Basics of Light Measurement

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Light, which is the visible part of the electromagnetic radiation spectrum, is the medium through which human beings receive the major part of environmental information. Evolution has optimized the human eye into a highly sophisticated sensor for electromagnetic radiation. Joint performance between the human eye and the visual cortex, which makes up a large part of the human brain, outshines even the latest technical and scientific developments in image processing and pattern recognition. As a matter of fact, most of the information flow from external stimuli to our brain is transferred visually. Photometry deals with the measurement of this visible light energy.

However, optical radiant energy does not only encompass visible “light”, but also radiation that is invisible to the human eye. The term optical is used because this radiation follows the laws of geometrical optics.

Radiometry deals with the measurement of all optical radiation, including the visible portion of this radiant energy.

This tutorial is an introduction to the radiometric, photometric, colorimetric, reflection and transmission principles as well as quantities, symbols, units and the basic nature of light and color. Sections covering a sampling of current applications, detectors, electronics and calibration are included. A list of reference sources is provided for future study.

SI (Système International) units are used throughout this tutorial. Many international organizations, including the *CIE (Commission Internationale de l'Eclairage)*, have exclusively adopted this system of units. The terminology used follows that of the CIE International Lighting Vocabulary.

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1 Properties and Concepts of Light and Color

Thorough knowledge of the physical nature of light and light perception provides the foundation for a comprehensive understanding of optical measurement techniques. Yet from a practical point of view, there is little necessity to fully understand formation and propagation of light as an electromagnetic wave as long as the reader accepts wavelength as the most important parameter describing the quality of light. The human eye perceives light with different wavelengths as different colors (s. Fig. 1) as long as the wavelengths are between 400 nm and 800 nm (1 nm = 1 nanometer = 10^{-9} m). In the electromagnetic spectrum optical range, the wavelength is sometimes also given in Ångstrøm (Å = 10^{-10} m). Outside this range, our eye is insensitive to electromagnetic radiation and we therefore cannot perceive ultraviolet (UV, below 400 nm) and infrared (IR, above 80 nm) radiation.

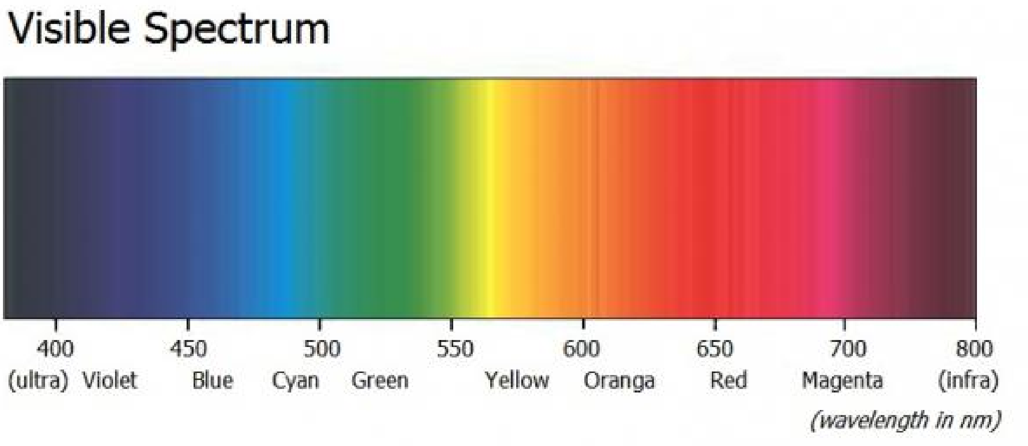

Fig. 1: Monochromatic electromagnetic radiation of different wavelengths between 400 nm and 800 nm causes the impression of different colors. Outside this wavelength range, the human eye is insensitive.

Source (valid as of 2002): http://www.cameraguild.com/technology/colorimetry.htm

1.1 The optical radiation wavelength range

According to DIN 5031, the term “optical radiation” refers to electromagnetic radiation in the wavelength range between 100 nm and 1 mm. The terms “light” and “visible radiation” (VIS) refer to the wavelength range between 400 nm and 800 nm, which can be perceived by the human eye. Optical radiation with wavelengths shorter than 400 nm is called ultraviolet (UV) radiation and is further subdivided in UV-A, UV-B and UV-C ranges. Optical radiation with wavelengths longer than 800 nm is called infrared radiation (IR) and is similarly divided into IR-A,

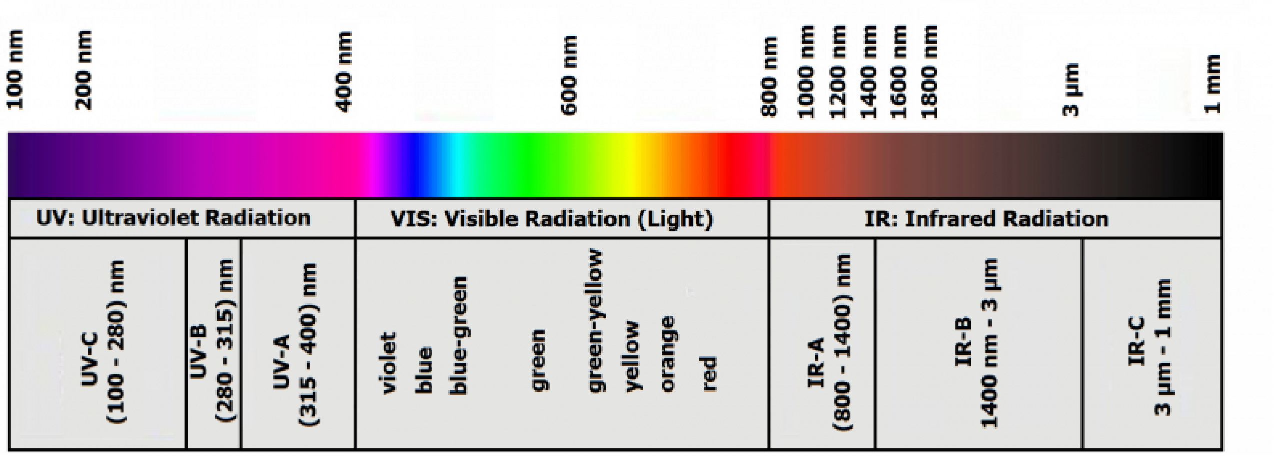

Fig. 1: Wavelength ranges of electromagnetic radiation.

It must be emphasized that this classification of electromagnetic radiation is a matter of convention and is not based on qualitative properties of the electromagnetic wave itself. Instead, it is largely motivated by the effects of the electromagnetic wave on matter. For instance, the UV-B range covers the wavelengths in the solar spectrum which is particularly responsible for DNA damage that causes melanoma and other types of skin cancer. Since the strength of radiation effects on matter does not change abruptly with wavelength, different authors define UVA and UVB ranges slightly different. For example, the US Food and Drug Administration (FDA) and the US Environmental Protection Agency (EPA) define the UV-A range as being between 320 nm and 400 nm. This is different from the definition by two of the main standardization authorities, the CIE and DIN, who define the UVA range as being between 315 nm and 400 nm.

Spectral sensitivity functions such as the CIE photopic response have also been defined in other biological effects of optical radiation, e. g. DNA damage, formation of erythema (sunburn) and of non-melanoma skin cancer, tanning of the human skin and the photosynthesis process in green plants, which have been studied and quantified by spectral sensitivity. Particularly with respect to certain biological reactions, the term “action spectrum” is often used instead of “spectral sensitivity”.

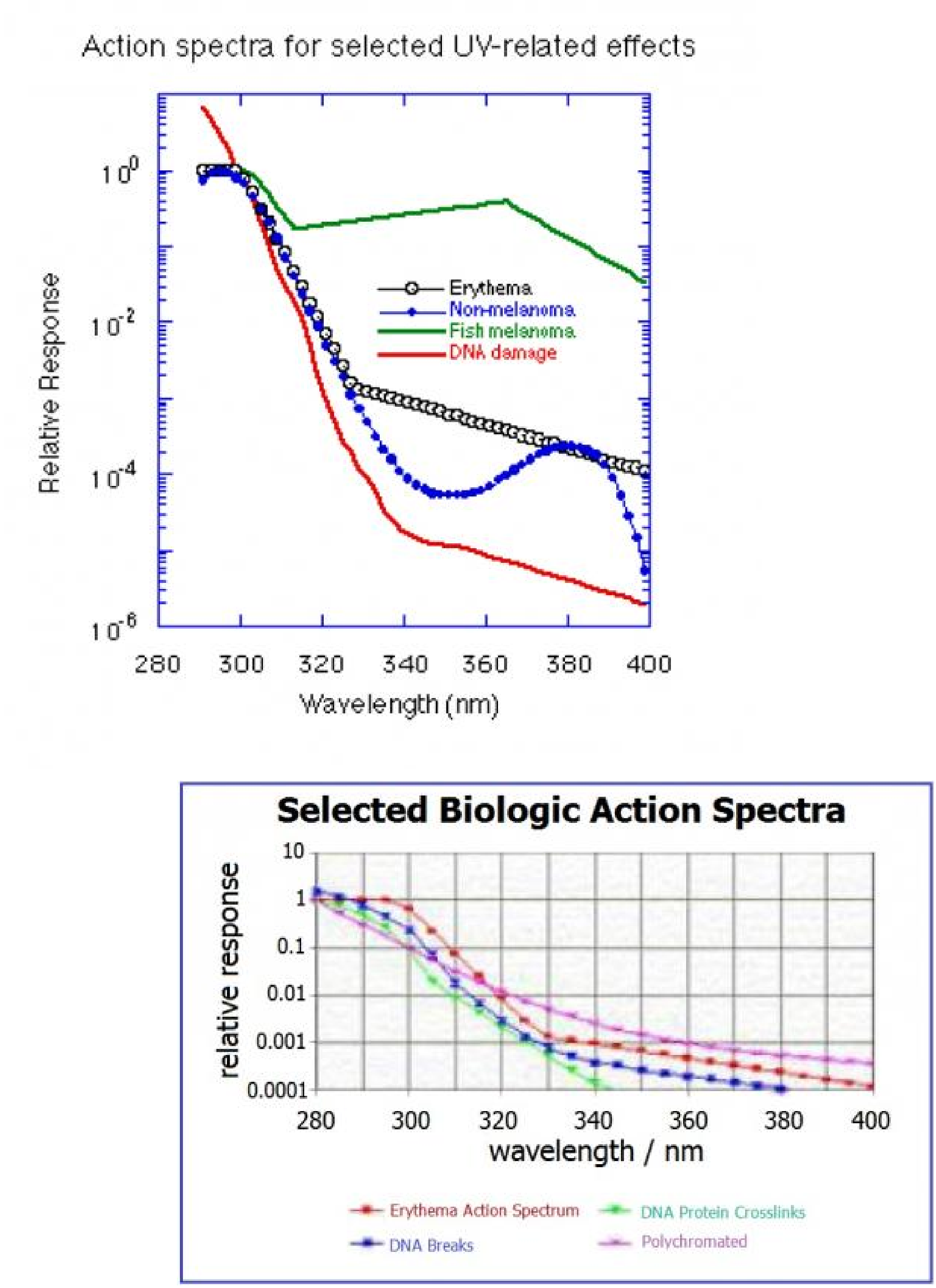

Fig. 2: Action spectra for various biological reactions to UV radiation

Source (valid as of 2002): http://sedac.ciesin.org/ozone/docs/AS.html

1.2 The measures of a wave: velocity, amplitude, wavelength and frequency

Like all other waves (waves in a string, water waves, sound, earthquake waves ...), light and electromagnetic radiation in general can be described as a vibration (more general: a periodical change of a certain physical quantity) that propagates into space. The propagation is caused by the fact that the vibration at a certain location influences the region next to this location. For example in the case of sound, the alternating rarefaction and compression of air molecules at a certain location results in periodic changes in the local pressure, which in turn causes the movement of adjacent air molecules towards or away from this location.

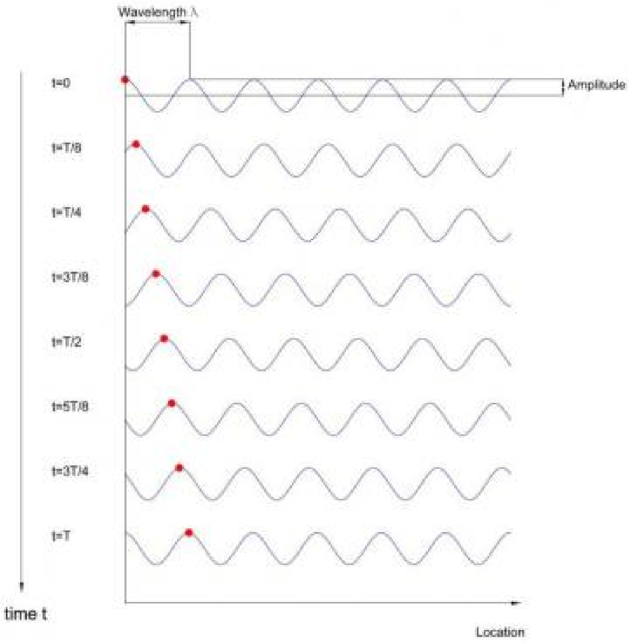

Fig. 1: Formation and propagation of a wave in a string

The propagation is caused by the fact that the vibration at a certain location influences the region next to this location. For example in the case of sound, the alternating rarefaction and compression of air molecules at a certain location results in periodic changes in the local pressure, which in turn causes the movement of adjacent air molecules towards or away from this location.

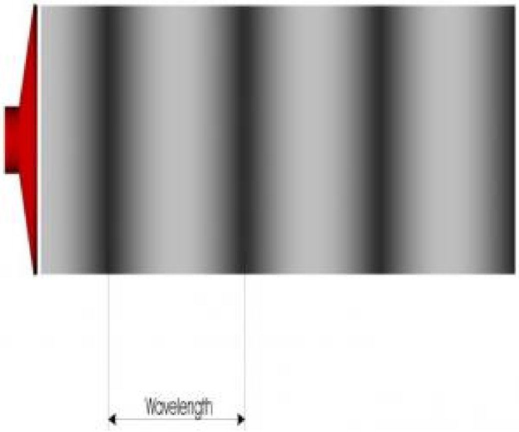

Fig. 2: Formation and propagation of a compression wave in air, a phenomenon colloquially called sound

In the case of an electromagnetic wave, the mechanism of propagation involves mutual generation of periodically varying electric and magnetic fields and is far more difficult to understand than sound. Yet, the result can still be described as a periodic change of a physical quantity (the strength of the electric and the magnetic field) propagating into space. The velocity of this propagation is generally abbreviated with the letter c (unit: meters per second, m / s) and depends on the medium and nature of the wave (see Tab. 1 below).

	Sound	**Optical (electromagnetic) radiation**		
		at λ = 434 nm	**at λ = 589 nm**	**at λ = 656 nm**
in vacuum	–	299792 km / s (n = 1)	299792 km / s (n = 1)	299792 km / s (n = 1)
in air	340 m / s	299708 km / s (n = 1.000280)	299709 km / s (n = 1.000277)	299710 km / s (n = 1.000275)
in water	1500 m / s	223725 km / s (n = 1.340)	224900 km / s (n = 1.333)	225238 km / s (n = 1.331)

Tab. 1: Velocities of sound and light in air and in water. For optical radiation, the respective index of refraction is given in parenthesis

In order to describe the basic properties of a wave, the following quantities have been defined for all kinds of waves:

- The **amplitude** is the maximum disturbance of the medium from its equilibrium. In the case of a wave in a horizontal string, this value is identical with half of the vertical distance between the wave’s crest and its trough.

- The **wavelength λ** is the distance between two adjacent crests (or troughs) and is given in meters.

- The **period T** of a wave is the time that elapses between the arrival of two consecutive crests (or troughs) at a certain location X. This definition is identical with the statement that the period is the time the vibration at X takes to complete a full cycle from crest to trough to crest. The period of a wave is given in seconds.

- The **frequency f** of a wave is the number of vibration cycles per second at a certain location X. The unit of frequency is Hertz (Hz) and 1 Hz is the reciprocal of 1 second. As an example, a wave with a period T = 0.25 s takes ¼ of a second to complete a full vibration cycle (crest – trough – crest) at a certain location and thus performs four vibrations per second. Hence its frequency is f = 4 Hz. From this example, it is obvious that the period of a wave completely defines its frequency and vice versa. The relation between these quantities is given by f = 1 / T.
  If we look at a wave as a process that is periodical in space and in time, we can regard the wavelength λ as the distance between two repetitions of the process in space and the period T as the ”distance” between two repetitions of the process in time.

A basic relation between wavelength, frequency and velocity results from the following consideration:

During the time span, a crest needs to travel the distance of one wavelength λ from location X to location Y. This time span is identical with the wave's period T. And when a crest needs the time span T to travel the distance λ, its velocity c amounts to

$$c = \frac{\lambda}{T} = \lambda f$$

When a wave passes from one medium to another, its frequency remains the same. If the velocities of the wave in the two media differ, the wavelengths in the two media also differ as a consequence. Since the frequency of a wave does not depend on the medium the wave is passing, it is more convenient to use frequency instead of wavelength to characterize the wave. In acoustics, this is common practice – in most cases the pitch of sound is characterized by its frequency instead of its wavelength in a certain medium (for example air).

In optics, the situation is different: In most cases, wavelength is used instead of frequency although this leads to a certain complication: For example, green light has a wavelength of 520 nm in vacuum, but in water its velocity is smaller by a factor of 1.33 and thus, in water the same green light has a wavelength of only 520 / 1.33 = 391.0 nm. Hence, if we want to characterize a wave by its wavelength, we also have to state the medium for which the actual wavelength value is given. According to CIE regulations, which are applied throughout this tutorial, the term "wavelength" refers to "wavelength in air" unless otherwise stated. However, when applying the given wavelength figures to light passing through a medium other than vacuum, one should keep in mind that the light's wavelength changes according to the following relation

$$\lambda_{\mathrm{Medium}} = \frac{\lambda_{\mathrm{Vacuum}}}{n_{\mathrm{Medium}}} = \frac{\lambda_{\mathrm{Air}} \times n_{\mathrm{Air}}}{n_{\mathrm{Medium}}}$$

with

$$n_{\mathrm{Air}} = \frac{c_{\mathrm{Vacuum}}}{c_{\mathrm{Air}}}$$

and

$$n_{\mathrm{Medium}} = \frac{c_{\mathrm{Vacuum}}}{c_{\mathrm{Medium}}}$$

n_{Medium} is called the medium's index of refraction and is more commonly used to specify the optical properties of a material than c_{Medium}.

1.3 Spectra of various light sources

A spectrum generally describes the variation of a certain physical quantity as a function of wavelength. Without any further specifications, the term “spectrum” refers to the quantification of the monochromatic intensity as a function of wavelength (the term “spectrum” is also used for other (physical) quantities other than intensity, but with a specific prefix. As an example, the strength of a biological reaction (for example erythema, see “The optical radiation wavelength range”) to light with different wavelengths is described by an “action spectrum”). As an example, the next figure shows spectra of an incandescent bulb, natural sunlightand two types of discharge lamps.

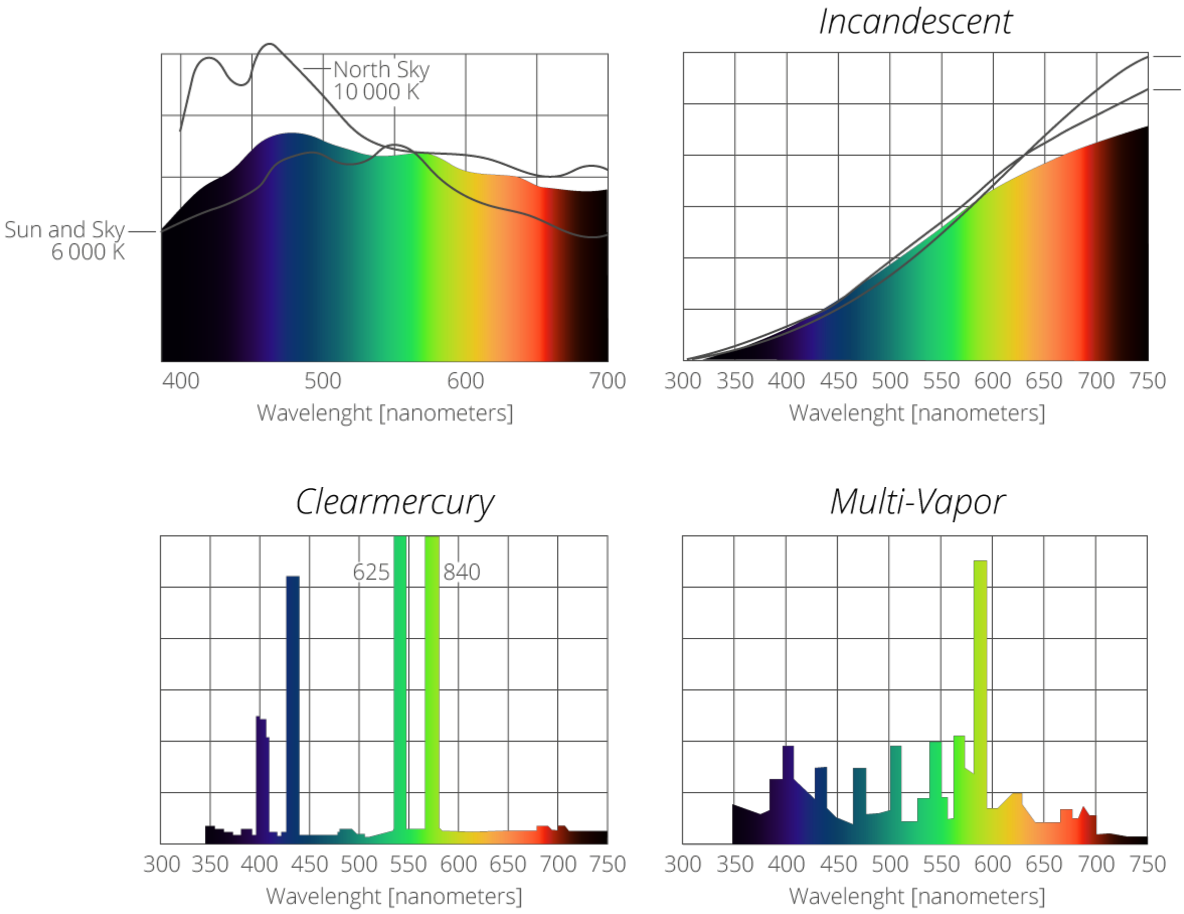

Fig. 1: Emission spectra of natural light from the sun and the sky and of artificial light from incandescent bulbs at different temperatures, from a mercury vapor lamp and from a multi-vapor lamp.

Source (valid as of 2002): Based on http://www.salsburg.com/lightcolor/lightcolor.html

When examining spectral intensity distributions of various light sources, it is possible to distinguish four significant types. These are:

- Monochromatic radiation
- Near monochromatic radiation
- Continuous spectra

- Band spectra

Typical sources of monochromatic radiation are lasers and the output signal from monochromators with narrow bandwidths. Typical sources of near monochromatic radiation are light emitting diodes and band pass filtered sources.

If a mixture of radiation covers a relatively large range of wavelengths without gaps, this radiation has a continuous spectrum. Typical examples of continuous radiation spectra include direct and diffuse sunlight as well as light emitted by incandescent bulbs. On the other hand, in a band spectrum there are gaps separating individual regions of radiation. If a spectrum has a number of lines of monochromatic intensity, it is called a line spectrum. Typical sources emitting a line spectrum are gaseous discharge lamps, such as helium or xenon lamps, and metal vapor lamps such as the mercury vapor lamp. Multi-vapor discharge lamps are used to achieve a more uniform spectral distribution (see fig. 1).

1.4 Basic radiometric quantities

The whole discipline of optical measurement techniques can be roughly subdivided into **photometry** and **radiometry**. Whereas photometry focuses on determining optical quantities that are closely related to the sensitivity of the human eye, radiometry deals with the measurement of energy per time (= power, given in watts) emitted by light sources or impinging on a particular surface. Thus, the units of all radiometric quantities are based on watts (W). According to CIE regulations, symbols for radiometric quantities are denoted with the subscript “e” for “energy”. Similarly, radiometric quantities given as a function of wavelength are labelled with the prefix “spectral” and the subscript “λ” (for example spectral radiant power Φ_λ).

Remark: The definitions of radiometric quantities cannot be understood without a basic comprehension of differential quantities. For an intuitive understanding of these quantities, which is the main objective of this paragraph, the differential quantities dλ, dA and dΩ can be regarded as tiny intervals or elements (Δλ, ΔA and ΔΩ) of the respective quantity. As a consequence of the fact that these intervals or elements are very small, radiometric quantities can be considered constant over the range defined by dλ, dA and / or dΩ. Similarly, $d\Phi_e$, dI_e, dL_e and dE_e can be regarded as small portions which add up to the total value of the respective quantity. Brief explanation of the concept of differential quantities and integral calculus for spectral radiometric quantities.

The following sections give information on:

- Definition of solid angle
- Radiant power or radiant flux Φ_e
- Radiant intensity I_e
- Radiance L_e
- Irradiance E_e
- Radiant exitance M_e
- Spectral radiant power $\Phi_\lambda(\lambda)$, spectral radiant intensity $I_\lambda(\lambda)$, spectral radiance $L_\lambda(\lambda)$, spectral irradiance $E_\lambda(\lambda)$ and spectral radiant exitance $M_\lambda(\lambda)$

Definition of solid angle

The geometric quantity of a solid angle Ω quantifies a part of an observer’s visual field. If we imagine an observer located at point P, his full visual field can be described by a sphere of an arbitrary radius r (see fig. 1). Here, a certain part of this full visual field defines an area A on the sphere’s surface and the solid angle Ω is defined as

$$\Omega = \frac{A}{r^2}$$

Since the area A is proportional to r², this fraction is independent of the actual choice of r.

If we want to calculate the solid angle determined by a cone (as shown in fig. 1) area A is the area of a spherical calotte. However, area A can have any arbitrary shape on the sphere’s surface because the solid angle is only defined for conical parts of the full visual field.

Although Ω is dimensionless, it is common to use the unit steradian (sr). The observer’s total visual field is described by the whole surface of the sphere, which is given by 4πr², and thus covers the solid angle

$$\Omega_{\text{total}} = \frac{4\pi\, r^2}{r^2} = 4\pi\ \text{sr} = 12.57\ \text{sr}$$

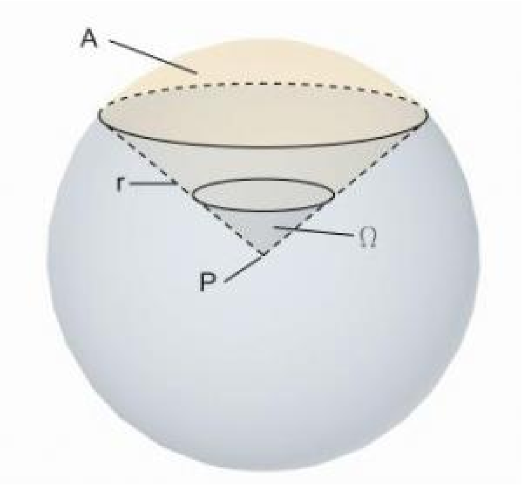

Fig. 1: The solid angle Ω quantifies a certain part of the visual field seen by an observer located at P

Source (valid as of 2002): http://whatis.techtarget.com/definition/0,,sid9_gci528813,00.html

Radiant power or radiant flux Φ_e

Radiant power Φ_e is defined as the total power of radiation emitted by a source (lamp, light emitting diode, etc.), transmitted through a surface, or impinging upon a surface. Radiant power is measured in watts (W). The definitions of all other radiometric quantities are based on radiant power. If a light source emits uniformly in all directions, it is called an isotropic light source.

Radiant power characterizes the output of a source of electromagnetic radiation only by a single number and does not contain any information on the spectral distribution or the directional distribution of the lamp output.

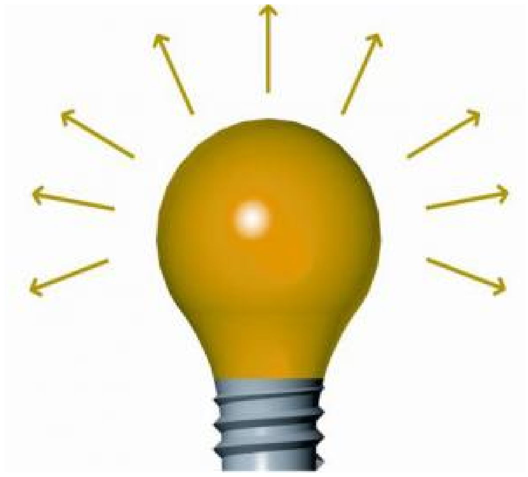

Fig. 2: The radiant power (Φ_e) of a light source is given by its total emitted radiation

Radiant intensity I_e

Radiant intensity I_e describes the radiant power of a source emitted in a certain direction. The source's (differential) radiant power $d\Phi_e$ emitted in the direction of the (differential) solid angle element $d\Omega$ is given by

$$d\Phi_e = I_e \, d\Omega$$

and thus

$$\Phi_e = \int_{4\pi} I_e \, d\Omega$$

In general, radiant intensity depends on spatial direction. The unit of radiant intensity is **W / sr**.

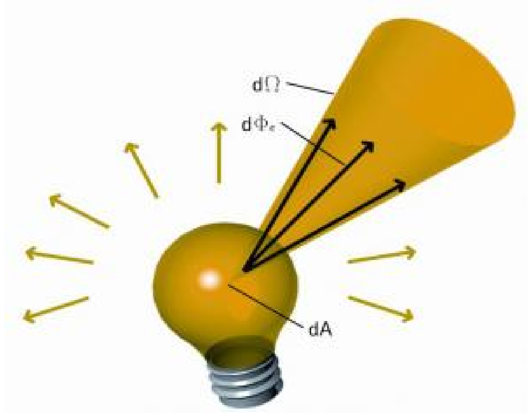

Fig. 3: Typical directional distribution of radiant intensity for an incandescent bulb

Radiance L_e

The radiance L_e is the intensity of optical radiation emitted or reflected from a certain location on an emitting or reflecting surface in a particular direction (the CIE definition of radiance is more general. This tutorial focuses on the most relevant radiance application describing the spatial emission characteristics of a source). The radiant power $d\Phi_e$ emitted by a (differential) surface element dA in the direction of the (differential) solid angle element dΩ is given by

Equation 1:

$$\mathbf{d\Phi_e = L_e \times \cos(\vartheta)\, dA\, d\Omega}$$

In this relation, ϑ is the angle between the direction of the solid angle element dΩ and the normal of the emitting or reflecting surface element dA.

From the definition of radiant intensity I_e, it follows that the differential radiant intensity emitted by the differential area element dA in a certain direction is given by

$$dI_e = L_e \cos(\vartheta)\, dA$$

Thus,

Equation 2:

$$\mathbf{I_e = {}_{emmiting\ surface}\int L_e \times \cos(\vartheta)\, dA}$$

whereby ϑ is the angle between the emitting surface element dA and the direction for which I_e is calculated.

