Radiant Presence

Optical Metrology Basics: Radiometry

Radiometry provides methods and quantities for the characterization of the intensity of radiation with emphasis on applications in optical metrology. Whenever the signal in an optical sensor in combination with the associated lighting system must be estimated, the quantities and concepts of radiometry come into play. Should you like to know whether ten LEDs will produce a sufficiently high lighting level in the field of view to saturate your camera signal, it my be a good idea to brush-up your knowledge about radiometry. The same holds true when you look at the data sheets of light sources or lighting systems from different manufacturers.

Radiometric Quantities

Radiometric quantities evaluate the energy of radiation. In this article, the focus is on applications in optical metrology. We thus narrow the field by looking at the visible spectral range, the UV and the near infrared, where radiation may be picked up with photodiodes, CCD- and CMOS-detectors. We assume the radiation to be unpolarized and incoherent, which means that the wave nature of radiation does not show up and interference phenomena are excluded. To further simplify the situation, let us first imagine a light source with small spectral bandwidth. A good example of a source which meets these requirements is a LED with emission of red light of 620 nm, e.g., which might have a spectral bandwidth of 20 nm. Packed into a plastic lens with a diameter of maybe 5 mm, the light emission might be bundled into a cone with a full angle of 20°. If you look at such a LED from a large distance, from 50 cm, e.g., the light seems to be emitted from a very small area, and we may treat the LED as a point source. Radiometry provides the tools to estimate the signal for a photodiode or a camera which is placed in this radiation field on the basis of just a few elementary quantities.

One elementary radiometric quantity is the total radiant energy Q of a light source. Q is the energy emitted into and integrated over all directions within a certain time interval. An example is the radiant energy of a strobe light source emitted within a single strobe. Q is an energy measured in the unit Joule. Usually, the radiant flux Φ will be specified rather than Q. Φ is the rate of change of Q with time. The radiant flux, being the total radiant energy per time interval, is measured in the unit of power, Watt, and may be viewed as the radiant power transported through the diameter of a bundle of rays. Total radiant energy Q and radiant flux Φ are conserved, which means they remain constant along the direction of propagation of the radiation as long as no energy is lost by absorption, scattering or refraction at boundaries. The manufacturer of the LED might thus specify a radiant flux of 10 mW, e.g., for a certain current and temperature, within an angle of emission of 20°. No matter how far away you are from the LED, you will always measure a flux of 10 mW flowing through the diameter of the bundle of rays emitted by the LED. Since the diameter will increase with increasing distance from the source, however, the radiant power will be distributed over an increasing area. This situation gives reason to define the flux density E, which is also called the irradiance. E is the radiant flux Φ related to the area A illuminated by the radiation:

$$E = d\Phi/dA$$

E is measured in the unit W/m². The sun, e.g., produces an irradiance of 1350 W/m² in space at the orbit of the international space station ISS. Our example-LED, on the other hand, shining at a piece of white paper at normal incidence in a distance of 50 cm, will produce a circle of light with a radius of 8.8 cm, which means an illuminated area of 244 cm², resulting in an mean irradiance of 10 mW/244 cm², roughly 0.4 W/m². Irradiance is a differential quantity with reference to area and may thus be given for every single point of the radiation field. Multiplication with the area dA of a detector or a pixel probing this radiation field gives the radiant flux dΦ upon this


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area. In general, on an illuminated surface, e.g., the irradiance will vary with position.

Photon Flux

The irradiance is well suited to describe the radiometric properties of a bundle of rays at a certain point in the optical path. Since radiant flux is conserved and an optical system basically just shapes the geometry of a bundle of rays, the flux can be tracked from the light source all the way to the detector plane, and the irradiance at the detector plane may be computed. Once the irradiance at the optical sensor or the detector array of a camera is known, the signal can be estimated. Photodiodes, CCD- und CMOS-sensors utilize the photoelectric effect for conversion of photons to electrons. The signal is a photocurrent or a total charge accumulated within a certain time interval. When absorbed within the detector material, every photon produces a single electron at most. The probability for a photon to release an electron is the quantum efficiency. A good data sheet will specify the quantum efficiency as function of the wavelength of the incoming radiation. Quantum efficiency may thus be quantitatively considered in an estimation of the signal, if necessary. By far more important, however, is the fact that the detectors mentioned above do not primarily detect radiant energy, but convert single photons to single signal electrons. As a consequence, it is more important to look at the number of photons hitting the detector rather than stare at the radiant energy absorbed. Needless to say, there is a close relationship between these two fundamental quantities. A photon with wavelength λ carries the energy:

$$E_{photon} = hc/\lambda$$

with h denoting Planck's constant and c the velocity of light. In optical metrology, the unit "electron volt" (eV) is preferred against Joule, since values for photon energies measured in Joule are quite small and unhandy. The electron volt is the product of the elementary charge and the unit Volt for the electrical potential difference with 1 eV equal to $1.6x10^{-19}$ J. When calculating photon energies, after some weeks you will have learned the value of the product hc by heart and realize that the energy of a photon with wavelength Φ simply is:

