The Photometric System

Light flux, for the purposes of illuminating engineering, is measured in lumens. A lumen of light, no matter what its wavelength (color), appears equally bright to the human eye. The human eye has a stronger response to some wavelengths of light than to other wavelengths. The strongest response for the light-adapted eye (scene luminance ≥ .001 lambert) comes at a wavelength of 555 nm. A light-adapted eye is said to be operating in the photopic region. A dark-adapted eye is operating in the scotopic region (scene luminance ≤ 10^{-8} lambert). In between is the mesopic region. The peak response of the eye shifts from 555 nm to 510 nm as scene luminance is decreased from the photopic region to the scotopic region. The standard lumen is approximately 1/680 of a watt of radiant energy at 555 nm. Standard values for other wavelengths are based on the photopic response curve and are given with two-place accuracy by the table below. The values are correct no matter what region you're operating in - they're based only on the photopic region. If you're operating in a different region, there are corrections to apply to obtain the eye's relative response, but this doesn't change the standard values given below.

Wavelength, nm	Lumens/watt	Wavelength, nm	Lumens/watt
400	0.27	600	430
450	26	650	73
500	220	700	2.8
550	680		

Following are the standard units used in photometry with their definitions and symbols.

Luminous flux, F, is measured in lumens.

Quantity of light, Q, is measured in lumen-hours or lumen-seconds. It is the time integral of luminous flux.

Luminous Intensity, I, is measured in candles, candlepower, or candela (all the same thing). It is a measure of how much flux is flowing through a solid angle. A lumen per steradian is a candle. There are 4π steradians to a complete solid angle. A unit area at unit distance from a point source covers a steradian. This follows from the fact that the surface area of a sphere is $4\pi r^2$.

Lamps are measured in MSCP, mean spherical candlepower. If you multiply MSCP by 4π you have the lumen output of the lamp. In the case of an ordinary lamp which has a horizontal filament when it is burning base down, roughly 3 steradians are ineffectual: one is wiped out by inter- ference from the base and two more are very low intensity since not much light comes off either end of the filament. So figure the MSCP should be multiplied by 4/3 to get the candles coming off perpendicular to the lamp filament. Incidentally, the number of lumens coming from an incandescent lamp varies approximately as the 3.6 power of the voltage. This can be really important if you are using a lamp of known candlepower to calibrate a photometer.

Illumination (illuminance), E, is the areal density of incident luminous flux: how many lumens per unit area. A lumen per square foot is a foot-candle; a one square foot area on the surface of a sphere of radius one foot and having a one-candle point-source centered in it would therefore have an illumination of one foot-candle due to the one lumen falling on it. If you substitute meter for candle you have a meter-candle or lux. In this case you still have the flux of one steradian but now it's spread out over one square meter. Multiply an illumination level in lux by .0929 to convert it to foot-candles. $(\text{foot}\div\text{meter})^2 = .0929$. A centimeter-candle is a phot. Illumination from a point source falls off as the square of the distance. So if you divide the intensity of a point source in candles by the distance from it in feet squared, you have the illumination in foot candles at that distance.

Luminance, B, is the areal intensity of an extended diffuse source or an extended diffuse reflector. If a perfectly diffuse, perfectly reflecting surface has one foot-candle (one lumen per square foot) of illumination falling on it, its luminance is one foot-lambert or $1/\pi$ candles per square foot. The total amount of flux coming off this perfectly diffuse, perfectly reflecting surface is, of course, one lumen per square foot. Looking at it another way, if you have a one square foot diffuse source that has a luminance of one candle per square foot (π times as much intensity as in the previous example), then the total output of this source is π lumens. If you travel out a good distance along the normal to the center of this one square foot surface, it will look like a point source with an intensity of one candle.

To contrast: Intensity in candles is for a point source while luminance in candles per square foot is for an extended source - luminance is inten- sity per unit area. If it's a perfectly diffuse but not perfectly reflecting surface, you have to multiply by the reflectance, k, to find the luminance.

Also to contrast: Illumination, E, is for the incident or incoming flux's areal density; luminance, B, is for reflected or outgoing flux's areal intensity. In the ideal case of illumination, incoming flux is more or less perpendicular to the surface being illuminated. But an extended source emits light according to the cosine law and a diffuse reflecting surface reflects according to the cosine law: the amount of flux emitted per unit surface area is proportional to the cosine of the angle between the direction in which the flux is being emitted and the normal to the emitting surface. A consequence of this law is that no matter from what direction you look at a perfectly diffuse reflecting or emitting surface, the luminance on the basis of projected area is the same. So if you have a light meter looking at a perfectly diffuse surface, it doesn't matter what the angle between the axis of the light meter and the normal to the surface is as long as all the light meter can see is the surface: in any case the reading will be the same.