The unit of radiance is **$W/(m^2sr)$**.

Irradiance E_e

The irradiance E_e is the amount of radiant power impinging upon a surface per unit area. In detail, the (differential) radiant power $d\Phi_e$ upon the (differential) surface element dA is given by

$$d\Phi_e = E_e\, dA$$

Generally, the surface element can be oriented at any angle towards the direction of the beam. However, irradiance is maximized when the surface element is perpendicular to the beam:

$$d\Phi_e = E_{e,normal}\, dA_{normal}$$

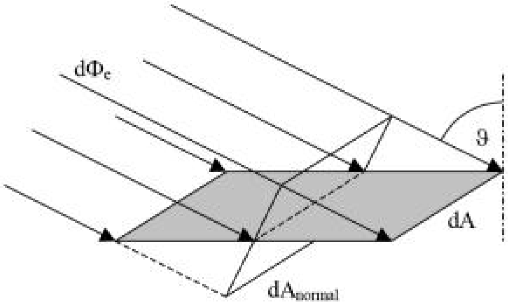

Fig. 4: Irradiance is defined as incident radiant power $d\Phi_e$ per surface area element dA

Note that the corresponding area element dA_{normal}, which is oriented perpendicular to the incident beam, is given by

$dA_{normal} = \cos(\vartheta)\, dA$

with ϑ denoting the angle between the beam and the normal of dA, we get

Equation 3:

$$\mathbf{E_e = E_{e,normal} \times \cos(\vartheta)}$$

The unit of irradiance is **W/m^2**.

Radiant exitance M_e

Radiant exitance M_e quantifies the radiant power that is emitted or reflected from a certain location on a surface per area. In detail, the (differential) radiant power $d\Phi_e$ emitted or reflected by the surface element dA is given by

$d\Phi_e = M_e\, dA$

Based on the definition of radiance, the (differential) radiant exitance dMe emitted or reflected by a certain location on a surface in the direction of the (differential) solid angle element dΩ is therefore given by

$dM_e = L_e \cos(\vartheta)\, d\Omega$

and consequently

Equation 4:

$$\mathbf{M_e} = \int_{2\pi sr} \mathbf{L_e \times \cos(\vartheta)\, d\Omega}$$

The integration is performed over the solid angle of 2π steradian corresponding to the directions on one side of the surface and ϑ denotes the angle between the respective direction and the surface's normal.

The unit of radiant exitance is **W/m²**. In some particular cases, $M_e = E_e$ (see "Reflectance ρ, Transmittance τ and Absorptance α").

Spectral radiant power $\Phi_\lambda(\lambda)$, spectral radiant intensity $I_\lambda(\lambda)$, spectral radiance $L_\lambda(\lambda)$, spectral irradiance $E_\lambda(\lambda)$ and spectral radiant exitance $M_\lambda(\lambda)$

The radiometric quantities discussed above are defined without any regard to the wavelength(s) of the quantified optical radiation. In order to not only quantify the absolute amount of these quantities but also the contribution of light from different wavelengths, it is important to also define the respective **spectral** quantities.

Spectral radiant power is defined as a source's radiant power per wavelength interval as a function of wavelength. In detail, the source's (differential) radiant power $d\Phi_e$ emitted in the (differential) wavelength interval between λ and λ+dλ is given by

$$d\Phi_e = \Phi_\lambda(\lambda)\, d\lambda$$

This equation can be visualized geometrically (see Fig. 5). Because dλ is infinitesimally small, spectral radiant power $\Phi_\lambda(\lambda)$ is approximately constant in the interval between λ and λ+dλ. Thus, the product $\Phi_\lambda(\lambda)d\lambda$ equals the area under
the graph of $\Phi_\lambda(\lambda)$ in the interval between λ and λ+dλ. This area describes the contribution of this very wavelength interval to the total value of radiant power Φ_e, which is graphically represented by the total area under the graph of spectral radiant power $\Phi_\lambda(\lambda)$.

Mathematically, this can be expressed by the integral

$$\Phi_e = \int_0^\infty \Phi\ \lambda(\lambda)\, d\lambda$$

The unit of spectral radiant power is **W/nm** or **W/Å**.

The other spectral quantities are defined correspondingly and their units are given by the unit of the respective quantity, divided by nm or Å. Generally, a radiant quantity can be calculated from the respective spectral quantity by integrating over the wavelength from λ = 0 to λ = ∞. However, this integration is often restricted to a certain wavelength range, which is indicated by the respective prefix. For instance, UV-A irradiance is defined as

$$E_{e,UV\text{-}A} = \int_{315\,nm}^{400\,nm} E_\lambda(\lambda)\, d$$

since the UVA range is between λ = 315 nm and λ = 400 nm.

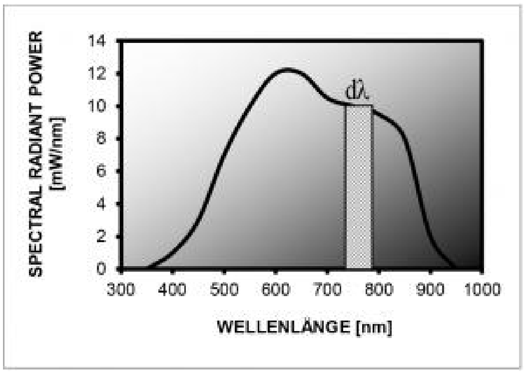

Fig. 5: Relation between spectral radiant power $\Phi_\lambda(\lambda)$ and radiant power Φ_e, visualized at a hypothetical example. Radiant power emitted in the wavelength interval between λ and $\lambda+d\lambda$ is given by the area of the shaded rectangle, which amounts to $\Phi_\lambda(\lambda)d\lambda$. The total amount of radiant power Φ_e emitted over the whole spectrum is given by the area under the curve describing $\Phi_\lambda(\lambda)$, which is mathematically expressed by an integral.

1.5 Calculation of radiometric quantities (Examples)

Example 1: Isotropic point source

A small source emits light equally in all directions (spherical symmetry). Its radiant power equals $\Phi_{e,source} = 10$ W.

If we are interested in the characteristics of this source at a distance (r) that is much larger than the geometric dimensions of the source itself, we can neglect the actual size of the source and assume that the light is emitted from a point. As a rule of thumb, this approximation is justified if distance r is at least 10 times larger than the dimensions of the light source.

a) Since the source emits light symmetrical in all directions, its radiant intensity is equal for all directions and amounts to

$$I_e = \frac{\Phi_{e,source}}{4\pi \text{ sr}} = \frac{10 \text{ W}}{4\pi \text{ sr}} = \mathbf{0.796 \text{ W / sr}}$$

b) An infinitesimal surface element dA at a distance r and perpendicular to the beam occupies the solid angle

$$d\Omega = \frac{dA}{r^2}$$

and thus the infinitesimal radiant power $d\Phi_{e,imp}$ impinging onto dA can be calculated by

$$d\Phi_{e,imp} = I \, d\Omega = \frac{\Phi_{e,source}}{4\pi \text{ sr}} \times \frac{dA}{r^2} = \frac{\Phi_{e,source}}{4\pi r^2} \times dA$$

The irradiance at distance r therefore amounts to

$$E_e = \frac{\Phi_{e,source}}{4\pi r^2}$$

This result can also be obtained by the following argument:

At distance r, all the radiant power $\Phi_{e,source}$ emitted by the source passes through the surface of a sphere with radius r, which is given by 4r²π. Because the light source emits light symmetrically in all directions, the irradiance has the same value at every point of this sphere. Thus, irradiance E of a surface at a certain distance r and oriented perpendicular to the beam can be calculated from its definition:

$E_e =$ radiant power impinging upon a surface or area of this surface $= \frac{\Phi_{e,source}}{4\pi r^2}$

which is identical with the result above.

Remark: The proportionality of E to r² is generally described with the “inverse square law”. However, it only holds true for distances much larger than the geometric dimensions of the source, which allows the assumption of a point source. In other cases, a source with considerable geometric dimensions might possibly be replaced by a “virtual” point source, for which the “inverse square law” would still apply at a distance r from this virtual point source (see Example 2). However, when the source cannot be equated with a point source and every point of the source emits light in more than a single direction, the “inverse square law” can no longer be applied. Fluorescent tubes are a good example in this case.

Example 2: Spot source

In a simple flashlight, a concave mirror reflects light from a small bulb (radiant power Φ = 200 mW) into a divergent cone (see Fig. 1). Assuming that the mirror reflects without any losses a uniform distribution of power over the cone is generated.

Note that the flashlight does not emit light symmetrically in all directions and the equations derived in Example 1 can therefore not be used.

a) At a distance of 25 cm from the flashlight’s front window, the whole radiant power of 200 mW (= 0.2 W) impinges on a circle with a 0.05 m radius. If we assume that irradiance is constant all over this circle and we neglect the fact that the surface is not perfectly even hence not strictly perpendicular to the beam, we can calculate the irradiance at a 25 cm distance from the flashlight’s front window:

E = radiant power impinging upon a surface or area of this surface = $\frac{0.2}{0.05^2 \pi}$ W / m²

E ≈ 25 W / m²

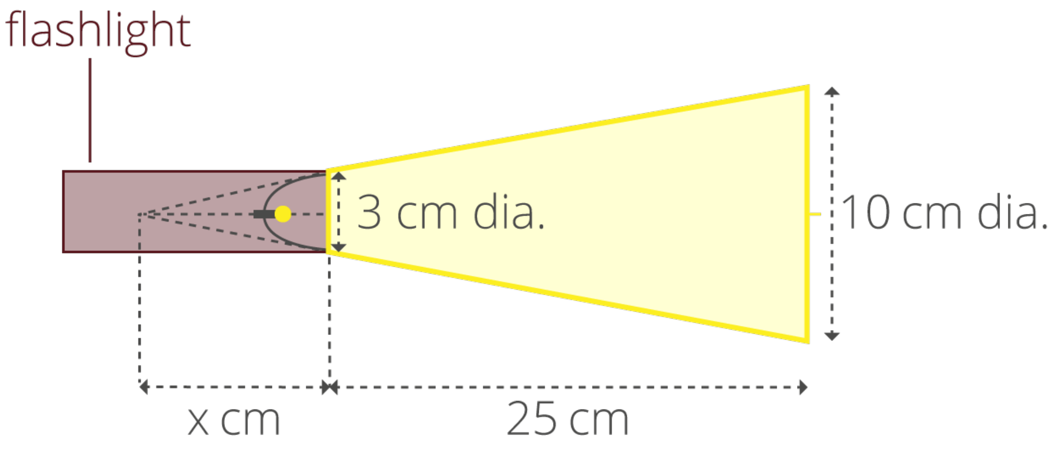

Fig. 1: Calculating the irradiance caused by a flashlight

Source (valid as of 2002): Based on http://omlc.ogi.edu/classroom/ece532/class1/intensity_flashlight.html

b) In order to determine the flashlight's radiant intensity, we have to determine the solid angle determined by the cone. Following the definition of solid angle and approximating the area of the spherical calotte using the area of a circle with a 5 cm radius (= 0.05 m), we get

$$\Omega = \frac{A_{circle}}{r^2}$$

where r is the distance of the circle from the cone's vertex.

From Fig. 1, we get

$$r = x + 0.25 \text{ m}$$

and

$$\frac{x}{x + 0.25} = \frac{0.03}{0.10}$$

which in turn gives

$$x = 0.107 \text{ m}$$

and

$$r = 0.357 \text{ m}$$

Thus, the cone defines a solid angle given by

$$\Omega = \frac{A_{circle}}{r^2} = \frac{0.05^2\,\pi}{0.357^2} = \mathrm{sr}$$

and the flashlight’s radiant intensity amounts to

$$I = \frac{\Phi}{\Omega} = \frac{0.2\ \mathrm{W}}{0.616\ \mathrm{sr}} = \mathbf{3.25\ W / sr}$$

Remark: Since a virtual point source located at the cone’s vertex produces the same spatial radiation distribution as the flashlight’s bulb together with its concave mirror, the “inverse square law” applies for this configuration. However, the distance r which the law relates to has to be measured from the position of the virtual point source.

Example 3: The Lambertian surface

By definition, a Lambertian surface either emits or reflects radiation with constant radiance (L_e) in all directions of a hemisphere (s. Fig. 2). Equation 2 shows that the directional distribution of radiant intensity is given by

$$I_e(\vartheta) = I_{e,0} \times \cos(\vartheta)$$

with

$$I_{e,0} = \int_{\text{emitting surface}} L_e \cos(0)\, dA = \int_{\text{emitting surface}} L_e\, dA$$

where $I_{e,0}$ denotes radiant intensity emitted in the direction perpendicular to the surface and $I_e(\vartheta)$ denotes radiant intensity emitted in a direction enclosing the angle ϑ with the surface’s normal. Calculating the surface’s exitance M_e from Equation 4 using the relation $d\Omega = \sin(\vartheta)\, d\vartheta\, d\varphi$ gives:

$$M_e = \int_{2\pi sr} L_e \cos(\vartheta)\, d\Omega = L_e \int_0^{2\pi} \int_0^{\pi/2} \cos(\vartheta) \sin(\vartheta)\, d\vartheta\, d\varphi = L_e \times \pi$$

The respective relations for photometric quantities (see Basic photometric quantities) characterizing a Lambertian surface can be derived by replacing the index “e” with the index “v”.

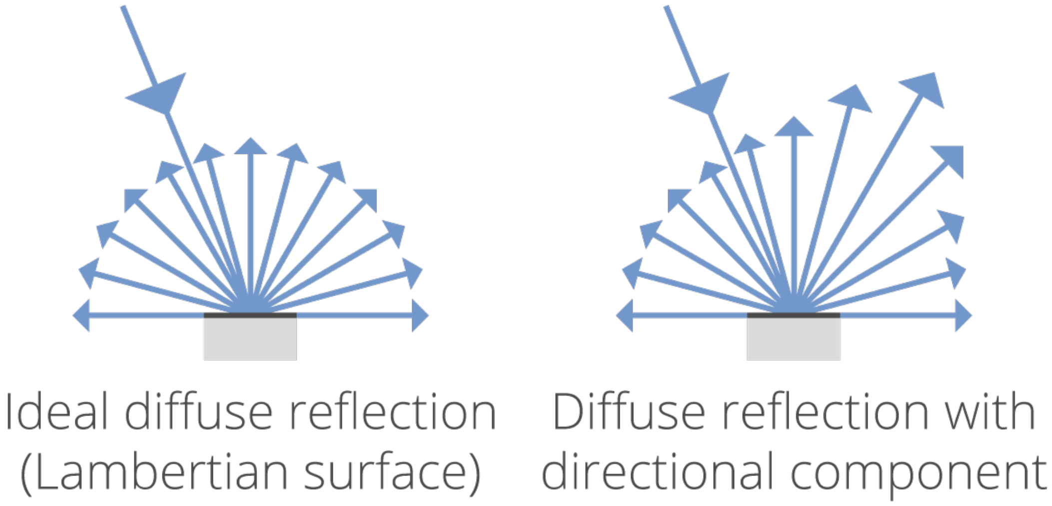

Fig. 2: Constant spatial distribution of radiance L_e after ideal diffuse reflection on a Lambertian surface

Reflecting Lambertian surfaces are widely used in light measurement for well defined, perfectly diffuse scattering that is fully independent of the direction of incoming beams. Thus, the radiance reflected in a certain direction from a certain location on the surface is proportional to the total radiant power impinging onto the reflecting surface. This allows the realization of detector geometries for radiant power, exitance and irradiance (or luminous flux, luminous exitance and illuminance), which have to be determined through integration over all directions of a solid angle of 4π or 2π. Lambertian reflection is of particular interest in the coating of integrating spheres, which are widely used for detector input optics or output optics of radiance or luminance standards.

1.6 Spectral sensitivity of the human eye

The sensitivity of the human eye to light of a certain intensity varies strongly over wavelengths between 380 nm and 800 nm. Under daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm, resulting in the fact that green light at this wavelength produces the impression of highest "brightness" when compared to light at other wavelengths. The spectral sensitivity function of the average human eye under daylight conditions (photopic vision) is defined by the **CIE spectral luminous efficiency function V(λ)**. Only in very rare cases is the spectral sensitivity of the human eye under dark adapted conditions (scotopic vision), defined by the spectral luminous efficiency function V'(λ), technically relevant. By convention, these sensitivity functions are normalized to a value of 1 in their maximum.

As an example, the photopic sensitivity of the human eye to monochromatic light at 490 nm amounts to 20 % of its sensitivity at 555 nm. As a consequence, when a source of monochromatic light at 490 nm emits five times as much power (expressed in watts) than an otherwise identical source of monochromatic light at 555 nm, both sources produce the impression of same "brightness" to the human eye.

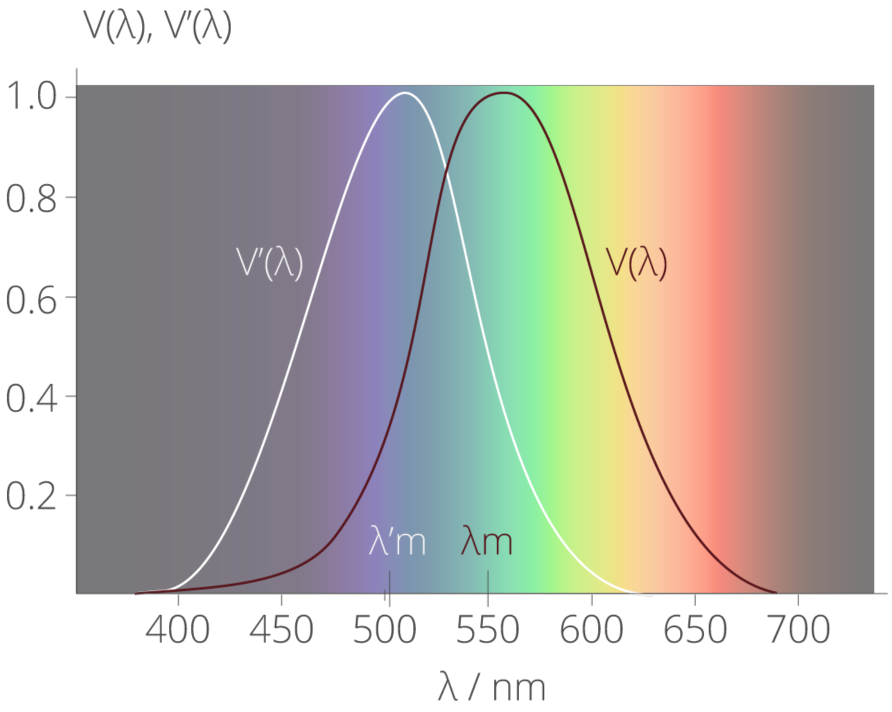

Fig. 1: Spectral luminous efficiency functions V(λ) for photopic vision and V'(λ) for scotopic vision, as defined by the CIE.

Source (valid as of 2002): Based on http://www.cameraguild.com/technology/colorimetry.htm

1.7 Basic photometric quantities

One of the central problems of optical measurements is the quantification of light sources and lighting conditions in numbers directly related to the perception of the human eye. This discipline is called "photometry" and its significance leads to the use of separate physical quantities that differ from the respective radiometric quantities in only one respect: Whereas radiometric quantities simply represent a total sum of radiation power at various wavelengths and do not account for the fact that the human eye's sensitivity to optical radiation depends on wavelength, the photometric quantities represent a weighted sum with the weighting factor being defined by either the photopic or scotopic spectral luminous efficiency function. Thus, the numerical value of photometric quantities directly relates to the impression of "brightness". Photometric quantities are distinguished from radiometric quantities by the index "v" for "visual". Furthermore, photometric quantities relating to scotopic vision are denoted by an additional prime, for example Φv'. The following explanations are given for the case of photopic vision, which describes the eye's sensitivity under daylight conditions and are therefore very significant for the vast majority of lighting situations (photopic vision takes place when the eye is adapted to luminance levels of at least several candelas per square meters, scotopic vision takes place when the eye is adapted to luminance levels below some hundredths of a candela per square meter. For mesopic vision, which is between the photopic and scotopic range, no spectral luminous efficiency function has been defined yet). However, the respective relations for scotopic vision can be easily derived by replacing V(λ) with V'(λ) and K_m (= 683 lm/W) with K'_m (= 1700 lm/W).

Since the definition of photometric quantities closely follows the corresponding definitions of radiometric quantities, the corresponding equations hold true – the index "e" only has to be replaced by the index "v". Thus, not all relations are repeated. Instead, a more general formulation of all relevant relations is given in the Appendix.

The following sections give information on:

- Luminous flux Φ_v
- Luminous intensity Iv
- Luminance L_v
- Illuminance E_v
- Luminous exitance M_v
- Conversion between radiometric and photometric quantities

Luminous flux Φ_v

Luminous flux Φ_v is the basic photometric quantity and describes the total amount of electromagnetic radiation emitted by a source, spectrally weighted with the human eye's spectral luminous efficiency function V(λ). Luminous flux is the photometric counterpart to radiant power. The luminous flux is given in lumen (lm). At 555 nm where the human eye has its maximum sensitivity, a radiant power of 1 W corresponds to a luminous flux of 683 lm. In other words, a monochromatic source emitting 1 W at 555 nm has a luminous flux of exactly 683 lm. The value of 683 lm/W is abbreviated as Km (the value of Km = 683 lm/W is given for photopic vision. For scotopic vision, K_m' = 1700 lm/W has to be used). However, a monochromatic light source emitting the same radiant power at 650 nm, where the human eye is far less sensitive and V(λ) = 0.107, has a luminous flux of 0.107 × 683 lm = 73.1 lm. For a more detailed explanation of the conversion of radiometric to photometric quantities, see paragraph Conversion between radiometric and photometric quantities.

Luminous intensity I_v

Luminous intensity I_v quantifies the luminous flux emitted by a source in a certain direction. It is therefore the photometric counterpart of the “radiant intensity (I_e)”, which is a radiometric quantity. In detail, the source’s (differential) luminous flux $d\Phi_v$ emitted in the direction of the (differential) solid angle element dΩ is given by

$$d\Phi_v = I_v \times d\Omega$$

and thus

$$\Phi_v = \int_{4\pi} I_v \, d\Omega$$

The luminous intensity is given in lumen per steradian (lm/sr). 1 lm/sr is referred to as **“candela” (cd):**

1 cd = 1 lm/sr

Luminance L_v

Luminance L_v describes the measurable photometric brightness of a certain location on a reflecting or emitting surface when viewed from a certain direction. It describes the luminous flux emitted or reflected from a certain location on an emitting or reflecting surface in a particular direction (the CIE definition of luminance is more general. This tutorial discusses the most relevant application of luminance describing the spatial emission characteristics of a source is discussed). In detail, the (differential) luminous flux $d\Phi_v$ emitted by a (differential) surface element dA in the direction of the (differential) solid angle element dΩ is given by

$$d\Phi_v = L_v \cos(\Theta) \times dA \times d\Omega$$

with Θ denoting the angle between the direction of the solid angle element dΩ and the normal of the emitting or reflecting surface element dA.

The unit of luminance is

$1 \text{ lm m}^{-2} \text{ sr}^{-1} = 1 \ \mathbf{cd\ m^{-2}}$

Illuminance E_v

Illuminance E_v describes the luminous flux per area impinging upon a certain location of an irradiated surface. In detail, the (differential) luminous flux $d\Phi_v$ upon the (differential) surface element dA is given by

$$d\Phi_v = E_v \times dA$$

Generally, the surface element can be oriented at any angle towards the direction of the beam. Similar to the respective relation for irradiance, the illuminance E_v upon a surface with arbitrary orientation is related to illuminance $E_{v,\,normal}$ upon a surface perpendicular to the beam by

$$E_v = E_{v,\,normal} \cos(\vartheta)$$

with ϑ denoting the angle between the beam and the surface's normal. The unit of illuminance is **lux (lx)**.

$$1\ \mathrm{lx} = 1\ \mathrm{lm\ m^{-2}}$$

Luminous exitance M_v

Luminous exitance M_v quantifies the luminous flux emitted or reflected from a certain location on a surface per area. In detail, the (differential) luminous flux $d\Phi_v$ emitted or reflected by the surface element dA is given by

$$d\Phi_v = M_v \times dA$$

The unit of luminous exitance is 1 **lm m^{-2}**, which is the same as the unit for illuminance. However, the abbreviation lux is **not** used for luminous exitance.

Conversion between radiometric and photometric quantities

Monochromatic radiation

In the case of monochromatic radiation at a certain wavelength λ, a radiometric quantity X_e is simply transformed to its photometric counterpart X_v by multiplication with the respective spectral luminous efficiency V(λ) and by the factor K_m = 683 lm/W. Thus,

$$X_v = X_e \times V(\lambda) \times 683\ \mathrm{lm/W}$$

with X denoting one of the quantities Φ, I, L, or E.

Example: An LED (light emitting diode) emitsnearly monochromatic radiation at $\lambda = 670$ nm, where $V(\lambda) = 0.032$. Its radiant power amounts to 5 mW. Thus, its luminous flux equals

$$\Phi_v = \Phi_e \times V(\lambda) \times 683\ \mathrm{lm/W} = 0.109\ \mathrm{lm} = 109\ \mathrm{mlm}$$

Since V(λ) changes very rapidly in this spectral region (by a factor of 2 within a wavelength interval of 10 nm), LED light output should not be considered monochromatic in order to ensure accurate results. However, using the relations for monochromatic sources still results in an approximate value for the LED's luminous flux which might be sufficient in many cases.

Polychromatic radiation

If a source emits polychromatic light described by the spectral radiant power $\Phi_\lambda(\lambda)$, its luminous flux can be calculated by spectral weighting of $\Phi_\lambda(\lambda)$ with the human eye's spectral luminous efficiency function V(λ), integration over wavelength and multiplication with $K_m = 683$ lm/W, so

$$\Phi_v = K_m \times \int_\lambda \Phi_\lambda(\lambda) \times V(\lambda) d\lambda$$

In general, a photometric quantity X_v is calculated from its spectral radiometric counterpart $X_\lambda(\lambda)$ through the relation

$$X_v = K_m \times \int_\lambda X_\lambda(\lambda) \times V(\lambda) d\lambda$$

with X denoting one of the quantities Φ, I, L, or E.

1.8 Reflection, Transmission and Absorption

Reflection is the process by which electromagnetic radiation is returned either at the boundary between two media (surface reflection) or at the interior of a medium (volume reflection), whereas **transmission** is the passage of electromagnetic radiation through a medium. Both processes can be accompanied by **diffusion** (also called **scattering**), which is the process of deflecting a unidirectional beam into many directions. In this case, we speak about **diffuse reflection** and **diffuse transmission** (Fig. 1). When no diffusion occurs, reflection or transmission of a unidirectional beam results in a unidirectional beam according to the laws of geometrical optics (Fig. 2). In this case, we speak about **regular reflection** (or s**pecular reflection**) and **regular transmission** (or **direct transmission**). Reflection, transmission and scattering leave the frequency of the radiation unchanged. Exception: The Doppler Effect causes a change in frequency when the reflecting material or surface is in motion.

Absorption is the transformation of radiant power to another type of energy, usually heat, by interaction with matter.

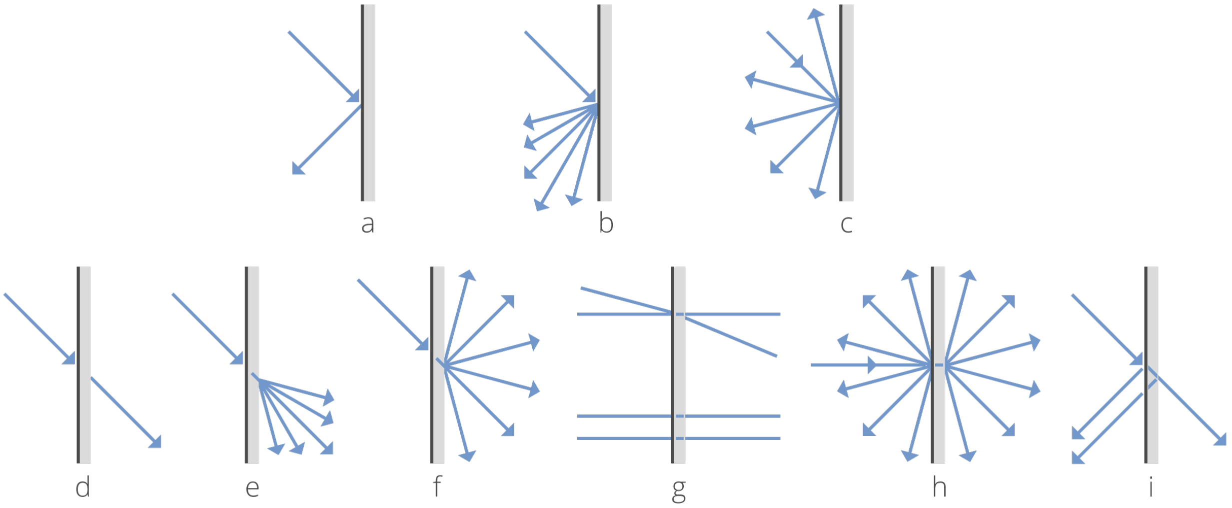

Fig. 1: top: Direct, mixed and diffuse reflection bottom: direct, mixed and diffuse transmission

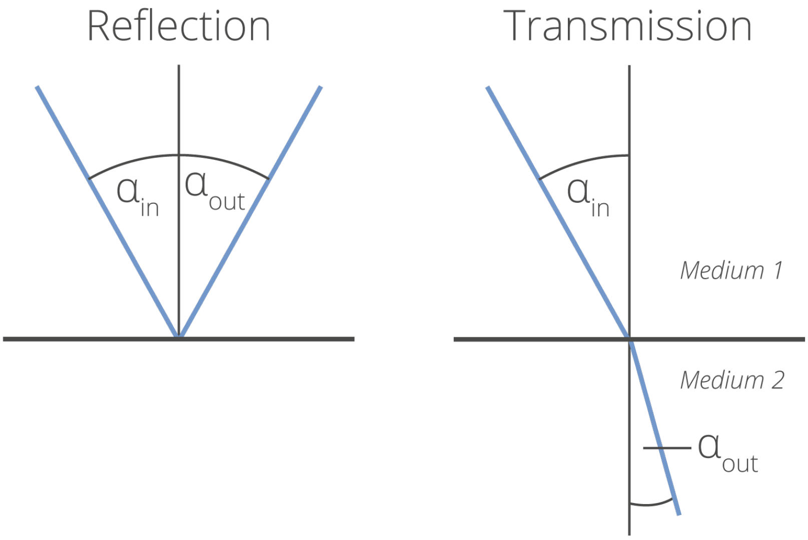

Fig. 2: When directly reflected or directly transmitted, a unidirectional beam follows the laws of geometrical optics: direct reflection (left): $ai_n = \alpha_{out}$, direct transmission (right): $n_1 \times \sin(\alpha_{in}) = n_2 \times \sin(\alpha_{out})$ with n_1 and n_2 denoting the respective medium's index of refraction

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Reflectance ρ, Transmittance τ and Absorptance α

In general, reflection, transmission and absorption depend on the wavelength of the affected radiation. Thus, these three processes can either be quantified for monochromatic radiation (in this case, the adjective “spectral” is added to the respective quantity) or for a certain kind of polychromatic radiation. For the latter, the spectral distribution of the incident radiation has to be specified. In addition, reflectance, transmittance and absorptance might also depend on polarization and geometric distribution of the incident radiation, which therefore also have to be specified.