$$E_{photon} = (1240/\lambda)\ eV \times nm$$

1240 divided by the wavelength measured in nm results in the photon energy measured in eV. An IR-photon at 1240 nm, e.g., carries the photon energy of just 1 eV. A red photon at 620 nm as emitted by our example-LED has the energy of 2 eV, whereas a blue photon at about 413 nm provides an energy package of 3 eV. As a consequence, radiation at longer wavelengths with the same amount of total radiant energy is made up by a larger number of photons than radiation at shorter wavelengths. The bundle of rays from our example-LED at 620 nm and with a radiant flux of 10 mW pushes the enormous amount of about $3x10^{16}$ photons per second through the diameter of the beam. For a 10 mW-LED at 413 nm, however, the number would be only $2x10^{16}$ photons per second, and the signal would decrease to 67 % of the signal at 620 nm, taken for granted the same quantum efficiency at these wavelengths. For an estimation of the detector signal the number of photons N and the photon flux dN/dt are key parameters. The photon flux can be calculated from the radiant flux:

$$dN/dt = \Phi/E_{photon}$$

It should be evident that this relation holds true for monochromatic radiation only and must not be used for light sources with a continuous spectrum. The value of 1350 W/m² for the solar irradiance at the ISS, e.g., can not simply be converted to a value for the photon flux per unit area, since solar emission is continuous with respect to the wavelength distribution and contains photons from the UV through the colours of the visible range and up into the infrared. The photon flux can only be calculated when the spectral distribution of the solar emission is precisely known and taken into account by integration over the photon fluxes of the spectral components. With varying spectral distributions, as in applications in the public domain, where daylight varies significantly with the seasons and during a day, the estimation of a detector signal becomes complicated. Even lighting systems with modern white LEDs in a controlled environment provide much more challenging radiometric calculations due to the continuous spectrum of emission than small-band LED-units.

Radiant Intensity

To wrap up this introduction, another radiometric quantity should be mentioned, which is of some importance for the comparison of light sources. Our example-LED radiates 10 mW into a cone within an angle of 20°. Without focusing lens, the radiant power would be emitted into the full half space above the chip. This would drastically reduce the irradiance. At a certain distance, 50 cm, e.g., the irradiance E would not any longer amount to about 0.4 W/m² as calculated above, but much less, since the total radiant energy now will be distributed over the surface of a half sphere with a radius of 50 cm rather than over the base of a cone with a radius of about 8.8 cm at a distance of 50 cm. Thus, a quantity taking into account the divergence and the consequences for the energy flow within the emitted bundle of rays, but independent from the distance from the source would be quite helpful. This radiometric quantity is the radiant intensity I, defined as the radiant flux dΦ per solid angle dΩ. The solid angle describes the cone cut out of a sphere, when the tip of the cone is in the centre of the sphere. To quantify the solid angle, take a sphere with radius r and calculate the area A of the cap cut out of the surface of the sphere by the cone defining the solid angle. The solid angle is then given by $\Omega = A/r^2$ with the unit steradian (sr). This concept is analogous to the measurement of plane angles as arc length divided by radius of a circle with the unit radian (rad). The solid angle for a full sphere thus will be equal to the surface area of a sphere with radius r divided by r^2, that is $4\pi r^2/r^2 = 4\pi$ sr. For a half sphere, the solid angle is 2π sr, and for our example-LED the solid angle of emission will be about 244 cm²/50² cm², which is roughly 0.1 sr. For small angles the solid angle is approximated by $d\Omega = dA/r^2$ with the area dA perpendicular to the radius instead of the spherical cap, in our case just the plane base of the cone. The mean radiant intensity for the example-LED amounts to I = 10 mW/0.1 sr = 0.1 W/sr. Since the radiant intensity is a differential quantity with regard to the solid angle, it can be given for every single point of the radiation field. Multiplication of I with the solid angle captured by the detector or the pixel results in the corresponding radiant flux or radiant power illuminating the device. In contrast to the irradiance, the radiant intensity of a point source will be constant for a light bundle propagating free, regardless of the distance from the source, whereas the irradiance decreases by $1/r^2$.

Photometric Quantities

LEDs are often specified by the radiant intensity on the symmetry axis of the emission cone as a figure of merit. The unit for this quantity is W/sr or sometimes, within the visible range, candela (cd). When comparing two LEDs, it should be kept in mind that the divergence of the emission strongly influences the value of these quantities. Should the manufacturer be able to develop a lens on top of the LED-chip which decreases the angle of emission by the factor 2 from 20° to 10° with the same total radiant energy, the radiant intensity will increase by the factor 4. Although the new LED will appear to be four times better, it will provide the same amount of radiant power on a target as its predecessor. With fixed distance from the LED, however, the radiant power will be distributed to a smaller area of the target. This may be a benefit for some applications, but may be irrelevant for others. Further irritations arise from the habit of some manufacturers to specify the "intensity" as luminous intensity with the photometric unit candela (cd). Luminous intensity is equivalent to radiant intensity, but weighted with the response of the human visual system to optical radiation. For optical metrology applications like in industrial image processing or automation human visual sensations usually are irrelevant. The photometric analogon to the quantity irradiance, which is then weighted with the response function of the human visual system, is the illuminance with the unit lux (lx). Sometimes, you will find data sheets for cameras specifying the sensitivity with the somewhat awkward entry "0 lx", which just means that the camera will produce a signal under infrared illumination. Since radiation in the IR is not visible for the human eye, the photometric evaluation of the intensity will result in an illuminance of 0 lx, no matter what the value of the radiometric quantity irradiance with the unit W/m² of this radiation field may be, even if it amounts to 10 W/m². For monochromatic light sources, in the visible range the photometric quantities can be converted to radiometric quantities with reference to the standardized sensitivity curve of the human eye. For light sources with continuous spectral distribution of the emission, there is no general means to convert from photometric to radiometric quantities. If such a conversion is possible at all, it must be based on precise knowledge of the spectral distribution.

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