There are a number of luminance units, but they are in categories: two of the categories are those using English units and those using metric units. Another two categories are those which have the constant $1/\pi$ built into them and those that do not. The latter stems from the fact that the formula to calculate luminance (photometric Brightness), B, from illumination (illuminance), E, contains the factor $1/\pi$. To illustrate:

$$B = (k*E)(1/\pi)$$
$$B_{fl} = k*E$$

where:

B = luminance, candles/foot^2
B_{fl} = luminance, foot-lamberts
k = reflectivity $0<k<1$
E = illuminance in foot-candles (lumens/ foot^2)

Obviously, if you divide a luminance expressed in foot-lamberts by π you then have the luminance expressed in candles /foot^2. ($B_{fl} \div \pi = B$)

Other luminance units are:

stilb = 1 candle/square centimetersb
apostilb = stilb /(π X 10^4) = 10^{-4}L asb
nit = 1 candle/ square meter nt
lambert = ($1/\pi$) candle/square cm L

Below is a table of photometric units with short definitions.

Symbol	Term	Unit	Unit Definition
Q	light quantity	lumen-hour lumen-second	radiant energy as corrected for eye's spectral response
F	luminous flux	lumen	radiant energy flux as corrected for eye's spectral response
I	luminous intensity	candle candela candlepower	one lumen per steradian one lumen per steradian one lumen per steradian
E	illumination	foot-candle lux phot	lumen/foot^2 lumen/meter^2 lumen/centimeter^2
B	luminance	candle/foot^2 foot-lambert lambert stilb nit	see unit def's. above = ($1/\pi$) candles/foot^2 = ($1/\pi$) candles/centimeter^2 = 1 candle/centimeter^2 = 1 candle/meter^2

Note: A lumen-second is sometimes known as a talbot.

To review:

Quantity of light, Q, is akin to a quantity of photons except that the number of photons is pro-rated according to how bright they appear to the eye.

Luminous flux, F, is akin to the time rate of flow of photons except that the photons are not given a value based on their wavelength or energy but rather on how bright they appear to the eye.

Luminous intensity, I, is the solid-angular density of luminous flux. Applies primarily to point sources.

Illumination, E, is the areal density of incident luminous flux.

Luminance, B, is the areal intensity of an extended source.

Photometry with a Photographic Light Meter

The first caveat to keep in mind is that the average unfiltered light meter doesn't have the same spectral sensitivity curve that the human eye does. Each type of sensor used has its own curve. Silicon blue cells aren't too bad. The overall sensitivity of a cell is usually measured with a 2856°K or 2870°K incandescent lamp. Less commonly it is measured with 6000°K sunlight.

The basis of using a light meter is the fact that a light meter uses the Additive Photographic Exposure System, the system which uses Exposure Values:

$$E_v = A_v + T_v = S_v + B_v$$

where: E_v = Exposure Value

A_v = Aperture Value = $\ln N^2/\ln 2$ where N = f/no.

T_v = Time Value = $\ln t^{-1}/\ln 2$ where t = time in sec.s

S_v = Speed Value = $\ln (0.3\ S)/\ln 2$ where S = ASA speed

B_v = Brightness Value = $\ln B_{fl}/\ln 2$

from which, for example:

$A_v(N=f/1) = 0$

$T_v(t=1\ sec) = 0$

$S_v(S=ASA\ 3.125) \approx 0$

$B_v(\ B_{fl} = 1$ foot-lambert$) = 0$

and therefore:

$B_{fl} = 2^{Bv}$

$E_v\ (S_v = 0) = B_v$

From the preceding two equations you can see that if you set the meter dial to an ASA speed of approximately 3.1 (same as $S_v = 0$), when you read a scene luminance level the E_v reading will be B_v from which you can calculate B_{fl}. If you don't have an ASA setting of 3.1 on your dial, just use ASA 100 and subtract 5 from the E_v reading to get B_v. (S_v@ASA100=5)

Image Illumination

If you know the object luminance (photometric brightness), the f-number of the lens, and the image magnification, you can calculate the image illumination. The image magnification is the quotient of any linear dimension in the image divided by the corresponding linear dimension on the object. It is, in the usual photographic case, a number less than one. The f-number is the f-number for the lens when focussed at infinity - this is what's written on the lens. The formula that relates these quantities is given below:

$$E_{image} = (t\pi B)/[4\ N^2\ (1+m)^2]$$

or:

$$E_{image} = (t\ B_{fl})/[4\ N^2\ (1+m)^2]$$

where:

- E_{image} is in foot-candles (divide by .0929 to get lux)
- t is the transmittance of the lens (usually .9 to .95 but lower for more surfaces in the lens or lack of anti-reflection coatings)
- B is the object luminance in candles/square foot
- B_{fl} is the object luminance in foot-lamberts
- N is the f-number of the lens
- m is the image magnification

References:

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