The reflectance ρ is defined by the ratio of reflected radiant power to incident radiant power. For a certain area element dA of the reflecting surface, the (differential) incident radiant power is given by the surface’s irradiance E_e multiplied with the size of the surface element, thus

$$d\Phi_{e,\,incident} = E_e\, dA$$

The (differential) reflected radiant power is given by the exitance M_e multiplied with the size of the surface element:

$$d\Phi_{e,\,reflected} = M_e\, dA$$

Thus,

$$\rho = \frac{d\Phi_{e,\,reflected}}{} = \frac{M_e \times dA}{} = \frac{M_e}{}$$

d E_e E_e
Φ $\times dA$

e, incide

nt

or

$$M_e = \rho\ E_e$$

Total reflectance is further subdivided in **regular reflectance ρ_r** and **diffuse reflectance ρ_d**, which are given by the ratios of regularly (or specularly) reflected radiant power and diffusely reflected radiant power to incident radiant power. From this definition, it is obvious that

$$\rho = \rho_r + \rho_d$$

The **transmittance τ** of a medium is defined by the ratio of transmitted radiant power to incident radiant power. Total transmittance is further subdivided in **regular transmittance τ_r** and **diffuse transmittance τ_d**, which are given by the ratios of regularly (or directly) transmitted radiant power and diffusely transmitted radiant power to incident radiant power.

Again,

$$\tau = \tau_r + \tau_d$$

The **absorptance α** of a medium is defined by the ratio of absorbed radiant power to incident radiant power.

Being ratios of radiant power values, reflectance, transmittance and absorptance are dimensionless.

Quantities such as reflectance and transmittance are used to describe the optical properties of materials. The quantities can apply to complex radiation or monochromatic radiation. The optical properties of materials are not a constant since they are dependent on many parameters such as:

- thickness of the sample
- surface conditions
- angle of incidence
- temperature
- the spectral composition of the radiation (CIE standard illuminants A, B, C, D65 and other illuminants D)

- polarization effects

The measurement of optical properties of materials using integrating spheres is described in DIN 5036-3 and CIE 130-1998.

Descriptions of the principle measurements are presented in the paragraph about Measurement of reflection and transmission properties.

Radiance coefficient q_e, Bidirectional reflectance distribution function (BRDF)

The radiance coefficient q_e characterizes the directional distribution of diffusely reflected radiation. In detail, the radiance coefficient depends on the direction of the reflected beam and is defined by the ratio of the radiance reflected in this direction to the total incident irradiance. In general, the reflected radiance is not independent from the directional distribution of the incident radiation, which therefore has to be specified.

In the USA, the concept of **bidirectional reflectance distribution function BRDF** is similar to the radiance coefficient. The only difference is that the BRDF is a function of the directions of the incident *and* the reflected beam (Fig. 3). In detail, the (differential) irradiance dE_e impinging from a certain direction causes the reflected radiance dL_e in another direction, which is given by

$$dL_e = \text{BRDF} \times dE_e$$

This BRDF depends on more arguments than the radiance coefficient. However, its advantage is the simultaneous description of the material's reflection properties for all possible directional distributions of incident radiation, whereas the radiance coefficient is generally valid for just one specific directional distribution of incident radiation.

The unit of radiance coefficient and BRDF is 1/steradian. The BRDF is often abbreviated as the Greek letter ρ, which can easily be confused with the reflectance (see previous paragraph Reflectance ρ, Transmittance τ and Absorptance α).

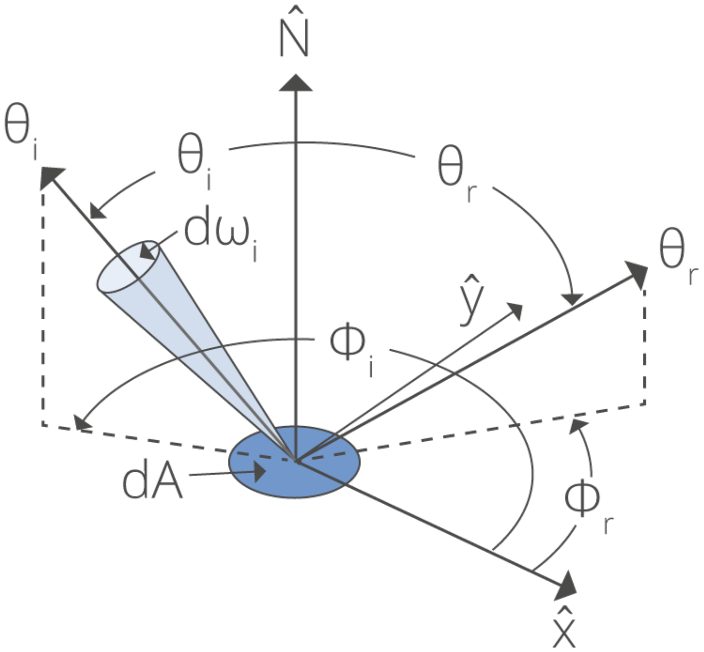

Fig. 3: Geometry used to define the bidirectional reflectance distribution function (BRDF).

The BRDF depends on the directions of incident and *reflected radiation.*
These are given by the angles ϑ_i *and* ϑ_r *(which are measured in relation to the reflecting surface's normal)*
and the azimuth angles φ_i *and* φ_{r}, *(which are measured in the plane of the reflecting surface)*

Source (valid as of 2002): http://math.nist.gov/~FHunt/appearance/brdf.html

1.9 The perception of color

Color sensations are human sensory perceptions, and color measurement technology must express them in descriptive and comprehensible quantities. Part 1 of DIN 5033 defines color as follows:

> ”Color is the visual sensation, associated with a part of the field of view that appears to the eye to be without structure, through which this part can be distinguished from another unstructured neighboring area when observed with a single, unmoving eye”.

This rather complicated but unambiguous definition of color allows the visual sensation of “color” to be distinguished from all the other impressions received when seeing. The insertion of “unstructured” into this definition also separates the texture of observed objects from the sensation of color.

Thus the texture of a textile, for instance, is not included in the color.

The definition also calls for observation with a ”single” eye which is ”unmoving”, conditionally excluding other factors such as spatial sensation, perception of the location of objects, their direction, and even their relative movement from the perception of color. Since single-eyed observation of an unmoving object with an unmoving eye does not allow for the perception of gloss, the evaluation of gloss is excluded from the perception of color.

In general, unlike mass, volume or temperature, color is not merely a physical property of an object. It is rather a sensation triggered by radiation of sufficient intensity. This can be the radiation of a self-emitting light source, or it can be reflected from a surface. This radiation enters the eye where receptive cells convert it to nervous stimulation. The nervous stimulation is in turn transmitted to the appropriate part of the brain where it is experienced as color. The sensation of color not depends only on physical laws, but also on the physiological processing of the radiation in the sense organs. Visual conditions, luminance (brightness) and the state of the eye’s adaptation are among the contributory factors.

Color manifests itself in the form of light from self-emitting light sources, surface colors (of light sources that are not self-emitting) and in the intermediate form of luminescent colors of dyestuffs such as optical brightening agents and day-glow paints that absorb photons from a short wavelength part of the spectrum and emit the energy in a part of the spectrum with longer wavelengths.

Physiological background

From the fact that spectral decomposition of white light produces the perception of different colors, it can be deduced that color perception is closely connected to the light wavelength (Fig. 1). As an example, light with a 650 nm wavelength is perceived as ”red” and light with a 550 nm wavelength perceived as ”green”. However, there are colors, such as purple, that cannot be directly related to a certain wavelength and therefore do not occur in the spectral decomposition of white light.

The perception of color is formed in our brain by the superposition of the neural signals from three different kinds of photoreceptors which are distributed over the human eye’s retina. These photoreceptors are called cones and are responsible for photopic vision under daylight conditions. Scotopic (night) vision is caused by photoreceptors called rods, which are much more sensitive than cones. Since there is only one kind of rods, night vision is colorless.

The three different kinds of cones differ in their spectral sensitivity to electromagnetic radiation. This is shown in Fig. 1 for the average normal sighted human eye. If monochromatic radiation irradiates the eye, as is the case with spectral decomposition of white light, the wavelength determines which types of cones are excited. For instance, monochromatic light at 680 nm only excites one type of cones, whereas the two other types are insensitive at this wavelength. The brain interprets signals from only this type of cones as color “red”. No signal is sent from the other cones. These cones are therefore called “red cones”.

Similarly, the two other types are referred to as “blue cones” and “green cones”.

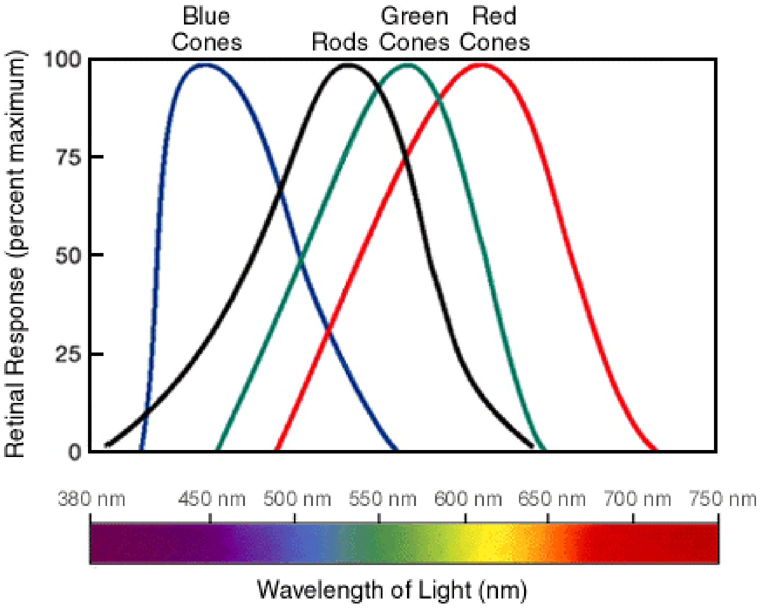

Fig. 1: Relative spectral sensitivity of all four types of the human eye’s retinal light receptors.
The three types of cones are responsible for photopic vision, whereas the rods are responsible for scotopic (night) vision

Quelle: http://lsvl.la.asu.edu/askabiologist/research/seecolor/rodsandcones.html

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Color addition

As discussed above, monochromatic light of a certain wavelength might predominantly excite a single type of cones, thus producing the color perception of “blue”, “green” or “red”. Depending on the actual wavelength, monochromatic light might also excite two types of cones simultaneously, thus producing the perception of another color. For instance, red and green cones are both excited by monochromatic light at 580 nm and a signal from these two types of cones – with the simultaneous absence of a signal from blue cones – leads to the perception of the color “yellow”.

However, our visual system cannot differentiate between monochromatic and broadband radiation as long as the excitation of the three types of cones remains the same. Thus, the perception of “yellow” can also be produced by a broadband spectrum between 550 nm and 700 nm as long as green and yellow cones are similarly stimulated and the blue cones not stimulated at all. In the same way, the perception of “cyan” is produced by simultaneous stimulation of blue and green cones, whereas the perception of “magenta” (or purple) is caused by simultaneous stimulation of blue and red cones (Fig. 1). Simultaneous stimulation of all three types of cones results in the perception of “white”.

This fact has an important consequence: Consider a light source consisting of three single sources with the colors red, green and blue. If it is possible to vary the intensities of the three single sources individually, all possible colors can be produced. This is the main idea of color cathode ray tubes commonly used in TV and computer monitors - every pixel (a point on the monitor) consists of three smaller individual spots in the colors red, green and blue (Fig. 2). As these individual spots are so close together, the human eye cannot resolve them. Instead, they produce the perception of a certain color by superposition of their respective intensities. For instance, the pixel appears yellow when only the red and the green spot are emitting light, and the pixel appears white when all three spots are emitting light. The entirety of colors produced through color addition forms the **RGB color space**, since they are based on the three (additive) primary colors red, green and blue.

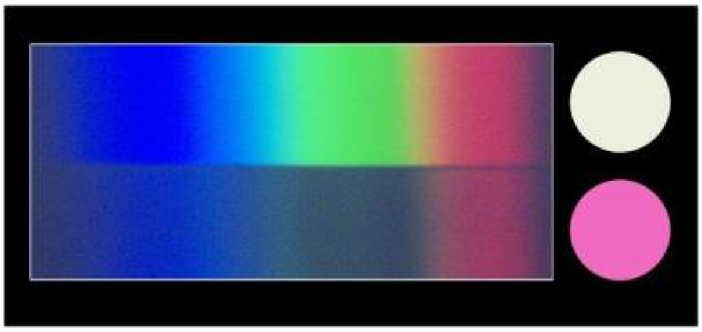

Fig. 2: The effect of color addition demonstrated with white light from an overhead projector before (top) and after (bottom) passing through a magenta filter.

The respective spectral decomposition is shown on the left whereas the circle on the right shows the resulting color impressions.

It can be clearly seen that the filter strongly absorbs light from the green part of the visual spectrum, whereas blue and red light passes the filter with low attenuation.

The impression of magenta is produced by simultaneous presence of light from the blue and red regions of the visible spectrum, whereas light from the green region is missing.

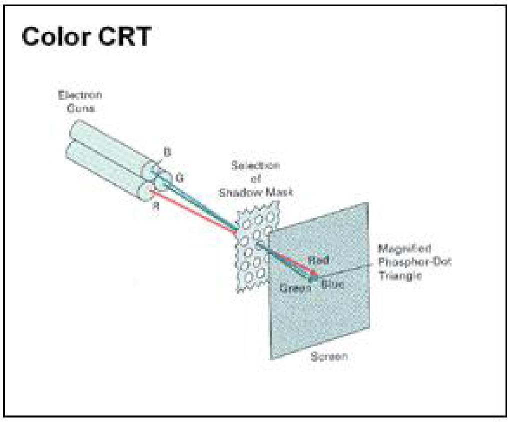

Fig. 3: An RGB monitor consists of tiny red, green and blue spots.

Variation of their brightness produces the impression of different colors by color addition.

Source (valid as of 2002): http://www.cs.princeton.edu/courses/archive/fall99/cs426/lectures/raster/img013.gif

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Color subtraction

Whereas color addition describes the perception of different colors caused by a superposition of red, green and blue light sources, the concept of color subtraction is based on the absorption of white light by filters or pigments. As an example, a yellow filter absorbs wavelengths below about 500 nm, corresponding to blue light, but transmits longer wavelengths corresponding to green and red light. Thus, when irradiated with white light, the filter only transmits wavelengths which stimulate the green and red cones, whereas the blue cones are not stimulated. As discussed above, this results in the perception of the color “yellow”. Similarly, a surface (better: pigments on a surface) absorbing wavelengths below 500 nm and reflecting wavelengths above appears yellow when irradiated with white light. Thus, when irradiated with white light, filters (or pigments) absorbing blue light appear yellow, filters (or pigments) absorbing green light appear magenta, and filters (or pigments) absorbing red light appear cyan. Because the effect of filters on transmitted light is the same as that of pigments on reflected light, the following conclusions derived for pigments are also valid for filters.

What happens if two pigments are combined? The combination of a yellow pigment, which absorbs short (blue) wavelengths with a cyan pigment, which absorbs long (red) wavelengths, leaves only medium (green) wavelengths to be reflected when irradiated with white light. As a result, the combination of yellow and cyan pigments results in green reflected light. Similarly, the combination of yellow and magenta pigments results in red and the combination of cyan and magenta results in green reflected light. In next figure, the effect of color subtraction is demonstrated for filters.

Ideally, a combination of yellow, cyan and magenta pigments should result in total absorption of the whole visible wavelength range and thus in the perception of a black surface.

However, the absorption properties of these pigments are never ideal in reality. This for instance explains why a four-color printer uses a black pigment in addition. Colors produced by a combination of cyan, yellow, magenta and black form the so called **CYMK color space**.

Fig. 4: Overlapping arrangement of yellow, cyan and magenta color filters on an overhead projector. In the overlapping regions, color subtraction results in green, red and blue light.

1.10 Colorimetry

The basic problem of colorimetry is the quantification of the physiological color perception caused by a certain **spectral color stimulus function $\varphi_\lambda(\lambda)$**. When the color of a primary light source has to be characterized, $\varphi_\lambda(\lambda)$ equals the source's spectral radiant power $\Phi_\lambda(\lambda)$ (or another spectral radiometric quantity, such as radiant intensity or radiance). When the color of a reflecting or transmitting object (for example a filter) has to be characterized, $\varphi_\lambda(\lambda)$ equals the incident spectral irradiance impinging upon the object's surface, multiplied by the object's spectral reflectance, its spectral radiance coefficient or its spectral transmittance. Since colors of reflecting or transmitting objects depend on the object's illumination, the CIE has defined colorimetric standard illuminants. The CIE Standard Illuminant A is defined by a Planckian blackbody radiator at a temperature of 2856 K, and the CIE Standard Illuminant D56 is representative of average daylight with a correlated color temperature of 6500 K (for the definition of color temperature, see below).

The following sections give information on:

- RGB and XYZ color matching functions
- The (x, y) and (u', v') chromaticity diagrams
- Correlated color temperature
- Color rendering index CRI
- Color preference and rendition metric CQS
- Planckian locus
- The dominant wavelength of a radiator
- The purity of a radiator
- MacAdam ellipses and binning

RGB and XYZ color matching functions

According to the tristimulus theory, every color which can be perceived by the normal-sighted human eye can be described by three numbers that quantify the stimulation of red, green and blue cones. If two color stimuli result in the same values for these three numbers, they produce the same color perception even when their spectral distributions are different. Around 1930, Wright and Guild performed experiments during which observers had to combine light at 435.8 nm, 546.1 nm and 700 nm in such a way that the resulting color perception matched the color perception produced by monochromatic light at a certain wavelength of the visible spectrum. Evaluation of these experiments resulted in the definition of the standardized **RGB color matching functions** $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$, which have been transformed into the CIE 1931 **XYZ color matching functions** $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. These color matching functions define the **CIE 1931 standard colorimetric observer** and are valid for an observer's field of view of 2°. Practically, this observer can be used for any field of view smaller than 4°. For a 10 ° field of view, the CIE specifies another set of color matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$ and $\bar{z}(\lambda)_{10}$. This set defines the **CIE 1964 supplementary standard colorimetric observer**, which has to be used for fields of view larger than 4 °.

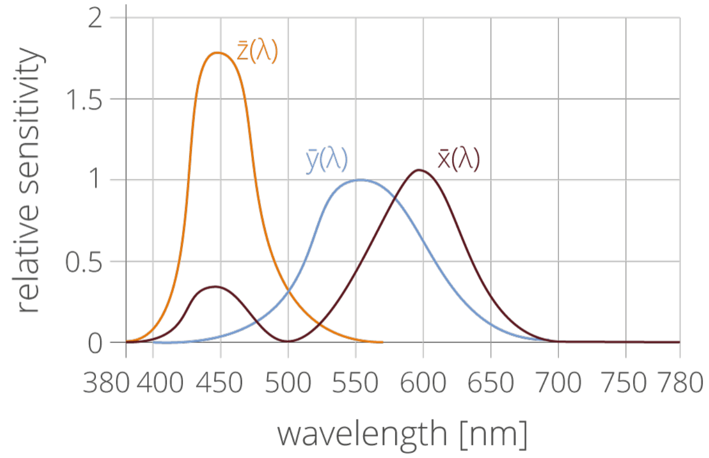

Fig. 1: XYZ color matching functions as defined by the CIE 1931 standard colorimetric observer. *$\bar{x}(\lambda)$ (solid black line) consists of a short- and a longwavelength part, and* *$\bar{y}(\lambda)$ (solid grey line) is identical with the CIE spectral luminous efficiency function $V(\lambda)$.*

Although RGB and XYZ color matching functions can be equally used to define three parameters where the numbers uniquely describe a certain color perception. The XYZ color matching functions are preferred because they have positive values for all wavelengths (Fig. 1). In addition, $\bar{y}(\lambda)$ is equal to the CIE spectral luminous efficiency function $V(\lambda)$ for photopic vision.

The XYZ tristimulus values of a certain spectral color stimulus function $\varphi_\lambda(\lambda)$ are calculated by

$$X = k \int_\lambda \varphi_\lambda(\lambda) \times \bar{x}(\lambda)\, d\lambda$$

$$Y = k \int_\lambda \varphi_\lambda(\lambda) \times \bar{x}(\lambda)\, d\lambda$$

$$Z = k \int_\lambda \varphi_\lambda(\lambda) \times \bar{x}(\lambda)\, d\lambda$$

The choice of the normalization constant k depends on the colorimetric task: When the spectral color stimulus $\varphi_\lambda(\lambda)$ describes a spectral radiometric quantity of a primary light source, k = 683 lm/W and consequently Y yields the corresponding photometric quantity. When the spectral color stimulus $\varphi_\lambda(\lambda)$ describes the spectral distribution of optical radiation reflected or transmitted by an object, k is defined by

$$k = \frac{100}{\int_\lambda E_\lambda(\lambda)\, \bar{y}(\lambda)\, d\lambda}$$

with $E(\lambda)$ denoting the incident spectral irradiance impinging upon the object's surface.

The (x, y) and (u', v') chromaticity diagrams

Although the XYZ tristimulus values define a three-dimensional color space representing all possible color perceptions, the representation of color in a two-dimensional plane is often sufficient for most applications. One possibility for a twodimensional representation is the **CIE 1931 (x, y) chromaticity diagram** with its coordinates x and y calculated from a projection of the X, Y and Z values:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

Although widely used, the (x, y) chromaticity diagram is largely limited by non-uniformity since geometric distances in the (x, y) chromaticity diagram do not correspond to perceived color differences. It is for this reason that in 1976, the CIE defined the **uniform (u', v') chromaticity scale (UCS) diagram**, with its coordinates defined by

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

Although this definition of the u' and v' coordinates does not provide a strict correspondence between geometric distances and perceived color differences, there are far less discrepancies than in the CIE (x, y) chromaticity diagram.

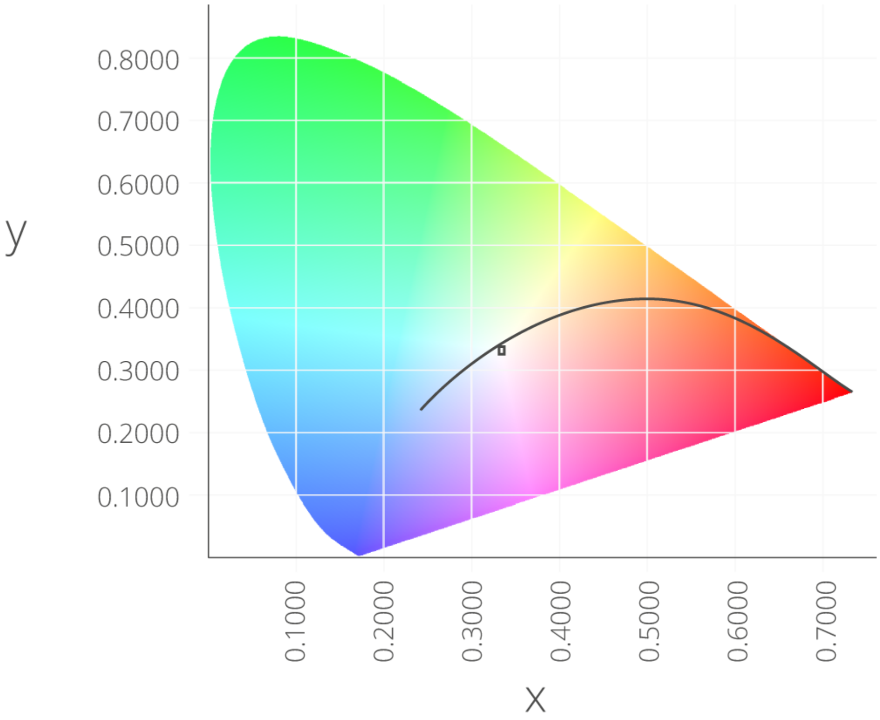

Fig. 2: The CIE 1931 (x,y) chromaticity diagram

Source (valid as of 2002): http://home.wanadoo.nl/paulschils/10.02.htm

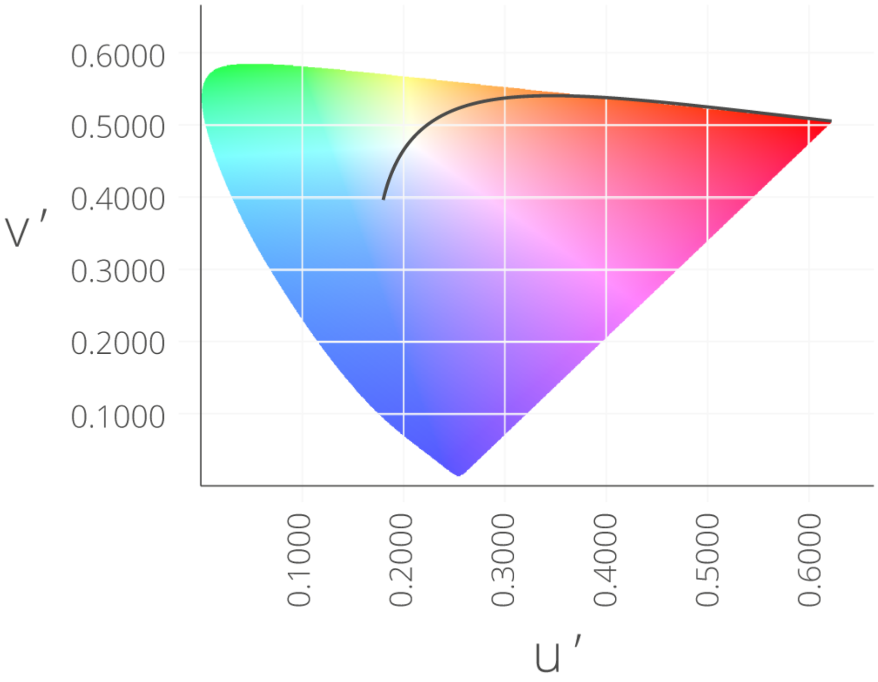

Fig. 3: The CIE 1976 (u′, v′) chromaticity diagram.

Source (valid as of 2002): http://home.wanadoo.nl/paulschils/10.02.htm

Correlated color temperature

The correlated color temperature is used to characterize the spectral distribution of optical radiation emitted by a light source. This characterization corresponds to the projection of a two-dimensional chromaticity diagram onto a onedimensional scale and is therefore very coarse.

In detail, the correlated color temperature is given in Kelvin (K) and is the temperature of the blackbody (Planckian) radiator whose received color most closely resembles that of a given color stimulus.

As a (simplified) rule of thumb, spectral distributions dominated by long (reddish) wavelengths correspond to a low correlated color temperature whereas spectral distributions dominated by short (bluish) wavelengths correspond to a high correlated color temperature. For example, the warm color of incandescent lamps has a correlated color temperature of about 2800 K, average daylight has a correlated color temperature of about 6500 K and the bluish white from a Cathode Ray Tube (CRT) has a correlated color temperature of about 9000 K.

Color rendering index CRI

The color rendering index (CRI) is a numerical description of the color rendition quality of a light source at the identical correlated color temperature. Here, the general color rendering index R_a represents the average of the first eight test color samples. Overall, 14 such test color samples that were defined by DIN 6169 and CIE 13.2. are currently used. In many cases, an additional CRI 15 that was added subsequently is also calculated. In order to perform the calculation, a black body radiator's color temperature of up to 5000 K is used. For temperatures above 5000K, daylight e.g. D65 (D65 = 6500 K daylight) is used instead. Fundamentally, the color rendering index does not depend on the color temperature. It only depends on the relation the light source's spectral distribution within the visible spectral range to that of a reference light source. Mathematically speaking R_a is defined by:

$R_a = 1/8\ \Sigma^{8}_{i=1}\ R_i$

where R_i are given by

$R_i = 100 - 4{,}6 \times \Delta E_i$

Here, ΔE_i is the Euclidian distance of the respective test color sample when illuminated by the light source under test as compared to the reference light source. Fig. 4 shows the spectral functions of the test color samples.

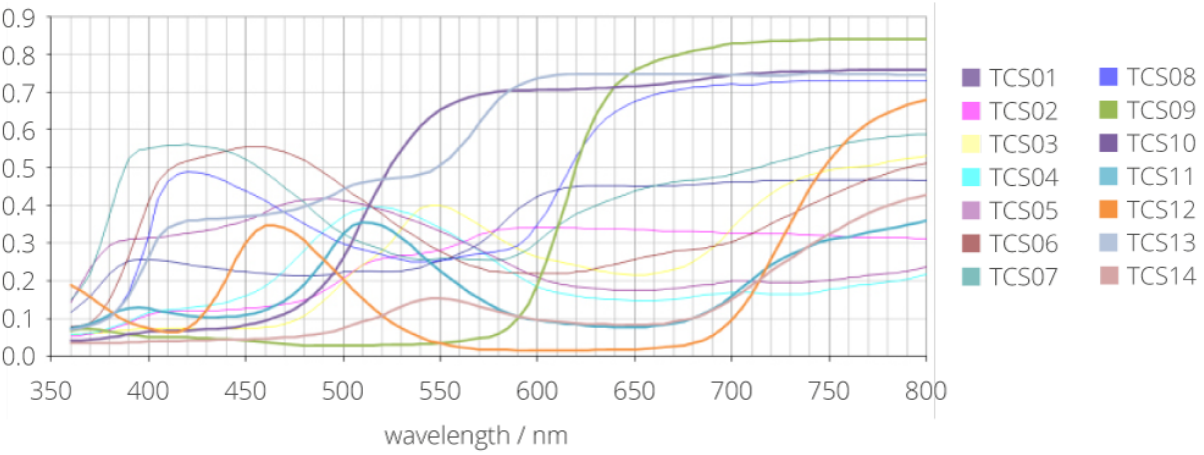

Fig. 4: Test color samples according to CIE 13.2

Color preference and rendition metric CQS

In addition to the CRI specified by CIE 1976, there are 15 test color samples of the colorquality scale (CQS) that are calculated in a similar way. The CQS method (version 7.5) uses 15 selected (saturated) test colors from the Munsell color system instead of the CIE test color samples. According to the CIE color rendering index, test light sources that increase the saturation of an object's hue as compared to a reference light source are evaluated with low CRI scores. Unlike the CQS reference light source, the CQS method does not evaluate an increase in saturation of a test device in a negative way in order to take into account an observer's tendency to prefer colors with a higher saturation. An increased saturation of the color rendition when an object is illuminated by a light source under test means a change in color perception. This again means that there is no conformity of the test light source and the reference thus leading to a decreased CRI score. By definition, the color quality scale is hence no pure color rendition metric. Instead, it is a combination of color preference and rendition metric. Its advantage is that the color preference is taken into account. At the same time, an objective evaluation of color rendition is not possible.

