | 650 | 0.107 |
| 460 | 0.060 | 660 | 0.061 |
| 470 | 0.091 | 670 | 0.032 |
| 480 | 0.139 | 680 | 0.017 |
| 490 | 0.208 | 690 | 0.0082 |
| 500 | 0.323 | 700 | 0.0041 |
| 510 | 0.503 | 710 | 0.0021 |
| 520 | 0.710 | 720 | 0.00105 |
| 530 | 0.862 | 730 | 0.00052 |
| 540 | 0.954 | 740 | 0.00025 |
| 550 | 0.995 | 750 | 0.00012 |
| 555 | 1.000 | 760 | 0.00006 |
| 560 | 0.995 | 770 | 0.00003 |
| 570 | 0.952 | | |

To convert, you need to know the spectral distribution of the radiation. Conversion from a radiometric quantity (in watts) to the corresponding photometric quantity (in lumens) simply requires multiplying the spectral distribution curve by the photopic response curve, integrating the product curve and multiplying the result by a conversion factor of 683.
Mathematically for a photometric quantity (PQ) and its matching radiometric quantity (SPQ).

$$PQ = 683 \int (SPQ_{\lambda}) \bullet V(\lambda) d\lambda$$

Since V(λ) is zero except between 380 and 770 nm, you only need to integrate over this range. Most computations simply sum the product values over small spectral intervals, Δλ :

$$PQ \approx (\Sigma_n (SPQ_{\lambda n}) \cdot V(\lambda_n)) \cdot \Delta\lambda$$

Where:
$(SPQ_{\lambda n})$ = Average value of the spectral radiometric quantity in wavelength interval number “n”
The smaller the wavelength interval, Δλ, and the slower the variation in $SPQ_{\lambda}$, the higher the accuracy.

## Example 2

Calculate the illuminance produced by the 6253 150 W Xe arc lamp, on a small vertical surface 1 m from the lamp and centered in the horizontal plane containing the lamp bisecting the lamp electrodes. The lamp operates vertically.
Curve values for this lamp (found at the end of this section) are for 0.5 m, and since irradiance varies roughly as $r^{-2}$, divide the 0.5 m values by 4 to get the values at 1 m. These values are in mW $m^{-2}$ $nm^{-1}$ and are shown in Fig. 4. With the appropriate irradiance curve you need to estimate the spectral interval required to provide the accuracy you need. Because of lamp-to-lamp variation and natural lamp aging, you should not hope for better than ca. ±10% without actual measurement, so don't waste effort trying to read the curves every few nm. The next step is to make an estimate from the curve of an average value of the irradiance and V(λ) for each spectral interval and multiply them. The sum of all the products gives an approximation to the integral.
We show the “true integration” based on the 1 nm increments for our irradiance spectrum and interpolation of V(λ) data, then an example of the estimations from the curve.
Fig. 4 shows the irradiance curve multiplied by the V(λ) curve. The unit of the product curve that describes the radiation is the lW, or light watt, a

hybrid unit bridging the transition between radiometry and photometry. The integral of the product curve is 396 mlWm$^{-2}$, where an lW is the unit of the product curve.

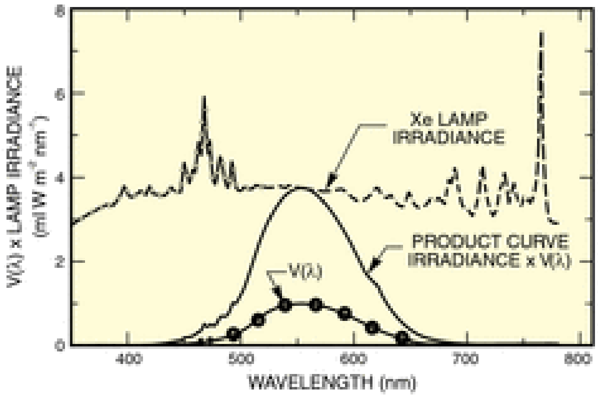


Fig. 4 Lamp Irradiance, V (λ), and product curve.

## Estimating:

Table 5 shows the estimated values with 50 nm spectral interval. The sum of the products is 392 mlWm$^{-2}$, very close to the result obtained using full integration.

Table 5 Light Watt Values

| **Wavelength Range (nm)** | **Estimated Average Irradiance (mW m$^{-2}$ nm$^{-1}$)** | **V(λ)** | **Product of cols 1 & 2 x 50 nm (mlW m$^{-2}$ )** |
|---|---|---|---|
| 380 - 430 | 3.6 | 0.0029 | 0.5 |
| 430 - 480 | 4.1 | 0.06 | 12 |
| 480 - 530 | 3.6 | 0.46 | 83 |
| 530 - 580 | 3.7 | 0.94 | 174 |
| 580 - 630 | 3.6 | 0.57 | 103 |
| 630 -680 | 3.4 | 0.11 | 19 |
| 680 - 730 | 3.6 | 0.0055 | 1.0 |
| 730 - 780 | 3.8 | 0.0002 | 0.038 |

To get from lW to lumens requires multiplying by 683, so the illuminance is:
396 x 683 mlumens m$^{-2}$ = 270 lumens m$^{-2}$ (or 270 lux).
Since there are 10.764 ft$^2$ in an m$^2$, the illuminance in foot candles (lumens ft$^{-2}$) is 270/10.8 = 25.1 foot candles.

## Tech Note

The example uses a lamp with a reasonably smooth curve over the VIS region, making the multiplication and summation easier. The procedure is more time consuming with an Hg lamp due to the rapid spectral variations. In this case, you must be particularly careful about our use of a logarithmic scale in our irradiance curves. You can simplify the procedure by cutting off the peaks to get a smooth curve and adding the values for the “monochromatic” peaks back in at the end. We use our tabulated irradiance data and interpolated V(λ) curves to get a more accurate product, but lamp-to-lamp variation means the result is no more valid.