Planckian locus

The Planckian locus is a diagrammatic representation of a black body radiator's emission with respect to the color temperature (see Fig. 5).

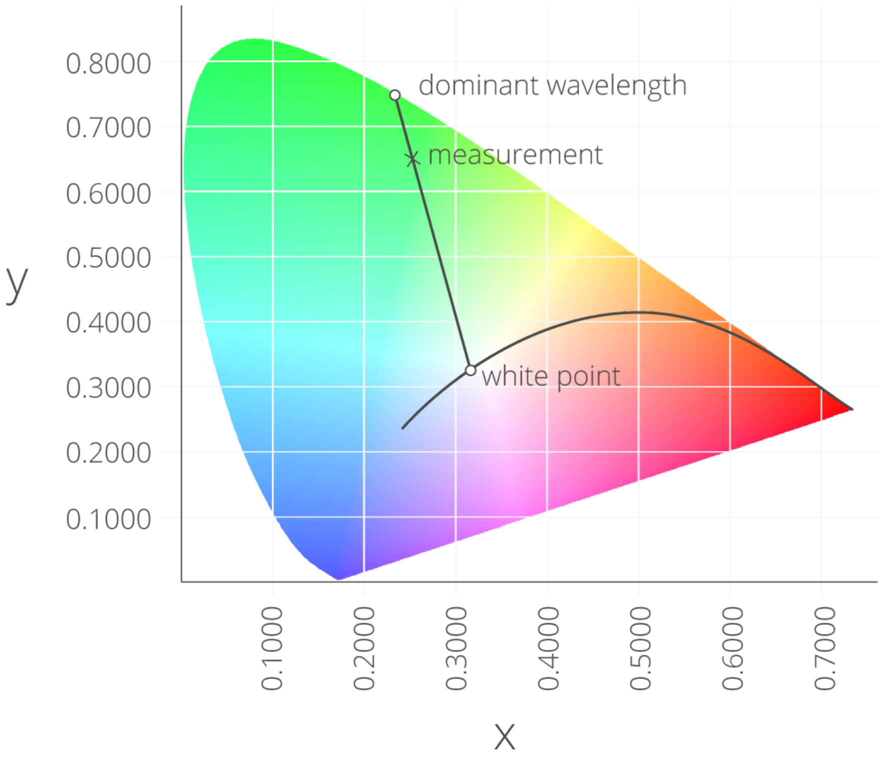

Fig. 5: Planckian black body locus

The dominant wavelength of a radiator

The dominant wavelength of a radiator is determined by the point where a straight line from the white point through the color coordinates of the radiator intersects with the spectral locus, the outer curved boundary of the CIE 1931 color space diagram. This is shown in Figure 6. The dominant wavelength cannot be determined directly from the spectrum. Instead, it represents an evaluation of a light source’s properties based on the color metric.

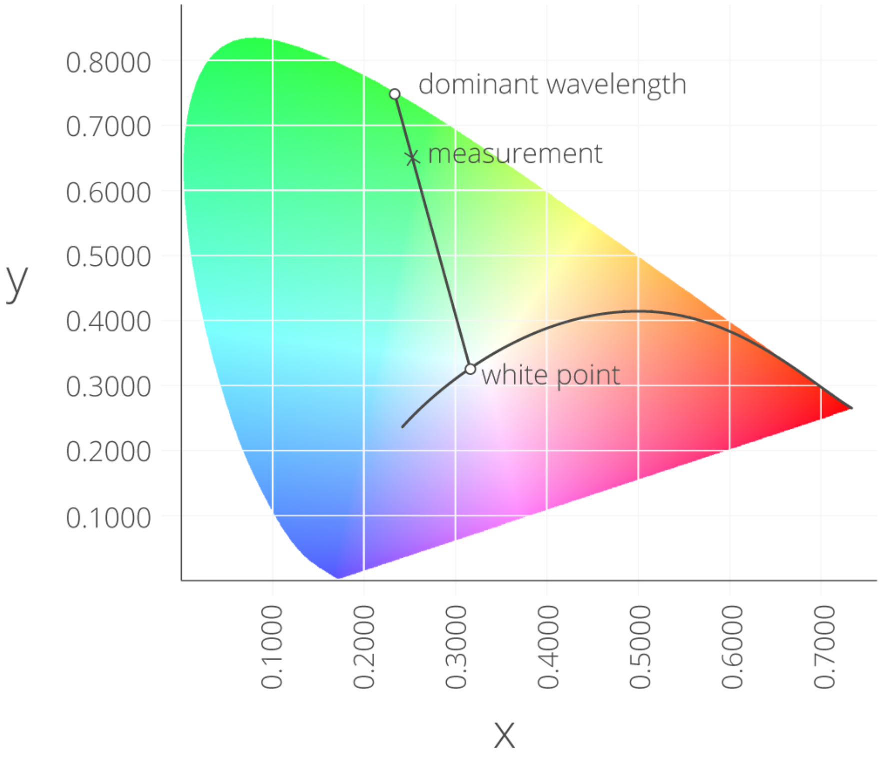

Fig. 6: Dominant wavelength in the CIE 1931 color space diagram

The purity of a radiator

The purity defines how close the color coordinate of a radiator is positioned in relation to the spectral locus in the CIE color space diagram. Geometrically, it can be depicted as shown in Figure 7.

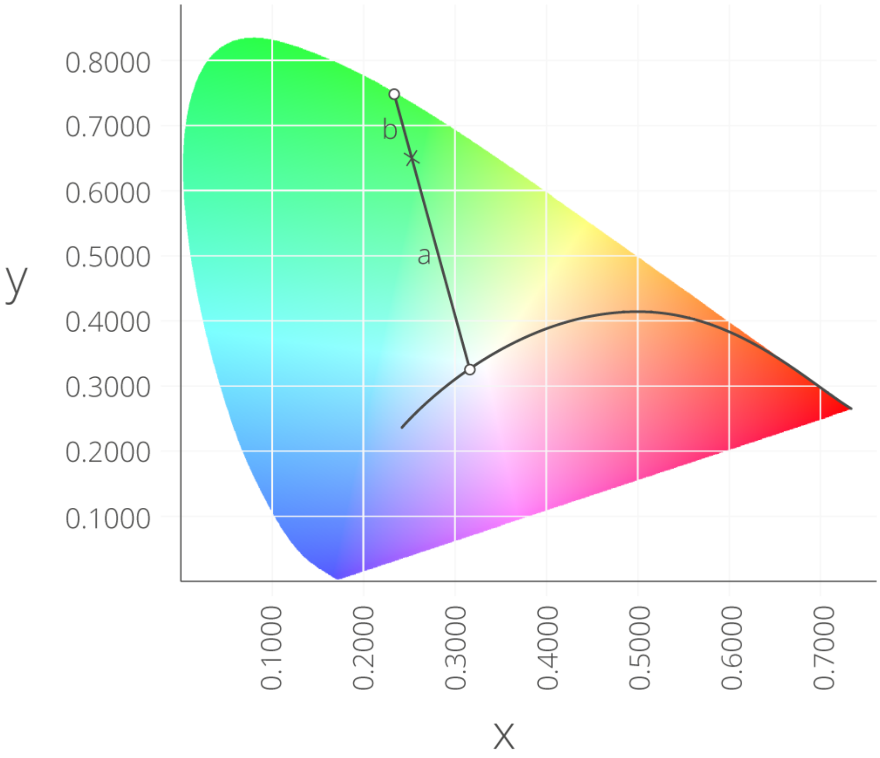

Fig. 7: Purity in CIE 1931 color space diagram

The color coordinate of the measurement is represented by the cross symbol. A line is drawn from the white point via the color coordinate towards the dominant wavelength of the measurement. The purity is now calculated as follows by evaluation of the sections of the line:

$$\text{purity} = \frac{a}{a + b'}$$

where a is the distance between the white point and the measurement point and b is the distance between the measurement point and the dominant wavelength. If the purity equals one, i. e. b equals zero, the light source has a pure single line spectrum e. g. a laser. If purity equals zero the radiator has a spectrum that is as broad as possible.

MacAdam ellipses and binning

Distances in the xy color space, which was defined in 1931 by CIE, do not reflect the distances as perceived by the human eye. This means that if two measurement points in the color diagram have the same distance to an arbitrary reference point, the perceived color contrast differs in general. In 1942, MacAdam tried to take this into account by adding ellipses into the color diagram as shown in Figure 8. Nowadays, so-called n step MacAdam ellipses are used. Here, n is the magnification of the ellipse in comparison to the one which was originally defined by MacAdam. Established values are 3x, 5x and 10x.

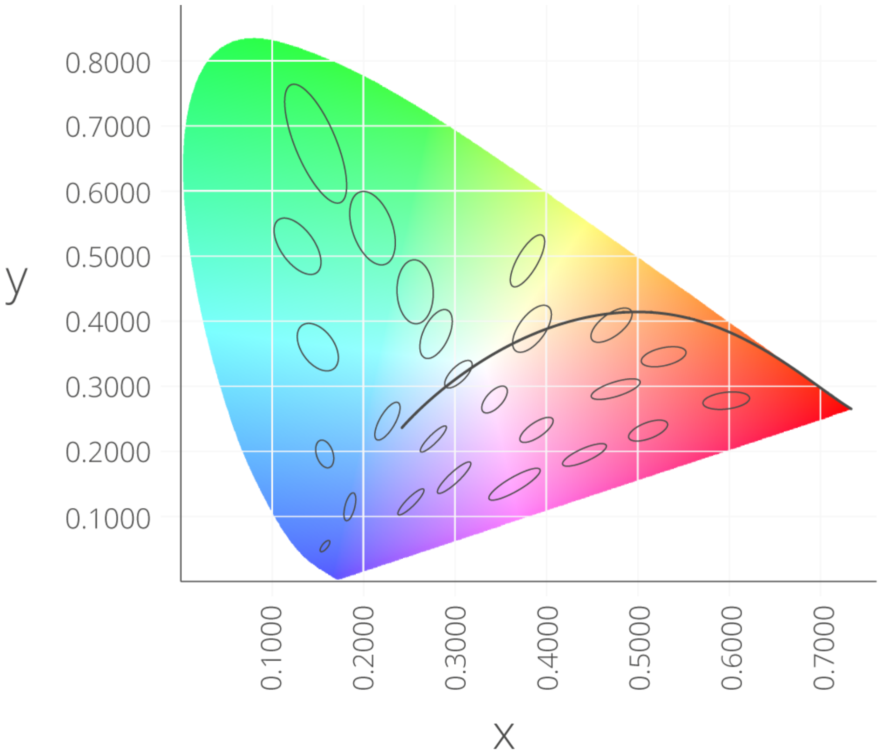

Fig. 8: MacAdam ellipses in xy color space

MacAdam’s research presented a huge progress and considering the options at that time in terms of experimental setups and computing power, his results are truly remarkable. In the 1960s, additional research was promoted which resulted in the CIE 1976 u'v' color space. Although the xy color space is the most widely accepted color space to date, CIE recommends using the u'v' color space.

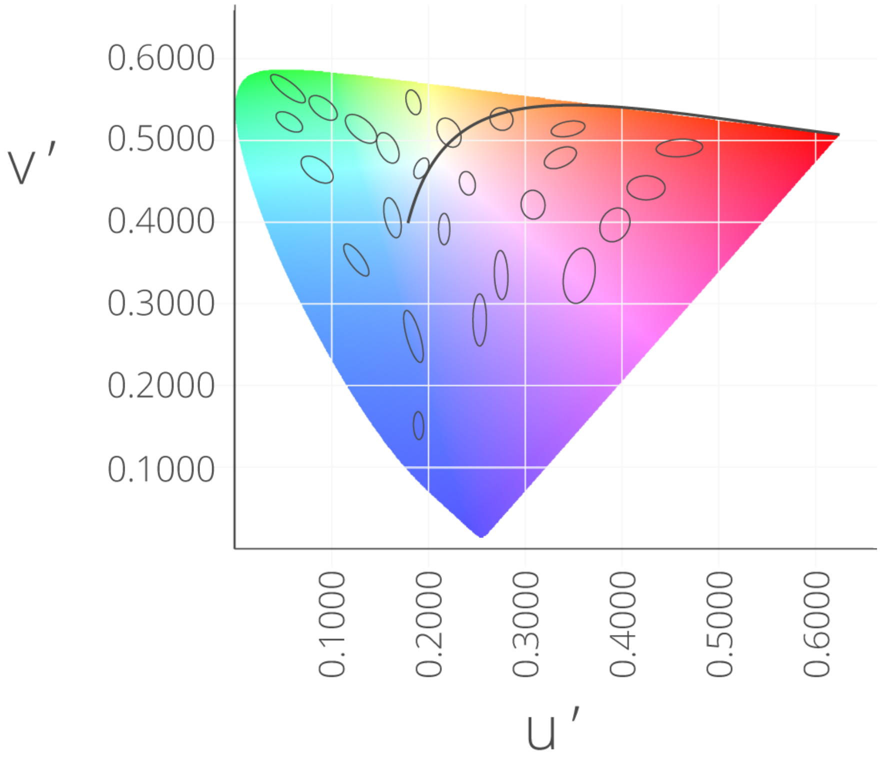

Fig. 9: MacAdam ellipses in u’v’ color space

Recent findings indicate that the ellipses are not the ideal choice for modern solid state lighting (SSL) luminaire technology such as light emitting diodes (LEDs). The original ellipses were determined using fluorescent lamps of six different color temperatures. Recent technologies are not subjected to the same restrictions. Thus, new regulations are required example e.g. as defined by ANSI (ANSI NEMA ANSLG. 2011. C78.377-2008) using eight nominal CCTs as well as CCTs in 100K steps (see Fig. 9).

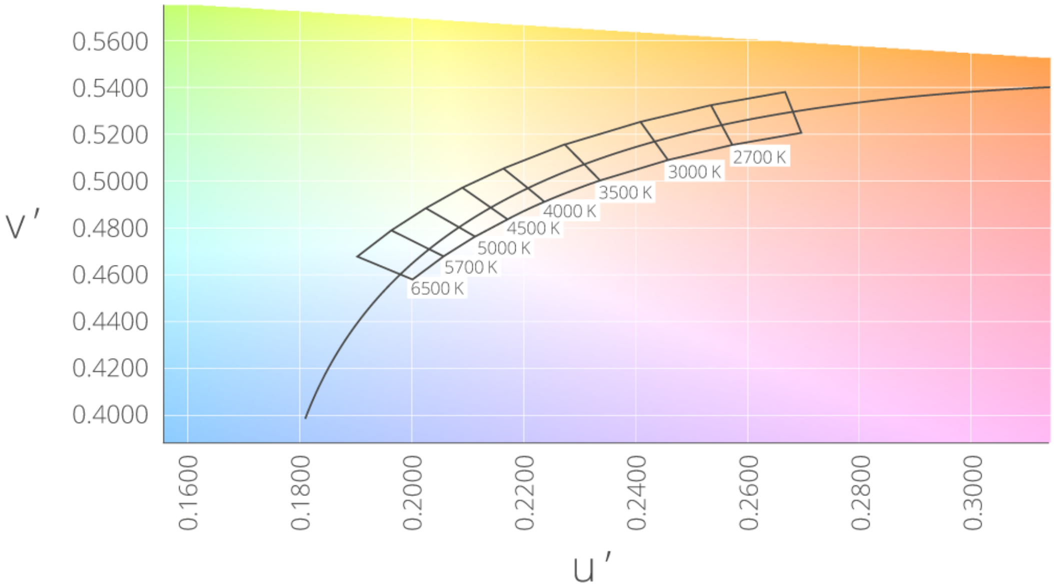

Fig. 10: ANSI bins in the u’v’ diagram

Most recent recommendations by the CIE (IEC 60081, IEC 1997) include the use of n step circles in u'v' color space with their centers at the position of the MacAdam ellipses. The radius of these circles can be adjusted as required. Their mathematical description is given by:

$$(u' - u'_c)^2 + (v' - v'c)^2 = (0.0011 \times n)^2$$

where u'_C and v'_C are their centre coordinates. With such a description, interpolation in terms of CCT becomes an option which reflects the diversity of LED technology. For binning purposes, either these or customized areas defined by the manufacturers are used in the selection and sorting of LEDs based on specific color properties. Such measurements require precise spectrometers that have a high wavelength precision, narrow optical bandwidth (or a bandwidth correction) and a verified absolute calibration. Additionally, highly sensitive devices that enable rapid measurements and fast data transfers are required. For a measurement device to be used in LED binning, it must meet these speed and precision requirements. Figure 11 shows the color bins of a LED manufacturer in the u'v' color space.

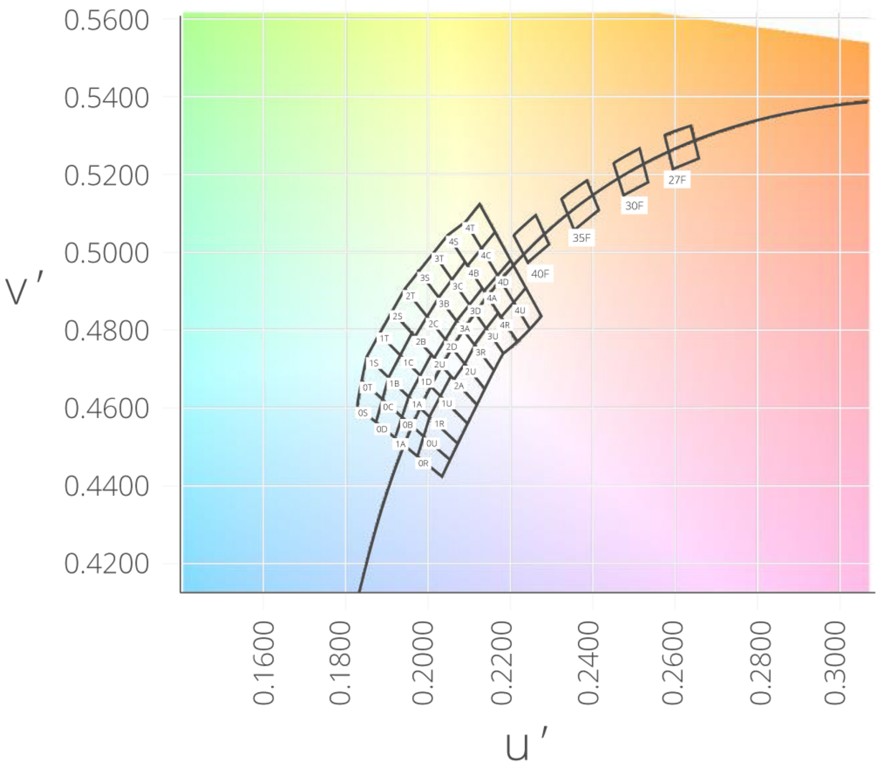

Fig. 11: Color bins of a LED manufacturer

1.11 Defining properties of a spectral line

The peak wavelength of an LED is typically described by a series of physical quantities. It should be noted that in case of a symmetric line spectrum, the centroid, peak and center wavelengths are identical since they coincide. Only the full width at half maximum value (FWHM) gives differing information.

- **Peak wavelength, λ_p**
  It is defined as the wavelength at which the spectral distribution or line reaches its largest value.

- **Centroid wavelength, λ_c**
  This wavelength defines the position of the spectral center of mass.

- **Centre wavelength, λ_s**
  The center wavelength is defined as the center of the FWHM.

- **Full width at half maximum (FWHM)**
  This quantity gives information about the width of a radiator at half the height of its maximum.

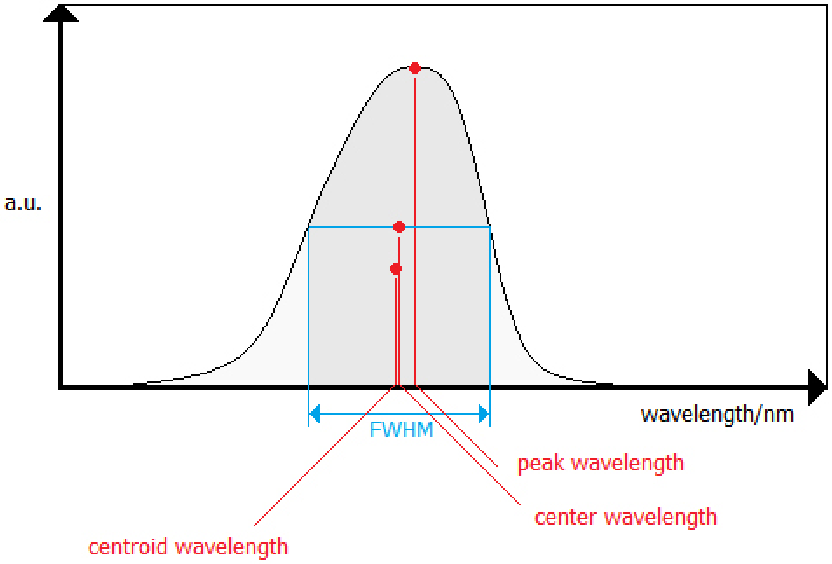

Fig. 1: Defining properties of a spectral line

2 Measurement of light with integral detectors

Spectroradiometry – the measurement of radiation intensity as a function of wavelength – is the only way to provide full spectral information about optical radiation emitted by a light source or radiation which impinges on a surface. Until quite recently, spectroradiometers tended to be highly sophisticated optical measurement devices requiring relatively complicated calibration, operation and maintenance. Modern designs such as the Gigahertz-Optik MSC15, BTS256 and BTS2048 make spectroradiometric measurements much more straightforward. However, for many applications (e. g. UV light measurement) integral detectors offer an economical and user friendly alternative. The term "integral" describes the fact that the output signal of an integral detector is proportional to the wavelength integral over the measured quantity's spectral distribution which is then multiplied with the detector's spectral sensitivity. Such detectors are applied in cases where determining the exact spectral distribution of the measured quantity is not necessary. Ideally, such cases require a detector that is specially designed to match a certain predefined spectral sensitivity function. As an example, the spectral sensitivity of photometric detectors is matched to the CIE spectral luminous sensitivity function V(λ) whereas detectors for solar UV irradiance, which is potentially harmful to the human skin, are matched to the CIE erythema action spectrum. Since integral detectors provide just a single output signal (usually voltage or photocurrent), they are much easier to characterize than spectroradiometers. The main parameters determining the usability and quality of an integral detector are:

- its input optics that determine its directional sensitivity
- its spectral sensitivity
- the dynamic range over which the detector's output is proportional to the input signal's intensity
- its time behavior

2.1 The detector's input optics and its directional sensitivity

Basically, the design of a detector's input optics is determined by its desired directional sensitivity, which in turn depends on the radiometric or photometric quantity to be measured:

- The determination of a light source's radiant and luminous flux requires constant directional sensitivity over the solid angle of 4π steradian or over the hemispherical solid angle of 2π steradian. This is achieved by using an integrating sphere where the light source is either placed inside the sphere or right at the sphere's entrance port.

- The determination of irradiance and illuminance requires a detector's directional sensitivity proportional to the cosine of the angle of incidence. This can either be done using a flat field detector or the entrance port of an integrating sphere.

- Radiant and luminous intensity

- Radiance and luminance are quantities that are defined as a function of the solid angle. Thus, the detector's field of view has to be limited to a small angle. This can be achieved by using baffles and/or lenses arranged in a tube.

The following sections give information on:

- Integrating spheres used with integral detectors
- Measurement of radiant power and luminous flux
- Measurement of irradiance and illuminance
- Measurement of radiant and luminous intensity
- Measurement of radiance and luminance
- Measurement of reflection and transmission properties
- Measurement of flicker

Integrating spheres used with integral detectors

In an ideal case, the inner surface of an integrating sphere is a perfect diffuse Lambertian reflector. The directional distribution of reflected radiation is therefore independent of the directional distribution of incident radiation, and no specular reflection occurs. Due to its geometry, an ideal integrating sphere is characterized by constant irradiance (or illuminance) over its entire inner surface. Furthermore, the level of this irradiance (illuminance solely depends on the total amount of radiant power (luminous flux) entering the sphere) is independent of its directional distribution.

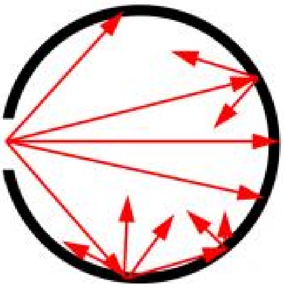

Fig. 1: Ideal multiple Lambertian reflections inside an integrating sphere

However, real surfaces do not show perfect Lambertian reflection properties. Although minimized by the properties of the respective material, a certain amount of specular reflection still occurs. Baffles placed at specific locations inside the sphere are used to prevent major measurement errors by specular reflection. Moreover, radiation is not reflected ideally at the input and exit ports due to the missing coating material. For these reasons, the quality of measurements performed using integrating spheres strongly depends on the sphere's coating material as well as the exact position of baffles and the size of the ports in relation to the sphere's diameter. As a general rule of thumb, the total area of entrance and exit ports should not exceed 5 % of the sphere's internal surface. Numerous standard setups are used in radiometric and photometric measurements to define the arrangement of the sphere's entrance ports, exit ports and internal baffles (see measurement of radiant power and luminous flux, irradiance and illuminance, radiant and luminous intensity, radiance and luminance and reflection and transmission properties.

In addition to their directional sensitivity, integrating spheres also offer the following advantages:

- The high number of internal reflections generally makes a detector insensitive to the incident radiation polarization.
- For the characterization of powerful light sources, an integrating sphere can be used for attenuation in order to prevent saturation effects of the detector. Since this attenuation results in an increase of internal temperature, the maximum power of the light source is limited by the operation temperature range of the sphere.
- In general, the geometric alignment of the source and integrating sphere is not very critical thus simplifying calibration and measurement procedures.

Click here for more detailed information about the theory and application of integrating spheres.

Measurement of radiant power and luminous fluxRadiant power and luminous flux of lasers and spot sources

Lasers, LEDs, spot lamps, endoscopes, optical fibers and other sources emit radiation with various directional distributions. As long the emission is limited to a hemispherical (2π steradian) solid angle, the source can be attached to the entrance window of an integrating sphere and therefore does not interfere with the sphere's internal reflections.

The entrance port has to be large enough to ensure that all radiation from the source enters the sphere. A baffle is necessary to shield the detector from direct irradiation by the source.

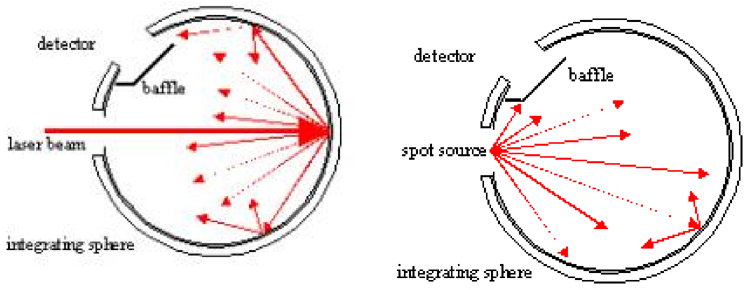

Fig. 2: Integrating sphere used for laser power measurements (left) and radiant power and luminous flux measurements of spot sources (right).

As an alternative, radiant power and luminous flux of collimated (parallel) beams can be measured directly using flat field detectors as long as the detector’s active area is larger than the beam’s cross section. Despite the simple measurement setup, this method has significant disadvantages in comparison to the use of an integrating sphere:

- The detector might possibly be sensitive to the beam’s polarization.
- The detector’s active area might possibly be inhomogeneous in its sensitivity. In this case, it is important to ensure equal illumination during calibration and measurement.
- Alignment of the detector with respect to the beam is critical.

Radiant power and luminous flux of lamps

Lamps emit radiation in all directions of the full (4π steradian) solid angle. A lamp must therefore be placed inside an integrating sphere in order to determine its total radiant power or luminous flux. As a consequence, the lamp itself and its accessories interfere with the sphere’s internally reflected radiation thereby resulting in measurement errors. These errors are cancelled out by use of an auxiliary lamp (see below).

In order to reduce measurement uncertainty, integrating spheres used to measure the radiant power or luminous flux of lamps must be well suited for the lamp under test. One important design parameter is that the diameter of the hollow sphere should be about ten times (twice for tube lamps) the maximum dimension of the lamp. For example, an integrating sphere setup to measure the luminous flux of fluorescent lamps with 120 cm (47 in) length should have a diameter of at least 2 m (79 in). Furthermore, the diameter of the sphere limits the maximum power of the lamp.

In actual measurements, the lamp must be placed at the center of the hollow sphere. This is typically accomplished using a tube holder, which carries the power and measurement leads into the sphere. A socket at the end of the tube holds and connects the lamp. In order to hold the lamp at the central position, hinged integrating spheres that can be opened and that have large diameters of more than 50 cm (20 in) are used. Spheres with smaller diameters may offer a large diameter port to mount the lamp at the center of the sphere. The port is normally closed with a cap during the measurement. The inside surface of the cap should be coated with the same diffuse coating as the hollow sphere surface. The detector is placed at a port on the integrating sphere. It must be baffled against direct irradiation by the lamp.

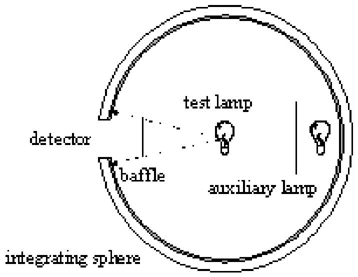

Fig. 3: Experimental setup for radiant power and luminous flux measurements of a lamp. The auxiliary lamp is used to reduce measurement errors caused by the interference of the lamp under test and its accessories with the sphere’s internally reflected radiation.

For precise measurements, the lamp must be aged before testing. The burn-in time depends on the lamp type. The burn-in time for tungsten lamps should be 2 – 5 hours (IEC 64) whereas about 100 hours (IEC 81) are recommended for arc lamps.

In precise luminous flux measurement applications, an auxiliary lamp with baffle(s) is recommended. The diffuse illumination generated by the auxiliary lamp can be used to reduce the negative effects of the lamp under test and its accessories according to the relation

$$\Phi_X = \Phi_N \times \frac{Y_X}{Y_N} \times \frac{Y_{HN}}{Y_{HX}}$$

Φ_X: luminous flux of the test lamp

Φ_N: luminous flux of the calibration lamp

Y_X: measurement signal of the test lamp (with auxiliary lamp switched off)

Y_N: measurement signal of the calibration lamp (with auxiliary lamp switched off)

Y_{HN}: measurement signal of the auxiliary lamp (with calibration lamp switched off)

According to Equ. 3 in Basic radiometric quantities, a detector for measuring the irradiance or illuminance of a surface has to weight the incident radiation with respect to the cosine of its angle of incidence. This can either be achieved using

- an integrating sphere that is specially designed for irradiance (or illuminance) measurements (see figure below) or
- a cosine diffuser. This is an optical element that shows purely diffuse transmission regardless of the directional distribution of the incident radiation (Fig. 5).

In both cases, the ideal directional cosine response can only be approximated. Deviations of a real detector's directional response from the ideal cosine response are quantified by the detector's **cosine error function**, which is given by

$$\text{cosine error}(\vartheta) = \frac{[\,S(\vartheta) / S(0)\,] - \cos(\vartheta)}{\cos(\vartheta)} = \frac{S(\vartheta) - S(0)\cos(\vartheta)}{S(0)\cos(\vartheta)}$$

In this equation, S(Θ) denotes the detector's signal caused by a ray of light impinging upon the detector's entrance optics at an angle Θ, measured relative to the normal (see Fig. 4).

S(0) denotes the detector's signal caused by the same ray of light impinging vertically upon the detector's entrance optics.

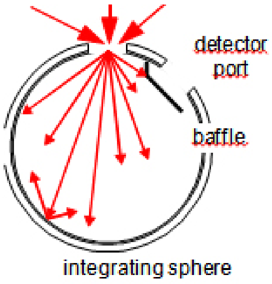

Fig. 4: Integrating sphere design for measurement of irradiance or illuminance of a horizontal surface. The baffle prevents direct illumination of the detector, and the knife edges at the sphere's entrance port prevent shading by the sphere's wall, which would distort the detector's cosine response.

Light Source	**Approximate Average Illuminance (lx)**
Overcast night	0.0001

Full moon	0.1
Office light	500
Clear bright sky	70000 – 85000

Tab. 1: Some average illuminance values

Fig. 5: 1st image: Irradiance detector heads with cosine diffuser and 2nd – 4th image: waterproof version for underwater and outdoor use

Measurement of radiant and luminous intensity

Radiant and luminous intensity describe the directional distribution of a source's emitted radiation. For determination of this directional distribution, the relative position between source and detector has to be varied. The **goniophotometer** is a mechanical setup allowing the variation of the source's orientation and/or the detector's position, whereby the distance between source and detector is kept constant. Since the directional characteristics of a source often depend on its internal temperature distribution and thus on its position relative to the vertical, rotating the source around the horizontal axis is not recommended in order to ensure accurate measurements of radiant and luminous intensity.

Because radiant and luminous intensity are defined by the surface integral of the radiance and luminance (see Equ. 4), the emitting source must completely be in the detector's field of view. Ideally, both quantities have to be determined with a setup that allows the source to be considered point like. As a crude rule of thumb, the distance between detector and source should be at least ten times the largest geometric dimension of the source.

For precise measurements, special care has to be taken to minimize reflections at the lamp's surrounding (walls, ceiling, the goniophotometer itself) in the direction of the detector. Blackening of the surrounding, use of additional baffles and the reduction of the detector's field of view are proper precautions.

Measurement of radiance and luminance

Radiance and luminance describe the directional distribution of the radiance emitted or reflected by a certain area element. Similar to radiant and luminous intensity, radiance and luminance can be determined using a goniophotometer, but the detector is placed much closer to the emitting or reflecting surface and the detector's field of view is limited to a few degrees. Thus, only radiation from a small part of the source's surface enters the detector.

Light Source	**Approximate Average Illuminance (lx)**
Self-luminous paints	$0.02\ 10^{-3}$
Candle flame	1
Computer screen	100
Overcast daytime sky	1000
Clear bright sky	5000 – 6000

Tab. 2: Some average luminance values

Measurement of reflection and transmission properties

Quantities such as reflectance and transmittance are used to describe the optical properties of materials (see Reflection, Transmission and Absorption).

Reflectance ρ

Reflectance ρ (for incident radiation of given spectral composition, polarization and geometrical distribution) is the ratio of the reflected radiant or luminous flux to the incident flux in the given conditions. The measurement of reflectance is made in comparison to a reflection standard (reflectance ρ_N) with a collimated or conical radiation beam.

The signals of the detector will be calculated as follow:

$$\rho = \frac{I\,(X) - I\,(stray)}{I\,(N) - I\,(stray)} \times \rho_N$$

I (X): signal with sample irradiation
I (N): signal with standard irradiation
I (stray): signal with open measurement port

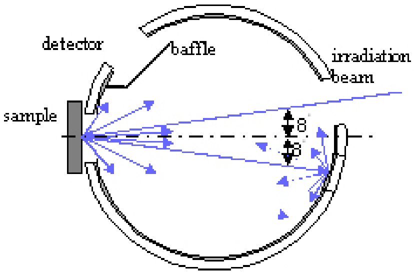

Fig. 6: Integrating Sphere Total Reflection Measurement Setup

Diffuse Reflectance ρ_d

This is the ratio of the diffusely reflected part of the (whole) reflected flux to the incident flux. The measurement of diffuse reflectance is made in comparison to a reflection standard (reflectance N) with a collimated or conical radiation beam. The signals of the detector are calculated as follows:

$$\rho_d = \frac{I\,(X) - I\,(stray) - \rho\,[\,I\,(mi) - I\,(stray)\,]}{I\,(N) - I\,(stray) - \rho_N\,[\,I\,(mi) - I\,(stray)\,]} \times \rho_N$$

I (X): signal with sample irradiation

I (N): signal with standard irradiation
I (stray): signal with open measurement port
I (mi): signal with irradiance of a mirror

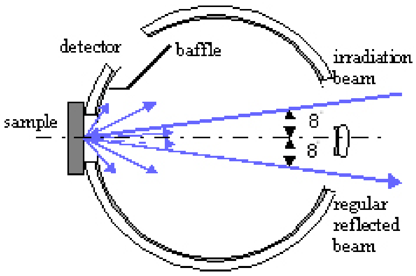

Fig. 7: Integrating sphere diffuse reflectance measurement setup

Transmittance τ

Transmittance τ (for incident radiation of given spectral composition, polarization and geometrical distribution) is the ratio of the transmitted radiant or luminous flux to the incident flux in the given conditions. The measurement of transmittance is made with a collimated or conical radiation beam. The signals of the detector are calculated as follows:

$$\tau = \frac{I\,(X)}{I\,(\text{open})}$$

I (X): signal with sample irradiation
I (open): signal with open measurement port

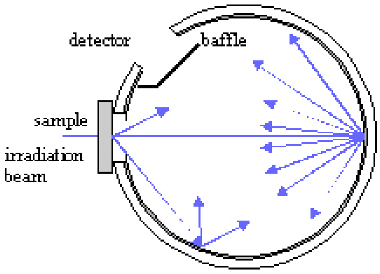

Fig. 8: Integrating sphere total transmittance measurement setup

Diffuse Transmittance τ_d

This is the ratio of the diffusely transmitted part of the (whole) transmitted flux to the incident flux.

The measurement of transmittance is made with a collimated or conical radiation beam. The signals of the detector are calculated as follow:

$$\tau_d = \frac{I\,(X) - \tau I\,(\text{stray})}{I\,(\text{open}) - I\,(\text{stray})}$$

I (X): signal with sample irradiation
I (open): signal with open measurement port and close output port
I (stray): signal with open measurement port and open output port

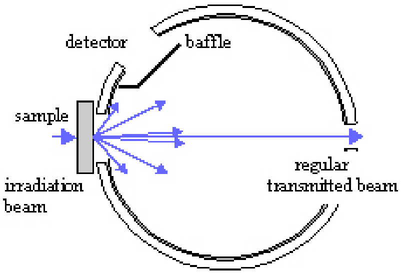

Fig. 9: Integrating sphere diffuse transmittance measurement setup

Measurement of flicker

New developments in solid state lighting (SSL) have enabled many new applications and products in the lighting industry. For instance, light sources using LEDs with pulse width modulation (PWM) or more advanced concepts can be dimmed and their colors changed. All these new functions are associated with often complex electronic control concepts. These electronic components can also contain high frequency components that may cause flicker in addition to typical low frequency oscillations. Several concepts have been developed in order to be able to examine and characterize these light sources. These include flicker frequency, flicker index and flicker percentage. As a result of these parameters, light sources can be compared with each other and optimized. This in turn results in new metrological tasks.

Flicker Frequency

The flicker frequency is defined as the reciprocal value of the cycle period T of the flicker oscillations.

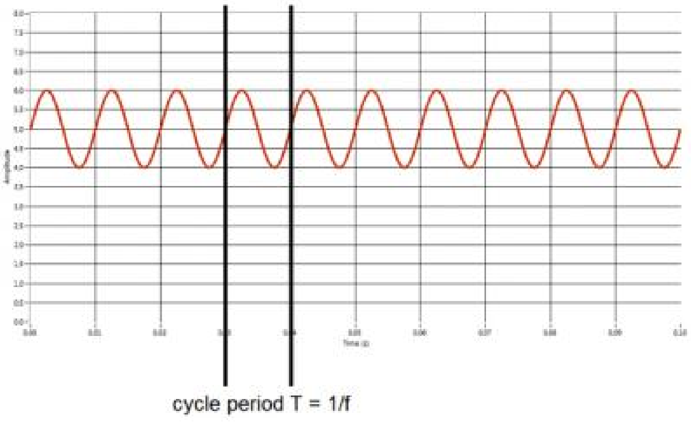

Fig. 10: Description of flicker frequency

Flicker percentage

The specification of the flicker percentage has proven to be highly meaningful. It indicates the magnitude (relative to the amplitude) of the waveform. The value lies between 0 and 1 or 0 % and 100 % respectively. 0 % signifies a pure DC waveform and 100 % a pure AC waveform. This value has no implications on the duty cycle of the signal. The flicker percentage of a signal f is defined as:

$$\text{Percent Flicker} = 100\,\% \times \frac{f_{max} - f_{min}}{f_{max} + f_{min}}$$

where f_{max} is the maximum functional value of f and f_{min} is the minimum functional value. Figure 11 shows the graphical representation of the flicker percent computation:

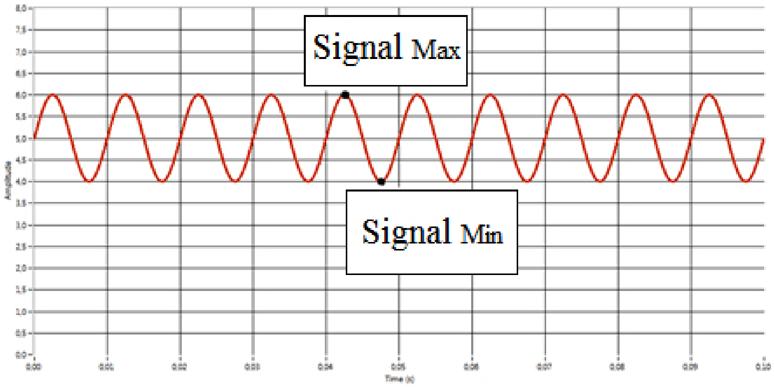

Fig. 11: Description of Percent Flicker

Flicker Index

Besides percent flicker, the flicker index is also very significant. It indicates the ratio of the area above the average light level and below the measured signal (Area 1, green) to the area below the average light level and the signal (Area 2, blue).The average light level is depicted in Figure 12 by the thick black line. A flicker index of 0 corresponds to a pure DC curve and a value of 1 corresponds to a pure AC curve. This factor specifies the duty cycle of the signal.

$$\text{Flicker Index} = \frac{\text{Area 1}}{\text{Area 1 + Area 2}}$$

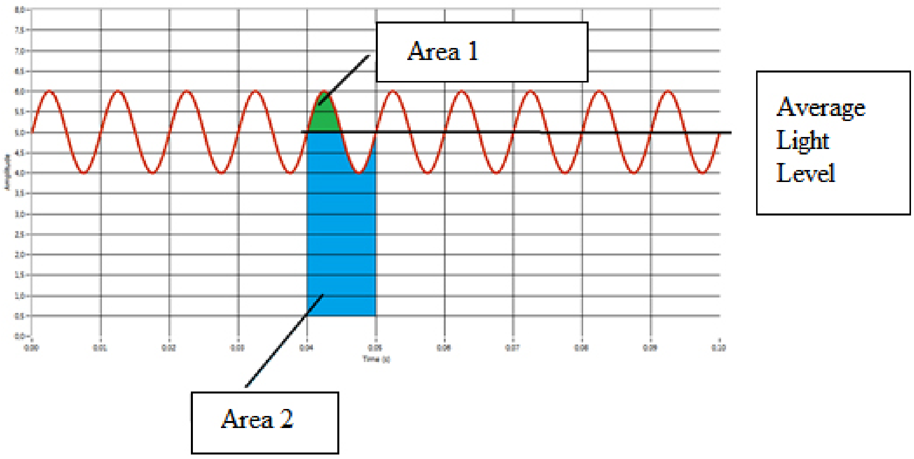

Fig. 12: Description of the flicker index

2.2 Spectral sensitivity of an integral detector

Within the normal range of operation of an integral detector, the relation between the input signal (the spectral radiometric quantity to be measured $X_\lambda(\lambda)$) entering the detector and its corresponding output signal Y has to fulfil the following condition of **linearity**:

Let Y_1 be the detector's response to the input signal $X_{1\lambda}(\lambda)$ and Y_2 the detector's response to the input signal $X_{2\lambda}(\lambda)$. The detector's response to the superimposed input signal $X_{1\lambda}(\lambda) + X_{2\lambda}(\lambda)$ is given by $Y_1 + Y_2$. Moreover, the detector's response is proportional to the input signal and therefore, the response to the input signal $a \times X_{1\lambda}(\lambda)$ is given by $a \times Y_1$ (where a denotes an arbitrary positive number). A detector might possibly show a certain **dark signal Y_0** (usually dark current or dark voltage), which is a nonzero output signal even when the detector is not exposed to any radiation at all. In this case, Y, Y_1 and Y_2 have to be substituted with $Y - Y_0$, $Y_1 - Y_0$ and $Y_2 - Y_0$.

Deviations from this behavior are called **nonlinearities** and cause measurement errors. It is however possible to experimentally determine the nonlinearities of a detector and correct them. An example of a nonlinearity effect is the saturation of a detector's output signal at high radiation levels, which represents the upper limit of a detector's range of operation.

When nonlinearity effects can be neglected, the detector's output signal under arbitrary polychromatic radiation can be regarded as a superposition of the detector's output signals under monochromatic radiation. This leads to the concept of spectral sensitivity.

In detail, the CIE defines a detector's **spectral sensitivity (also: spectral responsivity) s(λ)** as

$$s(\lambda) = \frac{1}{X_\lambda(\lambda)} \times \frac{dY}{d\lambda}$$

where $X_\lambda(\lambda)$ denotes the spectral radiometric quantity defining the detector's input signal and dY denotes the (differential) increase of the output signal caused by the input radiation in the (differential) wavelength interval between λ and λ + dλ. When linear behavior of the detector can be assumed, the detector's signal Y is given by

$$Y = \int_\lambda X_\lambda(\lambda) \times s(\lambda)\, d\lambda$$

Often, the spectral sensitivity function s(λ) is described by the product of a reference value s_m and the relative **spectral sensitivity $s_r(\lambda)$** is:

$$s_r(\lambda) = s_m \times s_r(\lambda)$$

In many cases, s_m is given by the maximum of s(λ), thus $s_r(\lambda)$ is normalized to a value of 1 in its maximum. Another possibility is the normalization of $s_r(\lambda)$ to a total wavelength integral value 1, which is achieved by the definition of

$$s_m = {}_\lambda\!\int s(\lambda) \times d\lambda$$

In terms of relative spectral sensitivity, the detector’s output signal Y is given by

$$Y = s_m \times \int_\lambda X_\lambda(\lambda) \times s_r(\lambda)\, d\lambda$$

This integral relation is equivalent to the definition of photopic quantities where the detector’s relative spectral sensitivity $s_r(\lambda)$ corresponds to the CIE spectral luminous efficiency function V(λ) and s_m corresponds to K_m = 683 lm/W. Similarly, the calculation of effective radiation doses relevant for certain biological reactions is based on a corresponding relation containing the respective biological action spectrum. For instance, the erythemal action spectrum is used for definition of **Sunburn Unit**, which is used for quantification of erythemally active solar UV irradiance.

This correspondence allows for the direct determination of photopic quantities or biologically active radiation using a specially designed integral detector. In particular, the detector’s relative spectral sensitivity $s_r(\lambda)$ has to be matched closely to the CIE spectral luminous efficiency function V(λ) or to the respective action spectrum. For the determination of chromaticity coordinates or correlated color temperature, it is necessary to simultaneously use three detectors with their spectral sensitivities that are specially adapted to the color matching functions defined by the CIE 1931 standard colorimetric observer.

Gigahertz Optik uses different combinations of photodiodes and filters to achieve proper spectral sensitivities for detectors used in photometry, radiometry and colorimetry.

Monochromatic radiometry

For radiometric characterization of monochromatic or near monochromatic radiation of a known wavelength, a detector’s spectral sensitivity does not necessarily have to match a certain predefined shape. A photodiode can therefore be used without any spectral correction filters as long it is sensitive at the respective wavelength.

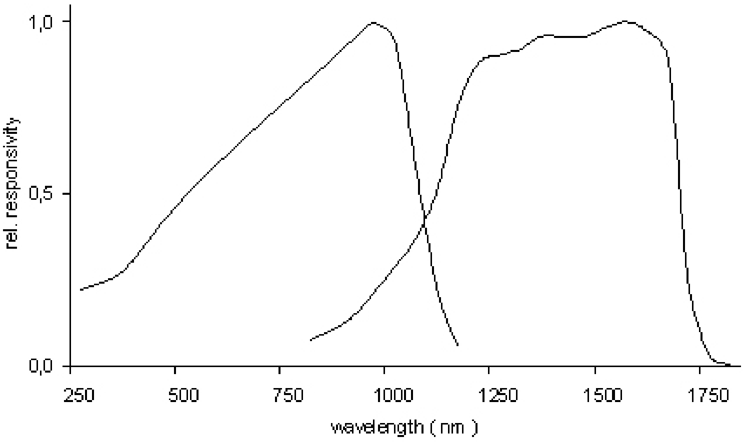

Fig. 1: Sensitivity ranges of various types of photodiodes

Typical tasks of monochromatic radiometry are the laser power measurements, characterization of LEDs with near monochromatic light output and power measurements in fiber optical telecommunication. Gigahertz Optik offers

- laser power meters equipped with a flat field detector (for lasers with collimated beams) or an integrating sphere (for lasers with noncollimating beams and LEDs)

- integrating spheres equipped with small area photodiodes whose low capacitance results in a detector time constant in the order of nanoseconds. These detectors are thus perfectly ideal for laser pulse analysis with high time resolution

- detectors equipped with integrating spheres that have a unique baffle design for measurements in fiber optics telecommunication. Additional adapters for standard fiber optic connectors are available

Polychromatic radiometry

The determination of total radiation power over a certain spectral range requires the detector’s spectral sensitivity function to closely match a rectangular shape.

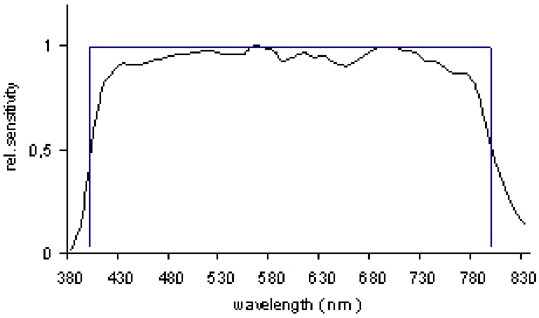

Fig. 2: Spectral sensitivity of Gigahertz Optik’s RW-3702 visible 400 – 800 nm irradiance detector closely matches the ideal rectangular shape.

Gigahertz Optik offers absolutely calibrated irradiance and radiant power meters equipped with a cosine diffuser or an integrating sphere whose spectral sensitivity is optimized for UVA, UVB, UVC as well as visible (VIS) and near infrared (NIR) ranges.

Photometry

For photometric measurements, the detector’s relative spectral sensitivity $s_r(\lambda)$ has to match the CIE spectral luminous efficiency function $V(\lambda)$ as close as possible. In order to quantify a detector’s inevitable spectral mismatch, the CIE recommends the evaluation index f_1', which is defined by

$$f_1' = \frac{{}_{\lambda}\int \mid s^*_r(\lambda) - V(\lambda) \mid d\lambda}{{}_{\lambda}\int V(\lambda)\, d\lambda}$$

where $s^*_r(\lambda)$ is given by

$$s^*_r(\lambda) = \frac{\int_\lambda S_A(\lambda)\, V(\lambda)\, d\lambda}{\int_\lambda S_A(\lambda)\, s_r(\lambda)\, d\lambda} \times s_r(\lambda)$$

where $S_A(\lambda)$ is the spectral distribution of the CIE Standard Illuminant A, which is the recommended photometric calibration source. High quality photometric detectors show a value of f_1' below 3 %, whereas a value of f_1' above 8 % isconsidered as poor quality. The DIN 5032, part 7 requires a spectral mismatch of $f_1' \leq 3$ % for "Class A" instruments and $f_1' \leq 6$ % for "Class B" instruments. Gigahertz Optik offers high quality illuminance, luminance and luminous flux detectors corresponding to Class A level ($f_1' = 3$ %) and, as an economical alternative, detectors meeting class B level ($f_1' = 5$ %). Furthermore, the BTS Technology allows for an online correction of the spectral mismatch factor.

Colorimetry

For the determination of a color stimulus X, Y and Z values as defined by the CIE 1931 standard colorimetric observer, the same stimulus has to be measured by three different detectors, whose spectral sensitivity functions have to be adapted to the CIE 1931 XYZ color matching functions. However, as the $\bar{x}(\lambda)$ color matching function consists of two separate sensitivity regions, the X value is often determined by two detectors. In this case, all four detectors are needed for the determination of the X, Y and Z stimulus values. Since the color matching function $\bar{y}(\lambda)$ is identical to the CIE spectral luminous efficiency function $V(\lambda)$, the respective detector can be calibrated definitely for simultaneous photometric measurements.

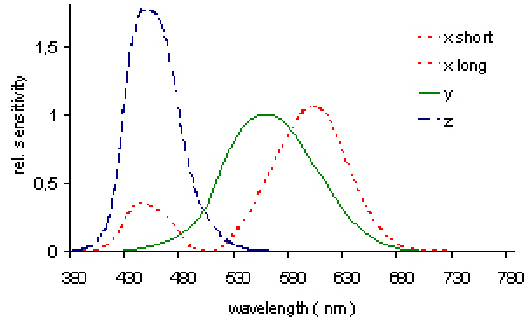

Fig. 3: Spectral sensitivity functions used for colorimetric measurements with Gigahertz-Optik's CT-3701 High Precision Color Meter.

2.3 The detector’s time behavior

A detector’s time resolution is limited by its response to an instantaneous change of the input signal. Due to electrical capacities of the light sensitive element and the electronics, the output signal does not change instantaneously but gradually increases or decreases until it reaches its final value. The detector’s **rise time** is defined as the time span required for the output signal to rise from a certain low percentage (usually 10 %) to a certain high percentage (usually 90 %) level of the maximum value when a steady input is instantaneously applied. The **fall time** is similarly defined as the time span required for the output signal to drop from a certain high percentage (usually 90 %) to a certain low percentage (usually 10 %) of the maximum value when a steady input is instantaneously removed.

Typically, the detector’s response to an instantaneous change of the input signal approaches the final value exponentially. The detector’s time behavior is thus best described by the **time constant τ**, which is the time span required for the output signal to vary from its initial value by 63 % of its final change (the value of 63 % is derived from 1 – 1/e, which equals 0.63). The temporal change of the output signal Y(t) from its initial value Y_0 to its final value Y_f is therefore given by

$$Y(t) = Y_0 + (Y_f - Y_0) \times e^{t / \tau}$$

Gigahertz Optik’s integral detectors use photodiodes that are typically characterized by time constants in µs. Since most variable light sources change their intensity levels in significantly longer time scales, the detector’s time constant is not really an issue for most applications. However, lasers in particular are often pulsed with a frequency in the order of 109 Hz (for example in telecommunication), which corresponds to signal periods in the order of 1 ns. Here, the relatively slow response of normal photodiodes prevents the accurate characterization of the laser signal’s time characteristics.

2.4 The detector’s dynamic range

A detector generally meets the linearity condition for only a limited range of the input signal level. There are two effects that define the boundaries of this **dynamic range:**

- At very low levels of the input signal, the detector’s output is largely dominated by **noise**. Noise is a random temporal fluctuation of the output signal that occurs even when the input signal is constant. The absolute level and the frequency distribution of these variations depend on the physical properties of the detector and the subsequent electronics. For many detectors, noise is largely independent from the absolute level of the input signal and can be neglected for input signals above a certain minimum level. However, for very low input signals, the output signal is dominated by noise and no longer quantifies the physical quantity to be determined. The lower limit of the measurement range, which is posed by noise, is quantified by the **noise equivalent input**. The CIE defines the noise equivalent input as the value of the respective physical quantity (radiant power or luminous flux, irradiance or illuminance, ...) that produces an output signal equal to the root mean square noise output. Since the shape of the noise signal depends on the temporal resolution that can be achieved of the recording electronics (often characterized by the electronics’ time constant), the noise equivalent input is defined for a specific frequency and bandwidth. Unless otherwise stated, a 1 Hz bandwidth is usually considered. Depending on the detector’s characteristics, its noise level can be reduced by longer detector integration times or by averaging subsequent measurements of the same input signal.

- At high levels of the input signal, the detector’s output signal no longer increases proportional to its input signal, and the detector therefore does not meet the linearity condition. Instead, physical limits of the light sensitive element and / or the electronics cause saturation of the output signal. This **saturation** increases disproportionately in relation to the input signal before reaching a constant level. To a certain extent, subsequent correction of the detector’s output signal can account for the effects of saturation and thus extend the detector’s dynamic range. This correction has to be based on a thorough laboratory investigation of the detector’s dynamic behavior and at the same time cause higher measurement uncertainties if the input signal levels are high.

The detector’s dynamic range depends on the type of the photodiode. The dynamic range of the overall measurement system depends on both the detector and electronic meter’s range capabilities. For example, a typical silicon photodiode can measure over 2 mA of current before saturating. However, the upper current measurement range of the meter may be limited to 200 µA.

This range covers extremely low intensity levels, for instance the quantification of erythemally active UV radiation, or very high intensity levels that are used for industrial UV curing processes.

3 Measurement of light with spectral radiometers

A spectrometer enables the spectral decomposition of optical radiation. The term spectral radiometry is used if an absolute calibration is used for the spectrometer.

In general, a spectroradiometer decomposes the impinging light into its spectral components and detects them independently e. g. with the help of a CCD array or a scanning monochromator. In comparison, an integral detector only interprets a signal in terms of its intensity according to its own spectral sensitivity while the spectral information is lost.

Most applications particularly require highly precise spectral information.

3.1 Setup of a spectroradiometer

A variety of optical designs are used for spectroradiometers. The following are the three most commonly used designs in light measurement engineering:

Czerny-Turner setup

In a Czerny-Turner setup, light enters through the entrance slit and is collimated via a mirror towards an optical diffraction grating. It is then decomposed spectrally and sent in parallel rays towards a focusing mirror. This mirror images the spectrally decomposed rays on the detector array. In principle, this is equivalent to the creation of an image of the entrance slit onto the array or the outlet slit through an additional spectral decomposition via the optical grating in the parallelized optical path.

The angle of the optical elements relative to one-another is used to dimension the spectrometer; this helps reduce aberration effects among other things. If only one mirror is used for collimating and focusing instead of two separate mirrors, the setup is called an Ebert setup.

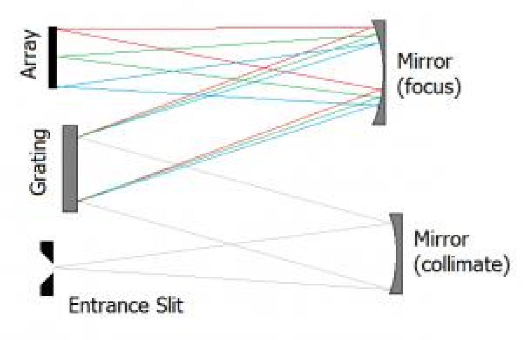

Fig. 1: Czerny-Turner monochromator

Crossover Czerny-Turner monochromator

The crossover Czerny-Turner monochromator aims at an improved optical path, i. e. a reduction of aberration effects. It also enables construction of more compact spectrometers.

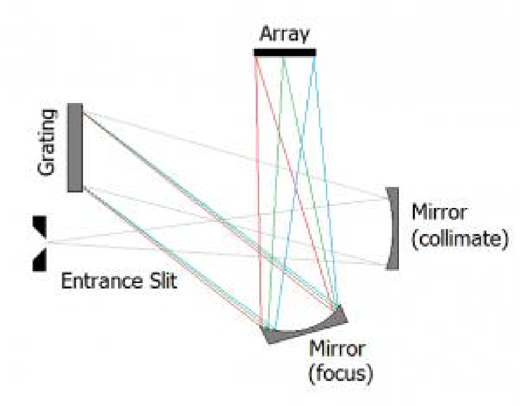

Fig. 2: Crossover Czerny-Turner monochromator

Direct imaging using a curved holographic grating

Special production processes can be used to come up with holographic gratings that enable direct imaging. This helps reduce the required optical elements and hence simply the beam path. It is however limited in the sense that such gratings have to be specifically designed for each application thus reducing their flexibility. In addition, the production costs are enormous.

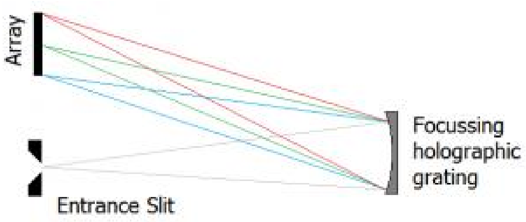

Fig. 3: Setup with a focusing holographic grating

3.2 Parameters of a spectroradiometer

The following sections give information on:

- Wavelength accuracy
- Absolute precision
- Reproducibility
- Pixel resolution
- Optical resolution / bandwidth
- Mathematical bandwidth correction
- Stray light
- Linearity
- Dynamic range
- Dark signal subtraction
- Baseline noise
- Input optics
- Averaging
- Interpolation
- Software
- Data transfer
- BTS technology
- Guideline for spectral measurements (in regards to applications)

Wavelength accuracy

The wavelength accuracy of a spectrometer is defined by a variety of quantities. In principle, the quality of the wavelength calibration presents the most important basis of its precision. For calibration purposes, intrinsic atomic transitions like the line spectra of Hg, Ar, Ne, etc. are used in most cases. Fabry-Pérot interferometers, so-called etalons, are currently also used in order to gain more precise information about the intermediate parts of the spectrum in between the emission lines. These physical emission lines have a very narrow FWHM and are almost undetectable by the spectral radiometers used in light engineering. This means that the lines seem to have a different width based on the bandwidth of the spectroradiometer. This can lead to an overlap of multiple lines particularly in the case of devices with a very broad optical bandwidth. These lines have to be interpreted for the calibration and the respective pixels of the spectrometer array mapped to a wavelength. Interpolation in between the determined sampling points is finally done. Here, it is vital to have enough sampling points over the entire spectrum of the spectrometer. Such an interpolation only offers limited precision. Extrapolation towards the pixels at the boundaries of the spectral range is critical and should be avoided if possible.

In terms of the precision of the calibration, the measuring task must also be taken into account. If for example a gas discharge lamp is supposed to be measured with many closely packed spectral lines (for instance 3 spectral lines with distances of 2 nm), it is impossible to resolve them with a spectrometer that has an optical bandwidth of only 10 nm. The precision is, among other things, limited via the optical bandwidth. In contrast to this, resolving the lines using a spectrometer that has a 2 nm bandwidth (see optical bandwidth) poses no problem at all.

The pixel resolution also has an effect on the wavelength accuracy. If a measurement device has a pixel size of 2 nm and an optical bandwidth of 2 nm, the good optical bandwidth can only be exploited in a limited way due to the small number of pixels. It is recommended to have the length of more than 3 pixels equal the optical bandwidth (see pixel resolution).

The wavelength accuracy, the optical bandwidth and the number of pixels generally have to match. Furthermore, the wavelength calibration over the whole spectral range has to be performed with sufficient precision using a sensible number of spectral emission lines or similar methods.

Absolute precision

The absolute precision of a spectral radiometer depends on the quality of the absolute calibration, the long-term stability of the measurement device, and hence also on the input optics. The quality of the calibration not only requires a certain calibration standard, but also the knowhow and a good equipment of the calibration facility. An absolute calibration is a very complex non-trivial matter.

Besides the calibration, the long-term stability of the measurement device is at least of equal importance since if such a device shows a drift of a few percent each year, it can only give reliable readings for a short amount of time. Since such changes happen over a long amount of time, they often end up unnoticed. Only a recalibration can make such ageing effects apparent. It is generally advisable to perform recalibrations on an annual basis. It might be necessary to perform the recalibration more than once per year if a measurement device shows stability issues. A side effect of this is that the devices are not available for use during recalibration procedures and machining time is lost. Device manufacturers often offer special “do-it-yourself” recalibration options (integrating spheres with calibration standards and software support). In some cases, calibrations on short notice are offered as well.

Basically, the surrounding environment, frequency of use, and storage conditions may influence device stability. Such influences determine the recalibration time cycle. Moreover, the full measurement system should also be taken into account in addition to the measurement device stability. For instance, the system can contain an integrating sphere whose coating might age. This again depends on the coating technology.

Reproducibility

A very high reproducibility of a spectral radiometer’s measurement is the basis for every accurate measurement. This is notably the case for sophisticated measurement tasks. The reproducibility depends on factors like stability of the measurement device, the calibration, noise, correction of environmental effects (like temperature), etc. For binning applications, the stability of the color coordinates may be used as a criterion. A good spectral radiometer provides for example a reproducibility of the x, y coordinates of 0.0001 to 0.0002 for typical white light LEDs.

Pixel resolution

When CCDs or CMOS detectors are utilized in a spectral radiometer, each pixel represents a wavelength. The mapping is defined when calibrating the device's wavelength. At least 3 pixels are necessary; more than 5 pixels are recommended for each bandwidth function of the spectral radiometer. This means that a device with a 2 nm bandwidth should have a pixel size of 0.6 nm or higher. The total number of pixels depends on the spectral range to be measured. A spectral radiometer which spans a wavelength range from 280 nm to 1000 nm at a bandwidth of 2 nm should at least have

$$\left(\frac{1000\text{ nm} - 280\text{ nm}}{2\text{ nm}} \times 5 = 1800\right)\text{ pixels}$$

Optical resolution / bandwidth

The optical bandwidth determines how precise an optical line (like the line spectrum of Hg / Ar) can be measured. Below the optical bandwidth, no spectral details can be resolved by the measurement device. Technically speaking, the optical bandwidth is mainly determined by the combination of the entrance slit, optical grating, and the imaging quality of the device. In the spectrometer, the entrance slit is imaged onto the detector. Depending on the spectral range of the device, this determines the optical bandwidth since the size of the entrance slit's image on the detector equals the optical bandwidth in nanometres. This dependency of the bandwidth on the size of the entrance slit can be exploited to modify the device's bandwidth. Smaller bandwidths offer a more precise resolution of the measurement data but also cause a reduction in signal intensity thus resulting in longer measurement durations. In other words, the optical bandwidth should be matched to the respective application. In general, bandwidths of 5 nm or below are recommended. Bigger bandwidths should only be used if broadband illumination sources are measured or if a mathematical bandwidth correction is applied to the data. Figure 1 shows a line spectrum (of an intrinsic line source) sampled at varying bandwidths. The higher the optical bandwidth is, the broader the sources' spectral peaks are. In addition, their peak intensity also decreases. In the case of broadband sources or, in other words, at multiples of the optical bandwidth, these effects can no longer be defined in such a defined manner.

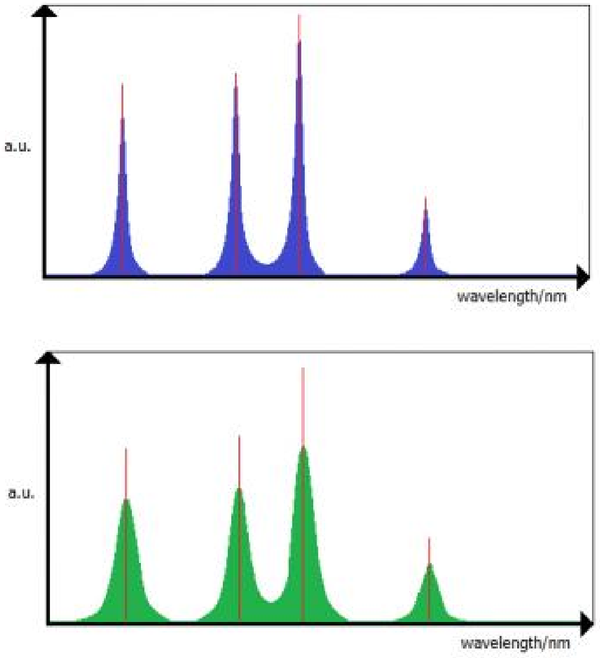

Fig. 1: Effect of the optical bandwidth on a measurement of line spectra

Mathematical bandwidth correction

Different approaches are currently used for mathematical bandwidth corrections. The easiest to implement is the Stearns and Stearns approach [2]. It produces satisfying results but the optical behavior of the measurement device itself cannot be taken into account since the approach assumes a triangular band-pass function. This is largely not the case for an actual measurement and only an inferior quality of the correction can thus be realized.

Ohno and Woolliams refined this methodology in such a way that allows for the measurement and direct correction of the device's band-pass function. These methods have established themselves in the meantime, with the method by Woolliams et al. (2011) [3] being recommended by CIE.

Figure 2 shows a bandwidth-corrected measurement of an LED at a 5 nm bandwidth. If a bandwidth correction is applied, the spectral distribution of the corrected data sets overlap with the reference measurement that was recorded at a bandwidth of 0.5 nm. In other words, bandwidth errors can be reduced or even eliminated using such a mathematical correction.

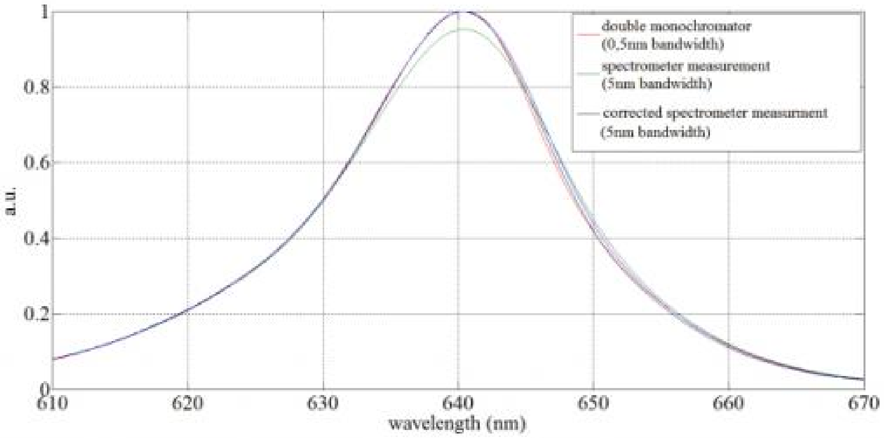

Fig. 2: Bandwidth-corrected measurement

Stray light

The topic of stray light is a rather complex one and cannot be easily summarized. Nonetheless, it is very helpful to understand the causes and effect of stray light. In a simplified manner, one can say that each kind of signal that does not represent the spectrum of the light source under test can be evaluated as stray light. Such signals may for example be caused by scratches on optical surfaces, inter-reflection within the device, grating ghosts, minor quality optical surfaces, etc. There are multifaceted causes that heavily depend on the spectral range. A good spectroradiometer should at least have a stray light suppression of 3 to 4 orders of magnitude. Here, the effects on later applications also have to be taken into account. If for instance measurements in the UV-VIS spectral range are pursued, a high quality stray light correction is required in order to visualize the large dynamic of the measurement. The typically much more pronounced visible signals may worsen the detection limit in the UV range in such a manner that these signals disappear under the stray light contribution. This means that stray light in the visible range produces a certain number of counts per pixel in the UV range which possibly makes the weak UV signal undetectable. In the visible spectral range, this issue may be much less critical since the dynamics of the measured signals is different.

Nonetheless, this topic should still be considered and ideally, a spectral radiometer with only a weak stray light level, or even a radiometer with a mathematical bandwidth correction, selected.

A variety of mathematical stray light correction algorithms can be applied. In case of less complex methods, color filters e. g. that block the UV-VIS signal can be used. This would mean that any remaining signal in this spectral range has to be attributed to stray light. This contribution can be subtracted from later measurements. This method enables a limited but simple and quick option of taking stray light into account.

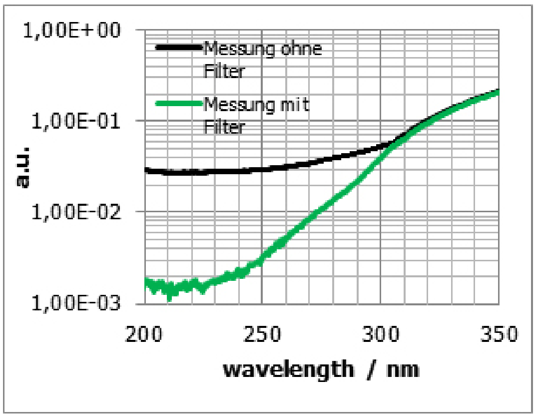

Fig. 3: Stray light correction by subtraction

Much more complex and taxing methods are the methods by Zong et al. (2006) [4] and Nevas et al. (2012) [1]. In order to apply these methods, the spectral radiometer has to be scanned and characterized using a tunable laser; in other words, the device is excited using a single wavelength and the spectral response function recorded. If this is performed using a large number of wavelengths, this methodology can be used to characterize the device over the whole spectral range. This means that the so-called line spread function (LSF) is measured and applied for the corrections.

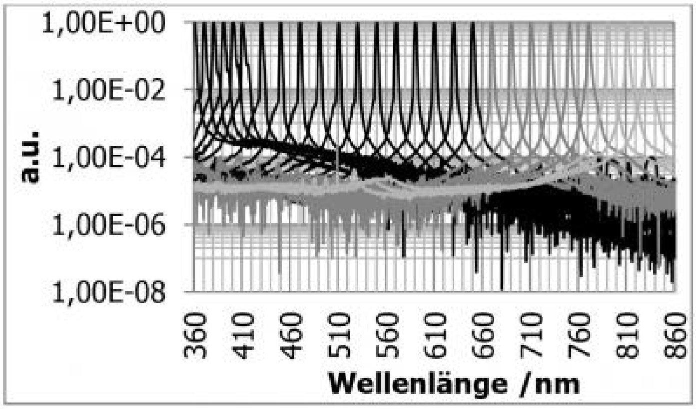

Fig. 4: LSF function of an array spectrometer

Figure 5 shows an uncorrected and a corrected measurement. The results can be improved by about a whole order of magnitude depending on the type of measurement. The LSF method is device-dependent and has to be determined individually for each measurement device. This increases the complexity of this method.

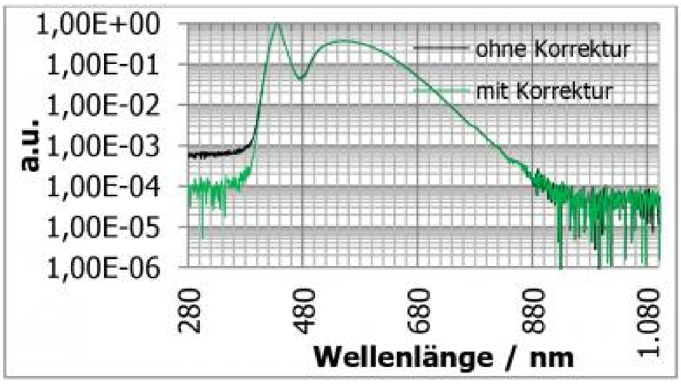

Fig. 5: Stray light corrected LED measurement

Linearity

Linearity is one important property of a spectroradiometer. If a measurement device behaves in a linear manner, a signal x causes a certain number of registered counts y and a signal 100 * x does not cause 97 * y but 100 * y instead. This is a crucial property since if a measurement device does not behave linearly, the measurement uncertainty will be dependent on the input signal. This is the reason why a high quality linearization over the full dynamic range of the device is very important. In most cases, this is performed by mathematical means by means of a linearity calibration curve. Gigahertz-Optik has developed the BTS technology for this purpose. Parallel to measurements with the spectroradiometer, a second set of measurements is performed using a linear diode whose linearity can be used to linearize the spectrometer.

Dynamic range

Most analytic spectrometers are not perfectly suited for light measurements. In this field, many applications span some decades of dynamics and hence the need for specifically designed measurement devices. This kind of dynamics is physically based on the fact that visual sensations are interpreted by the human eye on a logarithmic scale and as a result, the lighting situation in our everyday lives is also subjected to considerable dynamics. Furthermore, measurement devices are typically calibrated at certain intensities that do not have to correspond to their later application. Besides the very good linearity properties, a considerably broad dynamic range of the measurement device is also required. This also takes into account the spectral distributions of luminaires like LEDs or CFLs. These massive requirements have to be fulfilled by measurement devices. In addition to the detector's optical design – CCDs typically have a broader dynamic range than CMOS – the electronics also play a decisive role in determining the dynamic range. Optical density filters are often used to further increase the dynamic range.

Dark signal subtraction

Besides the linearity, wavelength accuracy and stray light, the quality of dark signal subtraction is also of utmost importance when performing measurements using a spectroradiometer. In other words, no signal should be detected by a spectroradiometer if there is no input signal. However, typical CCD and CMOS chips show the so-called base or dark signal. This largely consists of electronic and thermal noise. The signal level rises as the integration time increases – the increase is temperature-dependent. In order to ensure accurate measurement results, the dark signal has to be measured and subtracted from the actual light measurement.

For this to be effective, the dark signal has to be very stable i. e. the light measurement signal must not change during the time between dark and light measurement in order to avoid residual errors after the subtraction.

Furthermore, the dark signal should be kept as small as possible. This can be achieved by cooling to prevent the increase of the dark signal over time. As a rule of thumb, a temperature reduction step of 7° C halves the noise. A stable cooling system can therefore be recommended for a spectroradiometer that is designed for the measurement of small dark signals. This is however a very complex task. The cooling system has to be very stable in order to avoid errors that are induced by temperature changes between the dark and light measurement. A more attractive and elegant solution is offered by extremely short measurement durations. This ensures the dark signals remain low thereby minimizing their influence. Short measurement durations can be achieved by using sensitive back-thinned CCD chips as well as an optical design with a high signal throughput.

In general, each spectroradiometer, whether actively cooled or not, should be given a sufficiently long warm-up-phase in order to ensure it reaches a thermal equilibrium. Only then can stable dark signals be ensured.

Baseline noise

Baseline noise is generally defined as the noise that remains when a dark measurement is subtracted from a signal-free light measurement. This level should consist of a very low number of counts and should remain stable at a constant temperature thus making it possible to use one measurement device for multiple light measurements after a dark measurement. This is an important requirement for the stability of the device. Special spectroradiometers for outdoor measurements must either integrate correction options for temperature variations or allow for very fast dark measurements.

With respect to noise, the question about the number of counts that are required for a good measurement becomes significant as well. It is not possible to give a general answer. Basically, one can say that it primarily depends on the ADC of the spectroradiometer. A 12 bit ADC therefore has a resolution of 4096 counts whereas a 16 bit ADC offers a resolution of 65536 counts. The 16 bit ADC is preferable since it offers a finer resolution. However, a 12 bit ADC may be sufficient depending on the application. The number of counts for a good measurement mostly depends on the signal-to-noise-ratio of the spectroradiometer. If such a device has a baseline noise of 2 counts, measurements with 2000 utility counts can be performed at a SNR of 100. If the noise level is 20 counts, 20000 counts would be required for such a SNR - which is impossible using a 12 bit ADC. In other words, for the interpretation of the noise level, the resolution of the ADC has to be taken into account. A single count of noise with a 12 bit ADC is equivalent to 16 counts of noise with a 16 bit ADC.

Input optics

The composition of the input optics has to be customized for the specific application. For example, measurement of the irradiance requires a high-quality cosine diffuser. For measurements involving integrating spheres, the input optics of the spectroradiometer should be placed at sphere level in order to comply with the LM-79 among other recommendation. For the measurement of the average LED intensity type A or B, specific input optics or measurement adapters are required.

In general, the more stable the design of the input optics and its fitting to the spectrometer is, the more stable will be device’s calibration be. This is of particular importance when a device is used in multiple measurement geometries and has to be modified often. Here, the adapters and other components have to be designed such that they are mechanically and optically reproducible.

Averaging

In order to reduce measurement noise, multiple measurement repetitions and averaging are a common choice. The disadvantage of this method is the multiple measurement duration in respect to the averaging.

Another methodology is to measure neighboring pixels and calculate a weighted average. This leaves the measurement duration unchanged since only a single measurement is required. However, it results in a bandwidth increase and should therefore be performed only with wide spectra.

Interpolation

The resolution of a measured data point is defined by the pixel resolution of the array. Between these points, interpolation is possible without any issues as long as the pixel resolution is significantly larger than the optical resolution. There are several interpolation methods, with the spline interpolation being the most common one.

Software

Besides a good spectroradiometer, a good application software is also important. Among others things, it has to be well suited for spectral analyses, determination of typical measurands, and should also allow for a flexible measuring process. It should include functions such as substitution correction, recalibration and data export in common formats like IES or EULUMDAT for use with a goniometer. The application software should be intuitive and should support application-specific tools.

Besides this extensive requirement profile for an application software, a software development kit (SDK), which supports implementation of measurement device functions into an existing software, is often necessary. In other words, programming access to device functions should also be possible. The software should not have any restrictions in order to prevent application limitations.

Data transfer

In addition to optical parameters, data transfer duration is also an important characteristic. Data from fast measurements has to be available fast. USB and Ethernet connections are established for data transfer, where Ethernet is preferred in highspeed binning.

BTS technology

Spectroradiometers often have linearity issues. Low priced CMOS chips, especially such chips that are not designed for spectroradiometry, are nonlinear. Even the more expensive CCDs do have certain nonlinearities and instabilities. These nonlinearities can be corrected mathematically; but the stability (e. g. of the integrated photometric quantities) cannot be compared with that of a diode. BTS technology strives to combine all advantages of all components. On the one hand, spectral data from spectroradiometry is used to correct the diode's spectral error correction coefficient. The diode's linearity is on the other hand used to correct the data from the CCD or CMOS chip. Both sensors can therefore correct each other very well. Furthermore, BTS devices are advantageous in that continuous (CW) measurements can be done very fast using the diode e.g. in flicker or transient measurements. This is not possible with a spectroradiometer. BTS technology generally enables additional measurement options that are impossible with "normal" spectroradiometers. It is important to keep in mind that in the case of BTS technology, each sensor – the diode as well as the spectroradiometer – is a self-contained measurement system that can be used without the other one.

Guideline for spectral measurements (in regards to applications)

Measurements with a spectroradiometric handheld device

Besides the optical properties, the compactness, robustness and speed are also important for spectroradiometric measurements. In other words, a hand-held has to be able to withstand a certain amount of mechanical stress and also allow sufficiently fast measurements through a high spectral sensitivity. Many applications in which hand-held devices are used are not stable over time. In addition, the movement of the measurement device causes measurements errors. The device should be compact-built to make it ideal for mobile applications and allow for application flexibility. In terms of optical properties, a correction of environmental effects like temperature is also important besides the known photometric parameters. Here, a stable and easily correctable diode, which can correct the spectrometer in return, is recommended. This is for instance taken into account in BTS technology.

Measurements using a spectroradiometric laboratory apparatus

Measurements using a laboratory apparatus require certain flexibility. Such a device should not be limited to a single measurement function; instead, low priced enhancements should increase the number of functions. It is for this reason that a spectroradiometer can be utilized for illuminance measurements by adding a COSdiffuser or for measurement of the total luminous flux by combining it with an integrating sphere. In combination with the COS-diffuser, it can also be used as an illuminance detector head for a goniometer. For this purpose, modularity of the manufacturer is important in order to minimize the additional costs required for the large number of additional measurement devices.

Measurements using an industrial spectroradiometer

Long-term stability, precision and easy integration of the measurement device into a process are often important for industry-grade measurements. This integration refers to both mechanical integration and software implementation. An easy-to-use SDK (Software Development Kit) with extensive control opportunities of the measurement devices is therefore important. Additionally, high data transfer rates – faster than 10 ms for a full data set if possible – as well as extensive triggering options are necessary. In terms of optical properties e.g. in the context of binning, a good wavelength accuracy of ± (0.2 − 0.5) nm, an optical bandwidth between (2 − 5) nm, linearity (e. g. using a linear integral detector), a low stray light contribution (at most 10 − 3 or better), as well as a stable and precise absolute calibration are required. High sensitivity, which can be achieved by using back-thinned CCDs for short measurement durations, and a low noise contribution for good reproducibility are also advantageous. Additionally, a certain modularity and versatility of the manufacturer is helpful as this allows for the matching of optical measurement instruments in an ideal way depending on the measurement situation. For this purpose, standard products like integrating spheres, measurement adapters and the like should be available.

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[1] Nevas S, Wübbeler G, Sperling A, Elster C and Teuber A 2012 Simultaneous correction of bandpass and stray-light effects in array spectroradiometer data *Metrologia* **49** S43

[2] Stearns E I and Stearns R E 1988 An example of a method for correcting radiance data for bandpass error Color Res. Appl.13 257

[3] Woolliams E R, Baribeau R, Bialek A and Cox M G 2011 Spectrometer bandwidth correction for generalized bandpass functions *Metrologia* **48** 164

[4] Zong Y, Brown S W, Johnson B C, Lykke K R and Ohno Y 2006 Simple spectral stray light correction method for array spectroradiometers *Appl. Opt.* **45** 1111-9

4 Calibration of Detectors

Calibration is the determination of the correlation between an input and an output quantity. All measurement instruments, such as voltmeters, manometers, Vernier calipers, etc., must be calibrated to determine the variation of their reading from the absolute quantity. In radiometry, the input quantity is provided by standard lamps and optical radiation detector standards. Because of the many different measurement quantities involved, calibration standards for each quantity are required if an optical radiation calibration laboratory hopes to cover the whole range of possible calibrations. A “traceable” lab calibration standard should show an unbroken chain of links to national (better international) standards. However, this in itself does not guarantee accuracy or ability of the lab to meet its calibration uncertainty claims. Since calibration standards are subject to change with age and use, the calibration of the standards themselves must also be checked periodically. This at times means replacing the standards in order to maintain the calibration and traceability quality. The end user of the calibrated product may be required to audit the calibration facility to ensure its competency and traceability. In Germany, the *Deutsche Kalibrierdienst* (*DKD*, the German accreditation institution) and the *Physikalisch-Technische Bundesanstalt* (the German national standard laboratory) offer an accreditation service for industrial calibration laboratories where the lab’s calibration standards, calibration procedures and the stated re-calibration intervals are subject to auditing. This accreditation ensures that the traceability of the calibration is on an absolute level. The DKD also ensures the international acceptance of its accredited calibration laboratories. More information on national calibration organizations.

Fig. 1: Gigahertz-Optik calibration engineer

4.1 Traceability: an Unbroken Chain of Transfer Comparisons

Calibration is the most important prerequisite for accuracy in measurement instrumentation. It is the foundation upon which subsequent measurements are based upon. Optical radiation calibration is typically done by the transfer method where the relationship between the value indicated by a measuring instrument and the value represented by a calibration standard is compared with the former reading, adjusted as needed, recorded and certified. Since the reading of a meter-under-test is directly compared with that of the transfer standard, the qualification of this standard is of the highest importance.

A qualified standard should display an unbroken chain of transfer comparisons originating at a national standards laboratory. For example, the transfer standard of the national laboratory, primary standard (A) is used to calibrate the reference standard (B) at an accredited calibration laboratory. This reference standard is used to calibrate the laboratory work standard (C) to be used daily by the calibration lab. This work standard is then used to calibrate the final product (D) or device under test. The calibration path is thus described as A–B–C–D. This path is called the chain of traceability. Each transfer device in the chain should be subjected to periodic examination to ensure its long-term stability. The lab performing the calibration typically sets the time span between examinations and is self-audited.

Accredited calibration laboratories guarantee recalibration cycle times for their standards plus a review of their calibration procedures since they are subject to review by an official accreditation authority.

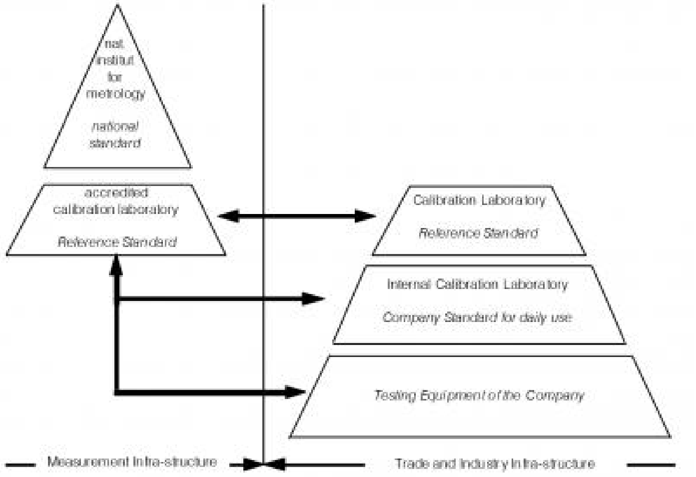

Fig. 1: Calibration hierarchy from primary standard to test equipment

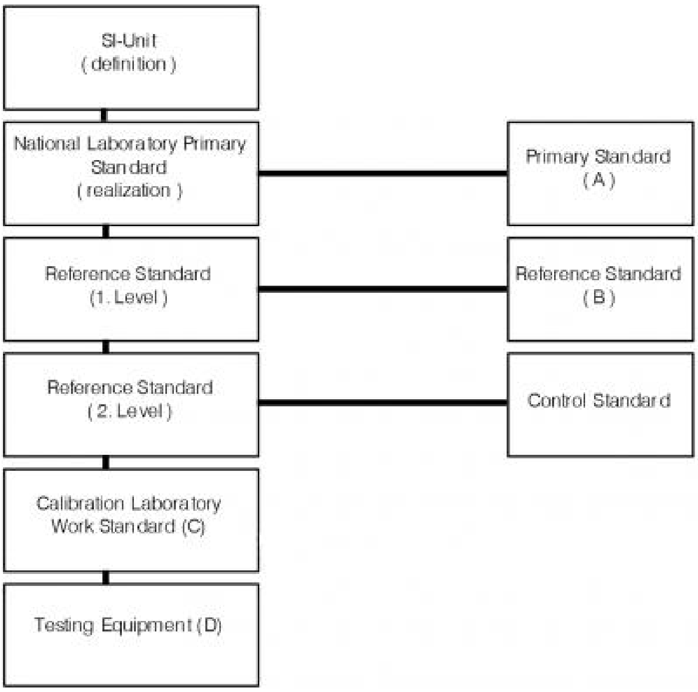

Fig. 2: Hierarchy of standards

4.2 ISO / IEC / EN 17025 (formerly ISO Guide 25 and EN 45001)

The aims of the General Requirements for the Competence of Calibration and Testing Laboratories are to provide a basis for use by accreditation bodies in assessing the competence of laboratories, establish general requirements for demonstrating laboratory compliance to carry out specific calibrations or test, and assist in the development and implementation of a laboratory's quality system. DKD accredited calibration laboratories fulfil the requirements of the European standard EN 45001 (general criteria to operate a testing laboratory, May 1990) without exception. This standard is not compulsory outside Europe. The ISO/IEC Guide 25 (General requirements on the competence of testing and calibration laboratories, December 1990) is recognized instead. The EN 45001 and ISO/IEC Guide 25, also known as ANSI/NCSL Z540-1 in the United States, are identical in terms of content. They form the basis for the mutual appreciation between the European cooperation for Accreditation (EA) and its partners outside Europe. In 1999, ISO/IEC 17025 took the place of EN 45001 and ISO/IEC Guide 25 thereby eliminating any formal differences.

4.3 Calibration Quantities

The following sections give information on:

- Spectral Precision
- Spectral Irradiance – W cm^{-2} nm^{-1}
- Spectral Radiance – W cm^{-2} sr^{-1} nm^{-1}
- Spectral Responsivity
- Illuminance Sensitivity – lux
- Luminance Sensitivity – cd/m^2
- Color Sensitivity
- Irradiance Sensitivity – W/m^2
- Spectral Reflectance
- Spectral Transmittance

Spectral Precision

Spectral calibration is usually performed using atomic intrinsic lamps e. g. Hq, Ne, Ar and Kr lamps. The wavelengths of these emission lines are perfectly known from atomic physics theory and can be used to calibrate spectral measurement devices such as array spectrometers or monochromators.

Spectral Irradiance – W cm^{-2} nm^{-1}

Irradiance (W/m^2) measured as a function of wavelength (nm) is known as spectral irradiance. This type of source calibration is performed using a spectral measurement device or spectroradiometer in comparison with a reference standard. The spectral range of the calibration depends on the source and spectral range of interest. A typical QH lamp can be spectrally scanned from 200 nm to 2500 nm using a fixed wavelength increment or variable bandwidth depending on the required resolution.

Spectral Radiance – W cm^{-2} sr^{-1} nm^{-1}

Radiance (W/cm^2 sr) measured as function of wavelength is called spectral radiance. Radiance in a given direction, at a given point of a real or imaginary surface is the optical unit used to calibrate optical radiation sources. Calibration is normally performed using a spectral measurement system or spectroradiometer equipped with a radiance lens assembly that has been calibrated using an integrating sphere-based radiance standard. The spectral range of the calibration depends on the source and spectral range of interest. A full spectral scan may cover wavelengths ranging from 350 nm to 2500 nm.

Spectral Responsivity

The sensitivity of optical radiation detectors, photodetectors and photodiodes changes depending on the wavelength. This spectral responsivity can be measured as a relative responsivity (as a percentage) across the active wavelength bandpass of the photo-device. For example, a silicon device scan could cover the wavelength range from 250 nm to 1100 nm at a set increment whereas a GaAsP photodiode covers a range between 250 nm to 700 nm. The increment setting could span from 1 nm to 50 nm depending on the required resolution. In some cases, the single point response at a particular wavelength may be all that’s required for some applications. Calibrations are performed by transfer comparison and certified against qualified reference standards.

Fig. 1: InGaAs Detector with sphere. Relative spectral response plot

Illuminance Sensitivity – lux

Calibration of the illuminance response of photopic detectors is normally performed as a transfer comparison with a photopic reference standard. The photometric responsivity of the reference standard can be qualified through radiometric measurement using red, blue and green filtered photodetectors. However, this is a complicated procedure that is often left to advanced radiometry laboratories. Illuminance sensitivity calibrations allow for direct reading of the photopically corrected detector in lux or footcandles. Most illuminance calibrations are mostly done using a tungsten source. If the photopic detector’s spectral response does not match the CIE photopic curve to a certain high degree, errors will occur when performing measurements on different types of sources.

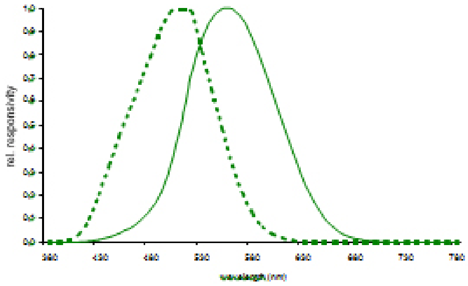

Fig. 2: CIE scotopic and photopic function

Luminance Sensitivity – cd/m^2

Luminance responsivity of photopic detectors equipped with field limiting input optics is achieved through comparison with a luminance reference standard detector. A uniform luminance field of is produced using a calibration source that has an integrating sphere or a source with an optically diffuse material. The luminance detector’s field of view is confined to a narrow angle so that the detection area is overfilled with a sample of the uniform luminance field. Luminance detectors are calibrated for measurements in the optical units of candela per square meter and foot-lamberts.

Color Sensitivity

Broadband colorimetric detectors are calibrated through comparison with reference standards based on CIE tristimulus values using a light source of known color temperature. Color temperature, luminance and illuminance calibrations may be included depending on the color meters capability. The color meter is calibrated to display the color chromaticity coordinates (x, y and / or u', v') of the light source under test.

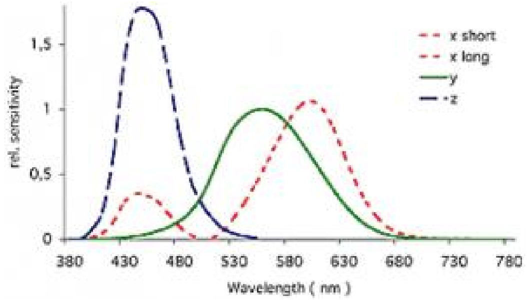

Fig. 3: Color detector tristimulus functions

Irradiance Sensitivity – W/m^2

Broadband irradiance detector calibrations are performed through transfer comparison with reference standards in respect to the spectral characteristics of the detector to be tested. Reference detectors are calibrated against spectral irradiance measurements using a double monochromator spectroradiometer, which has been calibrated using traceable spectral irradiance standards. Irradiance detectors are calibrated to display measurement values in the optical units of watts per square meter or watts per square centimeter over a specific wavelength range.

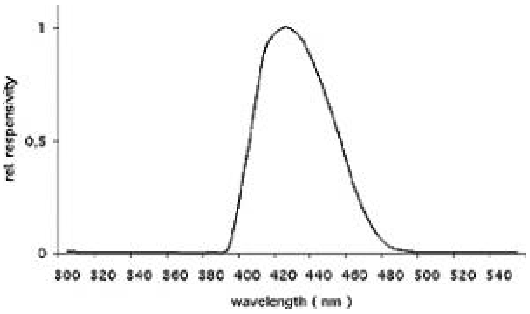

Fig. 4: Blue spectral response irradiance detector

Spectral Reflectance

Calibration of the spectral reflectance of materials is accomplished through comparison with reference reflectance standards that are used in the calibration of the spectrophotometric instrument used to perform the measurement. Single or double beam spectrophotometers can have a spectral range between 250 nm and 2500 nm with adjustable wavelength increments. When coupled to an integrating sphere, the spectrophotometer can be used to separately measure the total hemispherical, diffuse and specular reflectance. Without the sphere, the inline spectrophotometer setup only measure the normal specular reflectance component.

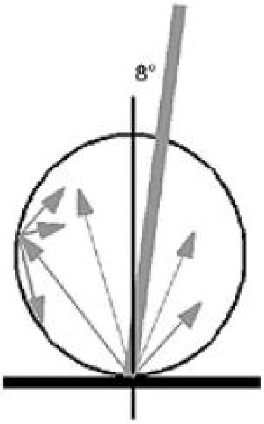

Fig. 5: 8 Degree reflectance measurement setup

Spectral Transmittance

Calibration of the spectral transmittance of materials is done through comparison with reference transmission standards that are used in the calibration of the spectrophotometric instrument used to perform the measurement. Single or double beam spectrophotometers can have a spectral range between 250 nm and 2500 nm with adjustable wavelength increments. When coupled to an integrating sphere, the spectrophotometer can be used to separately measure the total hemispherical, diffuse and regular (specular) transmittance. Without the sphere, the in-line spectrophotometer setup only measures the regular reflectance component. Calibration is performed as a percentage transmission against the wavelength.

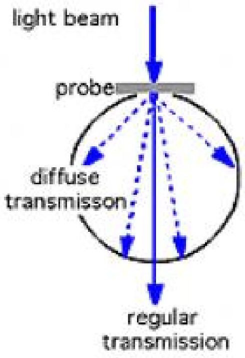

Fig. 6: Transmission measurement setup

4.4 Calibration Standards

Calibration standards are employed to generate an input quantity for the equipment used in the calibration. Since the calibration standard supplies a signal of known quantity, the difference of the output signal of the equipment to the signal of the calibration standard can be evaluated. These differences can then be used to calculate calibration correction factors and hence allowing for absolute readings when the output signal is corrected using these values. Different calibration standards are needed for photometric and radiometric measurement quantities:

Photometric quantity	Radiometric quantity
Luminous flux	Radiant power
Luminous intensity	Radiant Intensity
Luminance	Radiance
Illuminance	Irradiance

Tab 1: Photometric and radiometric quantities

Equivalent photometric and radiometric quantities exist if the measurements and hence the calibration geometries are the same. The only difference is the radiometric or photometric responsivity of the detection system. This means most calibration reference standards can be used for both photometric and radiometric calibration if the calibration data is available. For very precise or close tolerance calibrations, specially selected calibration standards are needed. Typically, calibration standards are used as transfer standards, meaning they transfer the values of the primary standard to a laboratory standard for subsequent transfer to a device under test. For traceable calibrations, an unbroken chain of transfer comparisons, which can be traced back to the national primary standard, is certified. Calibration uncertainty is of course dependent on the calibration hierarchy of the standard. Since the calibration transfer is a real hardware transfer of the standard itself, careful handling and operation of the calibration standard is extremely important. In imaging applications, the uniformity of response or transmittance is critical. Light sources with a uniform luminous area are therefore needed to determine the non-uniformity of a lens system or visual imaging detection system.

The following sections give information on:

- Source Based Standards
- Detector Based Standards
- Spectral Irradiance Standards
- Luminance Standards
- Spectral Radiance Standards
- Spectral Responsivity
- Reflectance Standards
- Geometry Adjusted Calibration Standards

Source Based Standards

Every optical radiation detection or measurement system needs to be calibrated in reference to an optical radiation source. There are two possible ways to perform the calibration:

- The source can be calibrated in the required quantity and the difference between the input signal generated by the source and the output signal of the detection system can be determined using the calibration data of the source
- The uncalibrated source can be operated under stable conditions and the calibration done by comparing the reading of the detection system with a calibrated detection system (reference standard). The reference standard must have the same measurement geometry and spectral response as the unit to be calibrated.

The most common optical radiation source used for calibration standards is the tungsten halogen lamp since its emission spectrum is close to a Planckian radiator (blackbody source). Other sources where optical radiation is produced by means of an element heated to incandescence by electrical current are also used. Both the position of the filament and the stability of the tungsten halogen lamp, which has a limited lifetime, are critical. Therefore, the lamp should only be operated in the position specified in the calibration certificate. Comparing the lamp output with other in-house reference standard sources or suitable reference detection systems must be done periodically in order to verify the stated lamp calibration uncertainty. In radiometric applications where the spectral characteristic of the source is used, the source should be operated in current controlled mode so as to ensure stability of the spectral characteristics. The minimum specification for current stability should be held at 10 A – 4 A. In photometric applications or radiometric applications with broadband detectors, intensity controllable standards can be used if changes in the spectral emission characteristics are not critical. If the tungsten halogen lamp is used as a spot source, the exact location on the filament used dur ing the calibration of the source must also be used subsequently. In luminance, radiance and imaging uniformity calibrations, tungsten halogen lamps must be fitted with a diffuse screen or placed within an integrat ing sphere. Sphere based luminance and radiance standards offer higher uniformity and a better diffuse function.

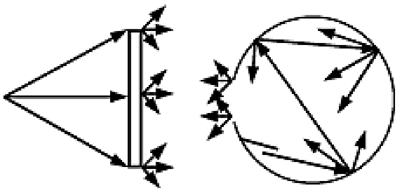

Fig. 1: Diffuse screen and integrating sphere

A diffuse transmitting screen can be used at the sphere output in the calibration of luminance and radiance meters with a limited field-of-view. In imaging applications, the uniformity and the diffuse function of currently available screen materials are not precise enough and thus, the open output port of the sphere is typically used. If the intensity of the tungsten halogen lamp is not high enough, which is the case especially in the UV range, arc lamps such as xenon lamps may be used. However, the increase in intensity can affect the calibration uncertainty.

Detector Based Standards

Due to the high levels of maintenance and care required to operate optical radiation source based calibration standards, detector based standards are very attractive alternatives. The detectors, particularly semiconductor detectors, have the advantage of long-term absolute and mechanical stability. The use of detector-based standards is very common in monochromatic radiometric applications such as the calibration of laser power meters for telecommunication testing. However, the use of detector based calibration standards must be carefully considered because of surface reflections, polarization effects, beam misalignment and beam ‘bounce-back’ errors. The use of spectrally broadband detectors as calibration standards is mostly limited to photometric applications where detectors with a precise filter corrected photometric spectral response are available. Calibration is performed by comparing the output signal of the reference detector to that of the device to be calibrated. The same stable source of optical radiation is used during the calibration procedure. For monochromatic calibrations, a monochromatic radiation source is needed. If a detector’s spectral responsivity is to be measured over its entire active bandpass, a tungsten halogen lamp with a monochromator attached to it can be used to create monochromatic radiation at all of the different required wavelengths.

Spectral Irradiance Standards

Tungsten Halogen lamps are the “workhorse” of spectral irradiance standards. FEL type lamps with a filament support arm are recommended for high intensity BLUE light and UV applications.

Fig. 2: FEL calibration standard lamp

Sylvania calibration grade lamps are recommended for visible and near IR applications where the best long term stability is required. In order to qualify for calibration as a standard, each lamp must undergo at least a 15-hour burnin procedure and must display a satisfactory burnin data trend during this period. The calibrated tungsten reference source provides spectral irradiance data from 250 nm to 2500 nm covering many typical UV-Vis-IR radiometric and photometric applications. The lamp is normally provided in a housing and socket made of ceramic or other material that ensures long-term stability and protection. Filament targeting aids may be provided for best measurement accuracy in the calibration laboratory. Since the lifetime is somewhat limited, lamp power supplies with on/off ramping functions are recommended for use with these sources.

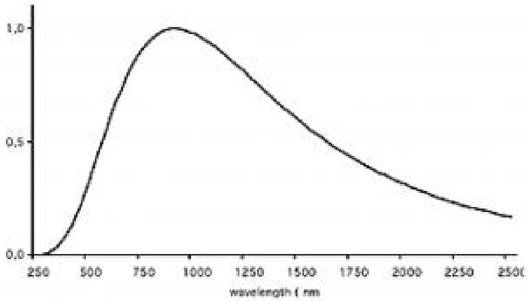

Fig. 3: Lamp spectral distribution

Luminance Standards

Luminance reference sources are used to calibrate the uniformity of imaging systems and luminance output of luminance meters, spot exposure meters and other photometric equipment.

Fig. 4: Luminance standard

The standard is constructed around the integrating sphere of various diameters designed to provide the highly uniform diffuse luminance at the exit port that is required for this type of calibrations. The spheres might be coated with barium sulfate or made using optically diffuse plastics. Seasoned tungsten halogen sources are typically used with lamp power supplies and temperature stabilized photometric reference detectors to form the complete system. Control feedback loop techniques control the luminance output intensity and help prolong the useable lifetime of the system. Any change in ambient and sphere body temperature affecting the output signal is eliminated through the temperature stabilized reference detector. This also reduces system warm-up time. An optimally designed sphere layout is capable of less than ± 0.7 % non-uniformity over 90 % of the port opening, which can be as large as 100 mm in diameter. Less than ± 5 % angular uniformity within ± 40° enables luminance output calibration of detection systems with wide acceptance angles. Luminance outputs can range from 0.5 cd/m^2 to 35000 cd/m². Some standards may offer a variable luminance output requiring more sophisticated electronics, multiple lamps and exhaust fans. In order to qualify as a calibration standard, the system itself must be calibrated by a competent calibration facility. Luminance output, uniformity and angular uniformity must be measured and certified.

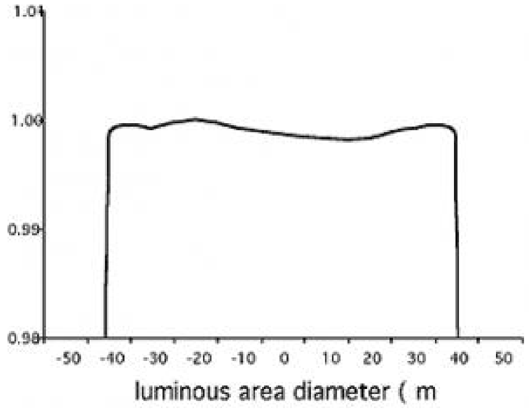

Fig. 5: Typical luminance uniformity response plot

Spectral Radiance Standards

Radiance reference sources are used to calibrate radiance detectors and other radiometric equipment. The standard is constructed around the integrating sphere of various diameters designed to provide the highly uniform diffuse radiance at the exit port that is required for this type of calibrations.

The spheres might be coated with barium sulfate or made using optically diffuse plastics. Seasoned tungsten halogen sources are typically used with lamp power supplies and temperature stabilized photometric reference detectors to form the complete system. Control feedback loop techniques control the luminance output intensity and help prolong the useable lifetime of the system. Any change in ambient and sphere body temperature affecting the output signal is eliminated through the temperature stabilized reference detector. This also reduces the system warm-up time.

An optimally designed sphere layout is capable of less than ± 0.7 % non-uniformity over 90 % of the port opening, which can be as large as 100 mm in diameter. Less than ± 5 % angular uniformity within ± 40° enables luminance output calibration of detection systems with wide acceptance angles. Some standards may offer a variable radiance output requiring more sophisticated electronics, multiple lamps and exhaust fans. In order to qualify as a calibration standard the system itself must be calibrated by a competent calibration facility. Radiance output, uniformity and angular uniformity must be measured and certified.

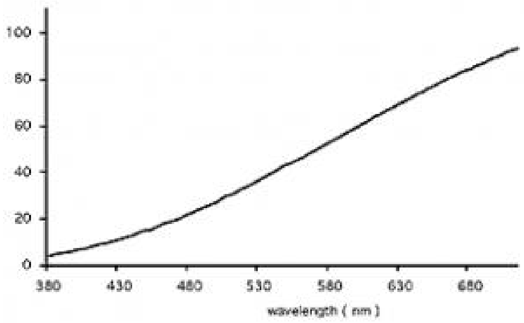

Fig. 6: Typical spectral radiance plot Plot

Spectral Responsivity Standards

Due to their long term stability and broad spectral coverage, silicon photodiodes are used as reference spectral standards by national and private calibration laboratories worldwide.

Fig. 7: Detector calibration standard

These photodiodes, which have active areas that are as large as 100 mm^2, are mounted into machined housings to protect and precisely fix the detector in a calibration setup together with targeting aids. Some housings may include an integral temperature sensor to monitor thermal characteristics during test sessions. In order to ensure best measurement uncertainty, temperature stabilization using cooling jackets that maintain the device temperature to within ± 0.5 °C are also used. UV enhanced Si devices offer spectral coverage from 250 nm to > 1100 nm. Calibration with certification from an accredited traceable calibration facility is required to qualify the device for use as a reference standard.

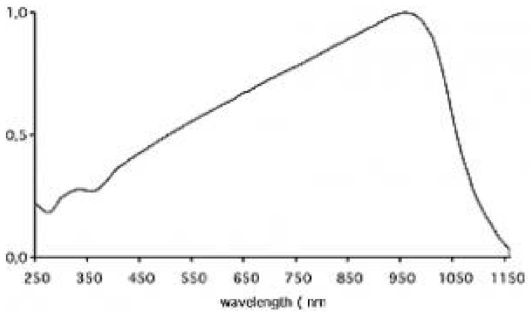

Fig. 8: Typical spectral responsivity plot of Si PTD

Reflectance Standards

White optically diffuse reflectance standards traceably calibrated for spectral reflectance over a spectral range from 250 nm to 2500 nm are used in the calibration of reflectance meters, optical distance measurement systems, densitometers, spectrophotometers and other optical and imaging systems. Qualifications of a reflectance standard include light and temperature stability and durability near the Lambertian diffuse reflectance and up to 98 % spectrally neutral reflectance over the spectral range of interest. Processed PTFE, which is cut into various shapes and thicknesses, is currently used for reflectance standards. High reflectance white, black and gray shades at varying reflectance values are available.

In order to maintain the quality of a calibrated standard, the standard is normally mounted into a protective housing with a removable lid to keep the material clean and covered when not in use.

Fig. 9: Optically diffuse reflectance standards

Geometry Adjusted Calibration Standards

For sophisticated measurement tasks, the type of calibration lamp becomes very important. For example, when measuring the total luminous flux of LEDs within an integrating sphere, the system should be calibrated to match the radiation distribution of the LED. **The “compare like with like”** basic principle applies. If a measurement system is typically used to characterize LEDs that only emit light into a half-space, this should also apply for the calibration light source. For this kind of calibration, only 2π standards should be used.

5 Detector Signal Measurement

A typical light detector or photoactive device converts impinging photons into a current or voltage proportional to the incoming signal. The detector connects to an electronic meter for amplification, possible conversion from an analog to digital signal (ADC), calibration and display of the measurement result. Together, the meter, photodetector and accessory components form an optometer, radiometer, photometer, color, laser or optical power meter and reflection/transmission measurement systems. A radiometer consists of a voltage or current meter coupled with a radiometric type detector. Photometers employ the same meters used with photometric type detectors. Multi-channel color meters are used with colorimetric detectors to display multiple quantities. The optometer is a term used to indicate that the meter can be used with either radiometric or photometric type detector heads. Microprocessor controlled units capable of measuring currents ranging from tenths of picoamperes up to a few milliamperes are available. This allows full utilization of the sensitivity range of most photosensitive devices. Measurement methodology might employ 16-bit signal digitization by means of an analog to digital converter (A/D) with sampling rates in the microseconds range. Selectable averaging calculation of the sampled results from microseconds to seconds provides more measurement flexibility for fast events or lowlevel signals. The device can be operated via a logical menu structure where user input is done through a front-panel keyboard or computer control via RS232 or IEEE computer interface.

The quantity or optical unit measured will depend on the detector type, its configuration in terms of filtering and input optic, and its calibration. Radiometers are available in hand-held mobile and bench-top models for laboratory use. Selfcontained cordless models are used for remote dynamic monitoring where a standard detector that connects to the meter via a cable might foul. Capabilities such as dynamic measurement range, operating modes (example: CW, dose, pulse energy) and features (example: auto-ranging, backlit display, digital interface, data logging) differentiate the various models. The type of application usually determines the specific capabilities that a radiometer system should have. For example, in a UV curing production process where multiple stations must be monitored, a multi-channel radiometer with an adjustable minimum / maximum reading feature, RS232 or IEEE interface and remote multiplexed detectors would be desirable.

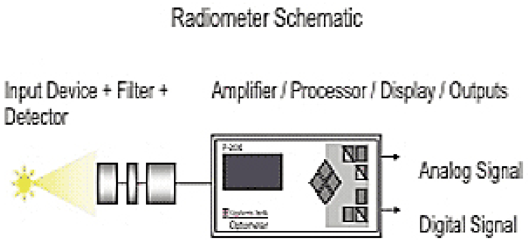

Fig. 1: Radiometer schematic

Source (valid as of 2002): http://www.coolibar.com/skin-cancer-in-the-us.html

The following is a list of various features, modes of operation and specifications offered in current light meters. Note that available features and functions will vary depending on the type of meter and manufacturer.

Operating Modes and Features	CW	*Continuous wave* is a run of continuous type measurements. The measurement frequency depends on the *integrating time* and the maximum *sampling rate* of the meter

CW Min / Max	CW measurement where the minimum or maximum value that occurred during the measurement run will be displayed. The min. or max. value can be reset via the RESET switch.
CW Level Check	CW measurement where the measurement values are compared with min.- max. threshold values. The threshold values are entered into the meter by the user.
CW Level Minimum / Maximum	Menu to adjust the threshold values for CW Level Check.
Run / Hold	Freezes a measurement value on the display and stops the continuous measurement.
Relative Ratio (%)	Measurement value as the relative ratio of a reference value (stored in the optometer) or a reference measurement value (2-channel optometer required).
Relative Ratio Factor	Measurement value as the relative ratio factor of a reference value (stored in the optometer) or a reference measurement value (2-channel optometer required).
Attenuation (dB or dBm)	Measurement value as the logarithmic ratio factor (attenuation) of a reference value e.g. dBm (stored in the optometer) or a reference measurement value e. g. dB (2-channel optometer required).
Dose	CW measurement values integrated over the dose measurement time. A preset dose measurement time or a max. dose value will stop the measurement.
Data Logger	Each measurement value of a CW measurement will be

	individually saved in the memory of the optometer. Each measurement may be triggered manually or automatically through a preset measurement cycle time. Measurement data can be output via a computer interface.
Color	Chromaticity coordinates (x,y and u',v') and the correlated color temperature are calculated from the ratio of the detector‘s signals.
Peak Maximum	Each CW measurement interval consists of a certain number of samples (number depends on integration time and sampling rate). Peak Maximum is the highest positive sample of a measurement interval. A new peak maximum is calculated and displayed for each measurement interval.
Peak Minimum	Each CW measurement interval consists of a certain number of samples (number depends on integration time and sampling rate). Peak Minimum is the least negative sample of a measurement interval. A new Peak Minimum is calculated and displayed for each measurement interval.
Peak to Peak	Each CW measurement interval consists of a certain number of samples (number depends on integration time and sampling rate). Peak to Peak is the difference between the highest and least sample of a measurement interval. A new Peak to Peak value is calculated and displayed for each measurement interval.
I-Effective	Measures and calculates the energy

	of light pulses based on the Schmidt-Clausen formula. The input signal is sampled with the max. sampling rate for one measurement interval (Pulse Measurement Time). First, the pulseenergy is calculated by integrating the samples. IEffective is calculated by using the pulse-energy and the peak-value of the measurement interval using the following formula: I-Effective = peak-value * pulse-energy / (peak-value * C + pulse-energy) C = IF-Time Constant (between 0.1 s and 0.2 s, depending on application)
IF Time Constant	Factor C for calculation of I-Effective (Schmidt-Clausen).
Pulse Energy	Measures and calculates the energy of light pulses. The input signal is sampled with the max. sampling rate for one measurement interval (Pulse Measurement Time). The energy is calculated by integrating these samples.
Pulse Measurement-Time	Measurement interval for I-Effective and Pulse Energy measurements.
Remote RS232	Enables RS232 interface of the device. RS232 is a standard for asynchronous transfer between computer equipment and accessories. Data is transmitted bit by bit in a serial fashion. The RS232 standard defines the function and use of all 25 pins of a DB-25 type connector. The

	basic configuration uses 3 pins (of a DB-9 type connector): ground, transmit data and receive data. On PCs, the RS-232 ports are either marked as “serial” or “asynch” and are either of 9 or 25 pin male type.
Remote IEEE488	The device’s IEEE488 interface is enabled. IEEE488 is a standard for parallel transfer between computer equipment and measurement instruments. Data is transmitted in a parallel fashion (max. speed 1MByte/s). Up to 31 devices (with different addresses) can be connected to one computer system.
USB	A communication standard that supports serial data transfers between a USB host computer and USB-capable peripherals. USB specifications define a signaling rate of 12 Mbs for full-speed mode. Theoretically, 127 USB-capable peripherals can be connected to one USB host computer. The connected devices can be powered by the host computer.
Ethernet	Is a technology that specifies software (protocols, etc.) and hardware (cables, distribution stations, network interface cards, etc.) for tethered data networks. It was originally intended for local area networks and hence the term LAN technology. It enables data exchange via data frames between locally tethered devices (computers, printers and the like) within the network. Currently, transfer rate of 10 Megabit/s,

	100 Megabit/s (fast Ethernet), 1000 Megabit/s (Gigabit Ethernet), as well as 10 Gigabit/s, 40 Gigabit/s and 100 Gigabit/s are specified.
Auto Range	When activated, the measurement range is automatically switched by the device to the optimal value (depending on the input signal).
Manual Range	When auto range is disabled, the measurement range can be manually fixed to a certain value. The device is not allowed to automatically switch measurement ranges. Manual range adjustment can be useful in cases where input signals change rapidly.
Calibration Factor	Optical sensors transform optical signals into current. This current is measured by the device. *The calibration factor determines the relationship between the measured current and the calculated and displayed measurement result (optical signal).*
Offset	The offset value is subtracted from the measured signal to calculate the result. The offset can be set to zero or to the measured CW-value. This function is useful in compensating for the influence of ambient light or if the measurement value is very small with regards to the adjusted measurement range.
Integration Time	Time period for which the input signal is sampled and the average value of the sampled values calculated (> CW). Integration time should be selected carefully. For example, if multiples of

	20 ms (50 Hz) are selected as the integration interval, errors produced by the influence of a 50 Hz AC power line can be minimized.
Sampling Rate	The rate which specifies how often the input signal is measured (sampled). The CW value is calculated using the average value of all samples of one measurement interval (integration time). A sampling rate of 100 ms means that 10000 samples per second are taken. If the measurement interval (integration time) is 0.5 s, there are 5000 samples used to get the CW value.

Tab. 1: Operating Modes and Features

Specifications

Slew rate	Shows how fast a signal changes. For example, a rate of 5 volt/ms means that the signal changes with a value of 5 volts every millisecond.
Rise time	Time needed for a signal to change from 10 % to 90 % of its final value.
Fall time	Time needed for a signal to change from 90 % to 10 % of its start value.
Input Ranges / Measurement Range	In order to achieve a dynamic measurement capability greater than six decades, different levels of measurement ranges (Gains) for the “current to voltage input amplifier” are necessary. Gains can span from 1 V / 10 pA to 1 V / 1 mA (depending on the device).
Linearity	The linearity of an optometer can be described as follows: Reading a value of 10 nA, with a max.

	gain error of 1 %, the possible error is ± 0.1 nA. Together with an additional offset error of 0.05 nA, the total measurement uncertainty would be 10 nA ± 0.15 nA or 1.5 %.
	At a reading of only 1nA in the same gain range, the gain error would be 1 % of 1 nA or 0.01 nA. The offset error would still be 0.05 %. The total measurement uncertainty would be 1 nA ± 0.06 nA or 6 %. The offset error is minimal with our optometers since these meters offer an internal offset compensation or allow an offset zero setting from the menu. Here, the only offset error is from the display resolution or the nonlinearity of the analog-digital converter (ADC).
Measurement Accuracy / Linearity	The max. possible error of a measurement result can be calculated as follows:
Total Error	Gain error + offset error
Gain Error	Displayed (or readout) result X (Gain Error (in percent) / 100)
Offset Error	Constant value depending on measurement range
	The offset error can be eliminated through offset compensation. Some errors cannot be compensated for because they are produced by the nonlinearity of the ADC (Analog Digital Converter) and the display resolution.
Maximum Detector Capacitance	The input current-to-voltage amplifier is sensitive to input capacitance. If the input capacitance is too large, the amplifier may oscillate. The maximum detector capacitance is the largest value of capacitance for which the

	amplifier will remain out of oscillation.
Measurement Range	The measurement range is typically specified by the resolution and the max. reading value. The user should however note that for a measurement with a max. measurement uncertainty of 1 %, the min. measurement value should be a factor of 100X higher than the resolution. On the other hand, the max. value may be limited by the detector specifications such as max. irradiation density, max. operation temperature, detector saturation limits, etc. and therefore the manufacturer‘s recommended measurement values should be adhered to.

Tab. 2: Specifications

6 Theory and applications of integrating spheres

Integrating spheres are very versatile optical elements designed to achieve homogenous distribution of optical radiation through multiple Lambertian reflections at the sphere's inner surface. The primary radiation source can either be located inside the sphere or in front of the source's entrance port. In the latter, only the optical radiation entering the sphere is relevant for the sphere's internal radiation distribution.

As long as we restrict ourselves to those regions that are shielded from direct irradiation by the primary source and are thus only illuminated by reflections at other of the inner surface, the theory of the ideal integrating sphere leads to two important conclusions:

- Irradiance of the sphere's inner surface is proportional to the total radiant power either emitted by a source inside the sphere or entering the sphere through its entrance port. Geometrical and directional distribution of the primary source's radiation do not influence irradiance levels as long as direct illumination of the respective location is prevented. This property becomes important particularly when an integrating sphere is used as the input optical element of a detector for radiant power.

- Radiance reflected by a region of the sphere's inner surface shielded from direct illumination is constant in its directional distribution and independent from the specific location where the reflection occurs. Thus, the sphere's exit port can be used as an ideal Lambertian source since optical radiation leaving the sphere is characterized by homogenous radiance and exitance distributions. This property becomes important particularly when a sphere is used as a standard calibration source.

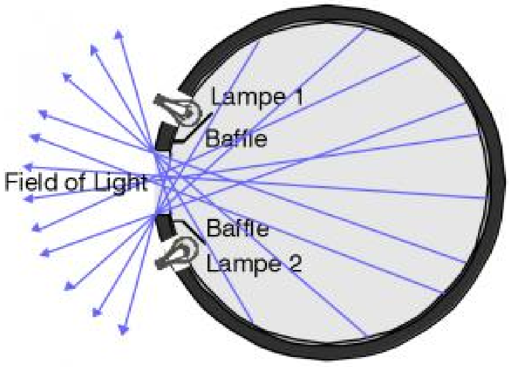

Fig. 1: Integrating sphere used as a standard source for optical radiation. Multiple Lambertian reflections inside the sphere result in homogenous radiance and exitance distributions at the sphere's exit port.

6.1 Theory of the ideal integrating sphere

The ideal integrating sphere, a theoretical construction which allows the explanation of the sphere’s basic principle of operation, is characterized by the following properties:

- Its entrance and exit ports are infinitesimally small.
- All objects inside the sphere, light sources and baffles, are also infinitesimally small and their influence on optical radiation after its first reflection at the sphere’s inner surface can be neglected.
- Its inner surface is a perfectly homogenous Lambertian reflector and its reflectance ρ is independent from wavelength. For a more detailed discussion of reflective materials largely fulfilling these properties, see Example 3: The Lambertian surface (chapter “Calculation of radiometric quantities – Examples”) and Integrating spheres used with integral detectors (chapter “The detector’s input optics and its directional sensitivity”)

During the following considerations, the symbol index describes the order of reflection. So, E_0 denotes the irradiance caused directly by the light source, whereas E_1, E_2, … denote the irradiance caused by light from the source after one, two, … reflections. Total irradiance is then given by the infinite sum

$$E_{total} = E_0 + E_1 + E_2 + \dots$$

For convenience, the index “e”, denoting radiometric quantities is omitted. However, if the reflectance ρ of the sphere’s coating material is independent from wavelength, the derived relations also hold true for photometric quantities, which would be denoted by the index “v”.

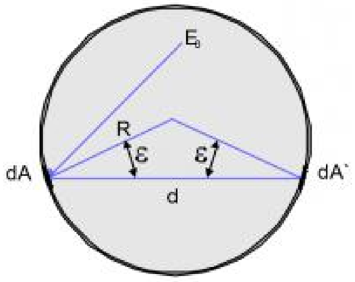

Fig. 1: Geometry of an ideal integrating sphere of radius R

Let’s consider an ideal integrating sphere of radius R, consisting of a hollow perfect Lambertian reflector with infinitesimally small entrance and exit ports. An inhomogeneous radiation source produces direct irradiance levels E_0 (the term “direct irradiance” refers to the fact that E_0 is directly caused by the source without any reflections) which depend on the respective location at the sphere’s inner surface (Fig. 1). As a first step, we want to calculate the irradiance E_1 of the sphere’s inner surface produced by the radiance L_1 after the first reflection. Due to the Lambertian reflection property of the sphere’s material, the radiation reflected by a certain area element dA is characterized by a constant directional radiance distribution L. According to the paragraph “Example 3: The Lambertian surface”, the area element’s exitance M_1 is related to the reflected radiance L_1 by

$$M_1 = L_1 \pi$$

and is further related to the element's direct irradiance E_0 by

$$M_1 = \rho E_0$$

whereby ρ denotes the total reflectance of the sphere's inner surface.

As a consequence,

$$L = \frac{\rho E_0}{\pi}$$

Although L does not depend on the direction relative to the surface element dA, it still depends on the location at the sphere's inside, which is a consequence of the generally irregular direct illumination by the light source.

If we want to calculate the radiant power emitted by the area element dA and impinging upon another area element dA', we have to calculate the solid angle of dA', as seen from dA (Fig. 1). As dA' is tilted by an angle ε relative to the line of sight between the two area elements, dA' occupies the solid angle dΩ', as seen from dA:

$$d\Omega' = \frac{\cos(\varepsilon)\, dA'}{d^2}$$

with d denoting the distance between dA and dA'.

According to Equ. 2 in "Basic radiometric quantities", the radiant power emitted by dA into the solid angle dΩ' and thus impinging upon dA' is given by

$$L \cos(\varepsilon)\, dA\, d\Omega' = L\, dA \times \frac{\cos^2(\varepsilon) \times dA'}{d^2}$$

and dividing this expression results in the (infinitesimal) irradiance dE_1 of the sphere's inner surface at the location of dA' which is caused by a single reflection of direct radiation from the source at the area element dA:

$$dE_1 = L \times \frac{\cos^2(\varepsilon)}{d^2} \times dA = \frac{E_0\, \rho}{\pi} \times \frac{1}{4\, R^2} \times dA$$

and the relation d = 2 R cos(ε), which can be easily seen from Fig. 1.

In order to obtain the irradiance E_1 at the location of dA', which is caused by a single reflection of the source's radiation at the whole inner surface of the sphere, the above expression for dE_1 has to be integrated over the sphere's inner surface:

$$E_1 = \int_{\text{inner surface}} \frac{E_0\,\rho}{\pi} \times \frac{1}{{}^{2}}\, dA = \frac{\rho}{4\,\pi\, R^2} \int_{\text{inner surface}} E_0\, dA = \frac{\rho\,\Phi_0}{4\,\pi\, R^2}$$

Here, Φ_0 is the total radiant power emitted by the source and impinging upon the sphere’s inner surface.

Note that the irradiance of the inner surface after the first reflection is independent from the actual location on the sphere, which is still the case despite the inhomogeneous direct irradiance caused by direct illumination from the source.

Deriving the irradiance E_2 caused by the source’s radiation after two reflections in the same way, we get

$$E_2 = \int_{\text{inner surface}} \frac{E_1\,\rho}{\pi} \times \frac{1}{4\, R^2}\, dA = \frac{\rho}{4\,\pi\, R^2} \int_{\text{inner surface}} E_1\, dA = \frac{\rho\, E_1 \times 4\,\pi\, R^2}{4\,\pi\, R^2} = \rho\, E_1 = \frac{\rho^2\,\Phi_0}{4\,\pi\, R^2}$$

Generally, the irradiance of the sphere’s inner surface caused by the source’s radiation after k reflections is given by

$$E_k = \frac{\rho^k\,\Phi_0}{4\,\pi\, R^2}$$

and the total irradiance is thus given by

$$E = E_0 + E_1 + \sum^{\infty} \frac{\rho^k\,\Phi_0}{} = E_0 + \frac{\Phi_0}{} \sum^{\infty} \rho^k = E_0 + \frac{\Phi_0}{} \times \frac{\rho}{}$$

$$E_2 + \ldots = E_0 + \quad {}^{k=0} \quad 4\pi \; R^2 \quad A_{sphere}\;{}^{k=0} \quad A_{sphere} \quad 1 - \rho$$

In this expression, only E_0 actually depends on the respective location on the sphere's inner surface. As a consequence, Etotal is independent of the actual location of the sphere's inner surface as long as we ensure that $E_0 = 0$ at this location. This means that no direct radiation from the source reaches the location, which can be achieved by using baffles. In this case, total irradiance is proportional to the total amount of radiant power Φ_0 reaching the sphere's inner surface directly from the source:

$$E_{total} = \frac{\Phi_0}{A_{sphere}} \times \frac{\rho}{1 - \rho} = \frac{\Phi_0}{A_{sphere}} \times K$$

Since the constant K describes the enhancement of irradiance relative to the average irradiance of a non-reflecting sphere, it is called “sphere multiplier” and, for an ideal sphere, solely depends on the coating material's reflectance ρ.

6.2 Real integrating spheres

Due to the simplifications assumed for an ideal integrating sphere, the relations derived in "Theory of the ideal integrating sphere" cannot be applied directly in practical applications. They have to be altered for the following reasons:

- The reflectance ρ might depend on wavelength. This results in a wavelength dependent sphere multiplier K and thus in a spectral distortion of the primary source's output. As a result, the relations for the ideal sphere, which have been formulated for radiometric quantities, can no longer be applied directly. The sphere's behavior for monochromatic radiation has to be determined by considering the respective relations for spectral radiometric quantities. If desired, radiometric quantities describing the sphere's radiation output can be determined by subsequent wavelength integration of the respective spectral radiometric quantities.

- Intensity considerations pose a lower limit for the size of the entrance and exit ports because the radiant power entering or exiting a sphere is proportional to the area of the respective port. As a result, these ports might reduce the amount of light reflected at the sphere's inner surface considerably. This can be accounted for by a modified sphere multiplier:

$$E_{total} = \frac{\Phi_0}{A_{sphere}} \times \frac{\rho}{1 - \rho\,(1 - a)} = \frac{\Phi_0}{A_{sphere}} \times K$$

with

$$K = \frac{\rho}{1 - \rho\,(1 - a)}$$

In these relations, ɑ denotes the relative share of the area of all ports and other non-reflecting areas on the sphere's total inner surface:

$$a = \frac{\text{sum of all non-reflecting areas}}{A_{sphere}}$$

The figure below shows the dependence of the sphere multiplier on reflectance ρ for different values of a. It can be noted that even a small variation of reflectance might cause significant change in the sphere multiplier.

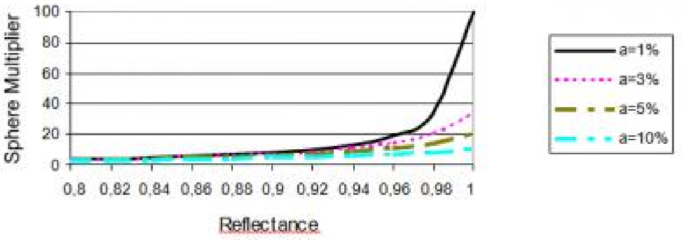

Fig. 1: Dependence of the sphere multiplier K on reflectance ρ for different values of the share of nonreflecting areas on the sphere's total inner surface

For this reason, a slight wavelength dependency of ρ may result in a strong wavelength dependency of the sphere multiplier.

- Objects inside the sphere, for example the light source itself, cannot generally be neglected in their influence on the reflected optical radiation. A possible solution is the determination of the light source's influence by means of an auxiliary lamp.
- Baffles inside the sphere and deviations of the coating material's reflectance properties from perfect Lambertian reflection cause further deviations of the sphere's behavior from the relations. Their influence can only be simulated by numerical Monte Carlo simulations, which basically use ray tracing techniques to follow the paths of a large number of individual photons.

Apart from these factors, integrating spheres are also subject to temporal variations of their optical properties, which are primarily caused by degradation of their coating material. In particular, the traditional coating material, Barium sulphate ($BaSO_4$), ages significantly when exposed to UV radiation.

Optically diffuse material (OP.DI.MA) is an optical grade plastic that is specially designed to work as a volume reflector. It has been designed to replace barium sulfate as a coating for integrating spheres in UV and high temperature applications. Its reflective properties depend on its thickness, generally specified at 10 mm which is the recommended minimum thickness for lighting engineering.

Apart from its temporal stability, OP.DI.MA offers additional advantages. Using different additives, its reflection factor can be adjusted to any value between 3 % (deep black) and 99 % (brilliant white), whereby uniform reflectance over a wide spectral range and over large geometrical areas can be achieved. Like other plastics, it can be processed by turning, drilling, sawing and milling and is available in raw blocks, plates and foils in various sizes for this purpose.

6.3 Self-absorption correction with an integrating sphere

Self-absorption correction is applied in measurements using integrating spheres in order to adapt the measured data sets to the device under test (DUT) or in other words, in order to take the DUT's influence during the measurement into account. The DUT blocks an open port of an integrating sphere to a certain extent thus causing a back reflection into the sphere and hence an additional signal within the sphere. This adds to the signal of the DUT and falsifies the measured value. This is the case for both spectral and integral measurements. Such kind of an error can be compensated via the so-called selfabsorption correction.

An integrating sphere is typically calibrated to match the geometry of an "open sphere" or an "empty sphere". An open sphere enables light of a DUT or an internal supporting lamp to exit the integrating sphere through inter-reflection (compare Fig. 1).

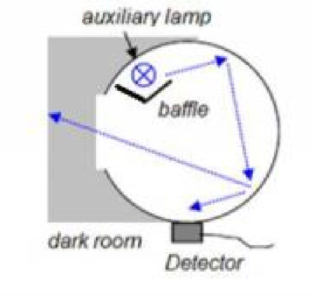

Fig. 1: Open sphere, light can exit the sphere

In case of the application, the measurement port is either blocked partially or fully with the DUT or the DUT is situated within the sphere; in both cases, the sphere is called "filled sphere" in both cases (Fig. 2). A part of the light that would exit in case of an open sphere is now reflected back into the sphere thereby increasing the signal. If the DUT is placed in the sphere, a part of the light is absorbed by the DUT's casing and does not contribute to the inter-reflection anymore, thus reducing the signal. The magnitude of the induced inter-reflection or the absorption error depends on the composition of the DUT and the way it is mounted. If for example the DUT is mounted to the outside of the sphere, is somehow large when compared to the port size and if it is strongly reflective, the induced error is going to be larger than in the case of a smaller absorbing DUT. If on the other hand, the DUT is placed within the sphere and if it is strongly reflective the induced error is going to be smaller than in case of a strongly absorbing DUT.

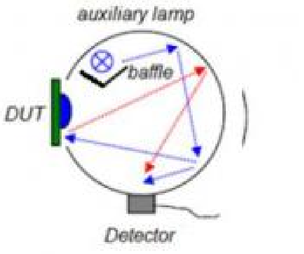

Fig. 2: Closed sphere, a part of the light is inter-reflected

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The caused discrepancies can be compensated via a self-absorption correction factor (Fig. 3). Here, the signal of the empty (open) sphere as well as the signal with the DUT attached to or placed within the (filled) sphere is measured. The differing measured intensities are used to determine a correction factor which represents the relation of both measured values. This compensation is performed for an integral detector or for a spectral array. Since the correction factors depend on the geometry as well as the spectral reflection of the DUT, the determined correction factors can be used for all light source of the same constructional type, e. g. for LEDs of the same type – assuming the measurement geometry remains unchanged.

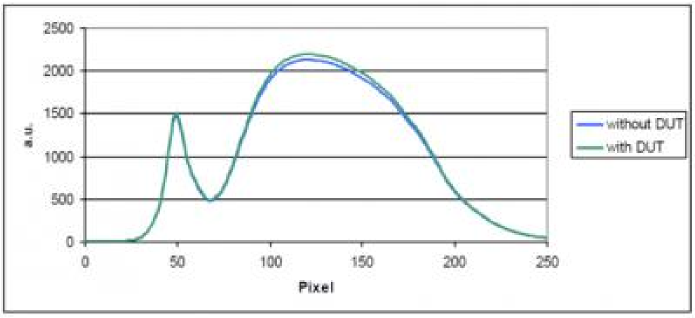

Fig. 3: Measurement of a LED (DUT) with and without the self-absorption correction of the DUT

Abb. 3: Messung einer LED (DUT) mit und ohne Korrektur des DUT

7 Applications for Light Measurement in Medicine, Technology as well as Industry and Environmental Science

For most technical applications of light, authorities like the International Commission on Illumination (CIE) or the Deutsche Industrienormen (DIN) have developed well-defined standards regarding its measurement. In virtually all areas connected with light, there is a strong demand for high quality measurement instruments. Many of these instruments must be specially designed and manufactured for the specific application. Moreover, these instruments must be calibrated against national standardization authorities, such as the National Institute of Standards and Technology (NIST) in the United States or the Physikalisch-Technische Bundesanstalt (PTB) in Germany.

Gigahertz Optik not only offers a wide variety of absolutely calibrated light detectors, but also offers its experience in light measurement technology for the development of specialized solutions based on customer requirements. Gigahertz Optik’s accredited calibration facility provides accurate, state of the art absolute calibration of instruments and secondary standard light sources.

7.1 Phototherapy and Radiation Protection

85 % of all sensory perceptions are optical in origin. However, optical radiation is not only involved in the process of human vision, it has many other biological effects as well.

The photo-biological effects of optical radiation, especially in the ultraviolet and blue (400 nm to 500 nm) spectral regions, can be therapeutic. For example, it is used in phototherapy to treat a variety of skin diseases and in postnatal treatment of Hyperbilirubinemia. For proper dosimetry, irradiance (W/m^2) and irradiance doses (J/m^2) delivered by UV sources in phototherapy processes need to be monitored and controlled through accurate measurements. These measurements are typically performed using a spectrally and spatially qualified UV-A, UV-B and UV-B$_{311}$ radiometer.

However, optical radiation also poses a potential health hazard for both human skin and eyes. For example, overexposure to ultraviolet and blue 'light' can cause common sunburn, photo-keratitis (welder's eye) and burning of the retina or cornea.

Because of the dramatic increase in global UV radiation and the cumulative nature of the harmful effects, the additional risk of UV exposure by artificial sources is a concern.

The efficiency of protective devices like sun creams, UV blocking fabrics and sunglasses are the subjects of study.

Photo-biologists, industrial hygienists, health and safety officers measure UV irradiance (W/m^2) and irradiance dose (J/m^2) of solar and artificial light sources in the lab, field and in the work place in order to study both the harmful and helpful effects of light and establish safe guidelines for its use. It is important to note that UV levels and subject exposure times typically vary and hence, data-logging is done over a significant time period.

Since Gigahertz-Optik is actively involved in the "Thematic Network for Ultraviolet Measurements" funded by the Standards, Measurements and Testing Program of the Commission of the European Communities, the detector and instrument designs are at the best available level. The CIE, Commission Internationale de l'Eclairage, is currently reviewing many of the concepts put forth by the European Commission in an effort to internationally standardize the evaluation of UV radiometric measurement instrumentation much like the way photometric instruments are characterized now.

The following sections give information on:

Incoherent Optical Radiation Protection

Even though there are many wide ranging and highly positive effects of light, there are also negative effects to consider. Naturally occurring optical radiation, especially in the UV range of the solar spectrum, poses a potential health risk to outdoor workers and people who spend a significant amount of time outdoors. The most serious long-term consequence of UV exposure is the formation of malignant melanoma of the skin, a dangerous type of cancer. In the US, skin cancer is the most frequently contracted type of cancer, and since the 1970s, the incidence rates of malignant melanoma have more than doubled. The same applies for other countries and as a result, the national and supranational networks of solar UV detectors have recently been established to monitor solar UV levels. In addition, the World Meteorological Organization is currently preparing guidelines for their characterization, calibration and maintenance.

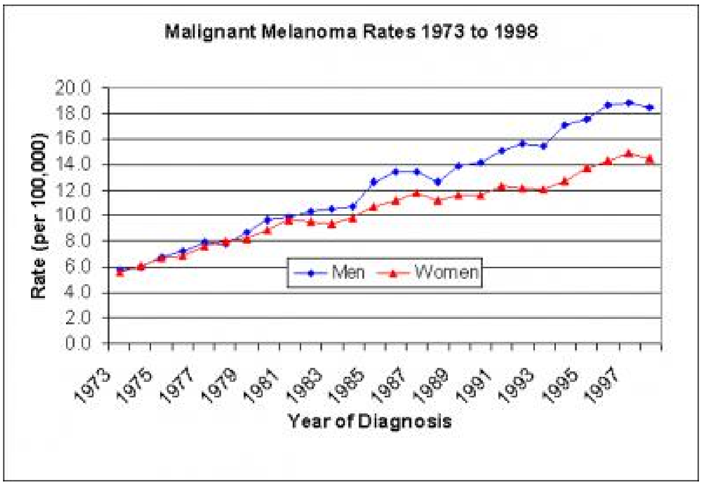

Fig. 1: Incidence rates of malignant melanoma in the US since 1973

In simple terms, incoherent optical radiation is optical radiation in the range of wavelengths between 100 nm and 1 mm, other than that emitted by lasers. The effect of incoherent optical radiation on the skin and the eye is increasingly being studied. The reasons for this lie in the rising exposure to radiation from sunlight, particularly in the UV range, and the growing use of high powered lamps in radiation therapy, radiation cosmetics, UV radiation curing, UV sterilization, vehicle headlamps, lighting equipment, etc. The high proportions of UV and blue light in the emission spectra of these lamps can, in addition to their desired effects, also result in radiation damage through both direct and indirect contact if the maximum permitted exposure levels are exceeded.

The shallow depth of penetration of optical radiation restricts the health hazards primarily to the eye and skin.

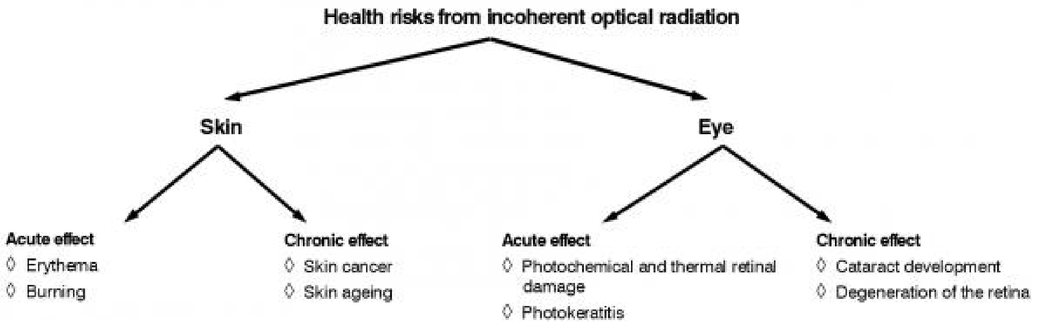

Fig. 2: Optical radiation health risks

Relevant Radiation Quantities

When evaluating the harm that might be caused by incoherent optical radiation, it is the effective radiance (or the time integral of the radiance) that is critical for the retina. On the other hand, the effective irradiance (or the exposure, also known as dose) is the critical quantity for the skin, cornea and eye lens. The exposure can for instance arise be at a workplace.

Photobiologically effective radiance

$W/(m^2 sr)$

$$L_{biol} = \int_0^\infty L_{e\lambda}(\lambda) \times s(\lambda)_{biol,\ rel} \times d\lambda$$

with $L_{e\lambda}(\lambda)$: spectral radiance of the radiation sources

Photobiologically effective irradiance

W/m^2

$$E_{biol} = \int_0^\infty E_{e\lambda}(\lambda) \times s(\lambda)_{biol,\ rel} \times d\lambda$$

$E_{e\lambda}(\lambda)$ is the spectral irradiance of the radiation sources

Photobiologically effective exposure

dose, J/m^2

$$H_{biol} = \int_0^{t1} E_{biol} \times dt$$

$s(\lambda)_{biol,\ rel}$ stands for the relevant spectral response functions of the skin and eye.

The following conditions should be maintained if exposure limits (E_{limit}) are given in guidelines as effective radiance, limit, or effective irradiance:

$E_{biol} \leq E_{limit}$ or $L_{biol} \leq L_{limit}$

If the exposure values are given as the time integral of the radiance L_i or as the exposure (dose), H, then the maximum permissible exposure duration, t, can be calculated:

$t = L_i / L_{biol}$ oder $t = H / E_{biol}$

ACGIH / ICNIRP Spectral Weighting Functions for Assessing UV Radiation Hazards

The spectral weighting function for the acutely harmful effects of UV radiation was developed by the *American Conference of Governmental Industrial Hygienists (ACGIH)* and the *International Commission on Non-Ionizing Radiation Protection (ICNIRP).*

If one examines the spectral curve describing this function, it is seen that the spectral effectiveness in the UV-C and UV-B ranges is very high, and that it falls drastically in the UV-A range. The reason for this is that the function is derived from the functions relating the radiation to erythema (skin reddening) and photo-kerato-conjunctivitis (corneal inflammation). The range of wavelengths from 315 nm to 400 nm (UV-A) corresponds to a rectangular function representing total UV-A. Threshold limit values given for the maximum permissible exposure of the skin define the range of wavelengths as 200 nm (180 nm) to 400 nm in reference to the ACGIH-ICNIRP function. The limits of maximum permissible exposure for the eye in the 200 nm (180 nm)to 400 nm range and 315 nm to 400 nm (UV-A) are defined separately. According to the ACGIH-ICNIRP definition, UV-C/B is measured in effective irradiance according to the spectrally weighted function and the UV-A level is assessed by measurement of the total UV-A irradiance (no spectral weighting function) for UV-A rich sources.

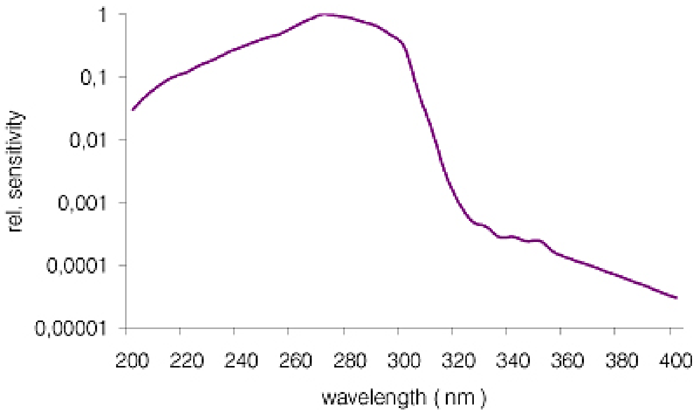

Fig. 3: ACGIH spectral function

Blue-Light Hazard and Retinal Thermal Hazard Functions for Photochemical and Thermal Risks to the Retina Blue Light Hazard (BLH)

If optical radiation with wavelengths between 380 nm and 1400 nm of sufficient intensity reaches the retina, it can cause photochemical and thermal injury. Radiation in the “blue” part of the spectrum between 380 nm and 700 nm (effectively 380 nm to 550 nm) triggers photochemical reactions. If the photon energy in the radiation is high enough, it converts chemically unstable molecules into one or more types of molecules. The spectral curve of the blue light hazard response function is shown in the following diagram. ICNIRP 1997 gives the following limits for the effective radiance of the BLH function:

$L_{BLH} \times t \leq 100\ J \times cm^{-2} \times sr^{-1}$ for $t \leq 10.000$ s

$L_{BLH} \leq 10\ mW \times cm^{-2} \times sr^{-1}$ for $t > 10.000$ s

L_{BLH} = effective radiance
t = duration of exposure

The blue light hazard function generally applies to exposure periods of more than 10 s. For shorter exposure times, the thermal retinal injury function applies.

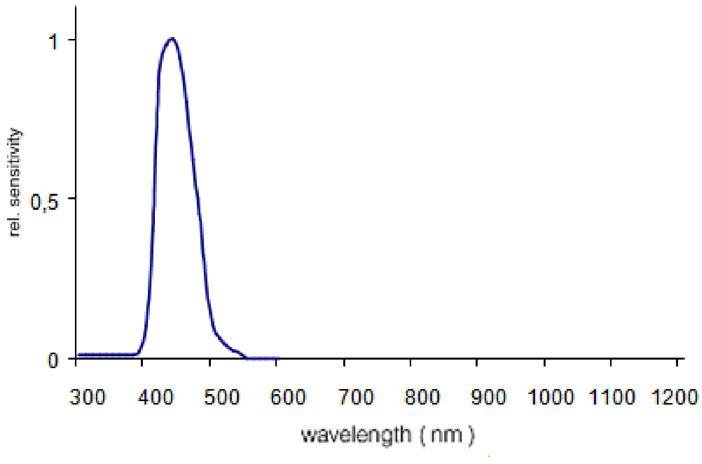

Fig. 4: Blue light hazard spectral function

Thermal Injury to the Eye - (RTH - Retina Thermal Hazard)

If the retina is exposed to high radiation intensities for short periods, a temperature rise to 45 °C leads to hyperthermia, a 60 °C rise causes coagulation, and a rise of over 100 °C results in vaporization. Cooling down the heat mostly depends on the capacity of the irradiated zone to transfer heat, and thus on the size of the image of the radiation source on the retina. The diagram above illustrates the spectral response function for thermal damage to the retina according to ICNIRP.

In the spectral range between 380 nm and 500 nm, the effect of the RTH function is larger than the BLH function by a factor 10. Whereas the latter rapidly falls to zero for wavelengths above 500 nm, the thermal function continues on for wavelengths up to 1400 nm. Since there are no industrially useable radiation sensors with spectral sensitivity for wavelengths ranging from 380 nm to 1400 nm, an appropriately simulated match using silicon photodiodes is used. In this context, it is adequate to measure the range up to 1200 nm since various light sources exhibit no more than 4 % difference in the integrated totals for wavelengths up to 1200 nm and to 1400 nm. This statement is also confirmed by ICNIRP in their working paper /1/.

For radiation sources whose emissions lie primarily in the near infrared range (IR-A) between 780 nm and 1400 nm, and that generate a visual luminance of less than 10 cd/m^2, the visual stimulus is so weak that the aversion reflex is not activated. In such applications, the measurement of radiance must, according to ICNIRP, take place exclusively in the IR-A region.

L(λ): spectral radiance of the radiation source being measured

RTH(λ): retina thermal hazard function

α: apparent radiation source.

Limits are also prescribed for the RTH function. Thus, for the case where

$10\ \mu s \le t \le 10\ s$

$L_{haz} \le 50 / (\alpha \times t^{0.25}) (kW \times m^{-2} \times sr^{-1})$

L_{haz} = effective radiance for the RTH function

α = size of the light source expressed in radians

For $t < 10$ µs, the limit must not be larger than L_{haz} for $t = 10$ µs. For $t > 10$ µs the limit must not be larger than L_{haz} for $t = 10$ s.

Metrological Considerations

Radiance is the quantity relevant to the evaluation of BLH and RTH hazards. The latest draft standards (IEC 825-1, November 1998) and ICNIRP (printed in Health Physics 1999) express views as to the angle of the measurement field of radiance meters. The applicable figures related to exposure durations are:

$t < 10$ s and $\alpha = 1.7$ mrad *

$t = 10$ s ... 100 s and $\alpha = 11$ mrad **

$t = 100$ s ... 10000 s and $\alpha = 1.1 \times t^{0.5}$ mrad / $s^{0.5}$ **

$t > 10000$ s and $\alpha = 100$ mrad **

* Dominance of thermal damage to the retina
** Dominance of blue light hazard

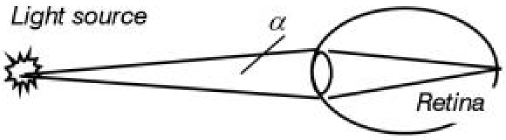

Fig. 5: Light Source – Subtended Angle – Retina

For RTH IR-A, evaluation ANSI/IESNA RP-27.1-96 recommends a field of view of 11 mrad, and of 100 mrad for very large radiation sources.

/1/ ICNIRP: guidelines of limits of exposure to broad-band incoherent optical radiation (0.38 µm to 3 µm) (September 1997).

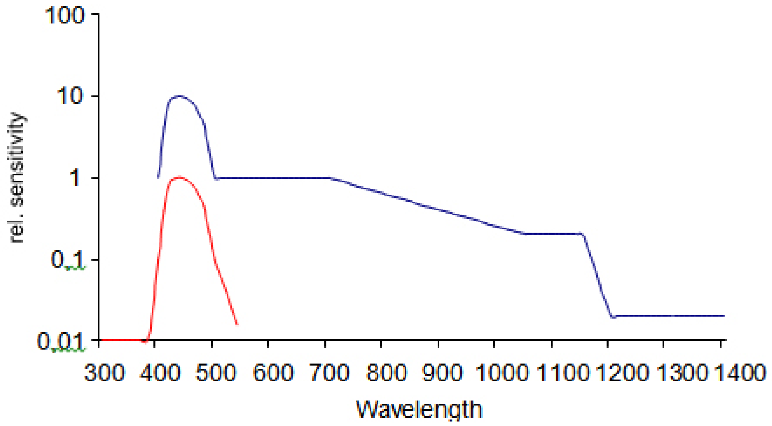

Fig. 6: Retinal thermal and blue light hazard spectral functions

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UV-Erythema

The typical symptom of UV erythema is acute skin inflammation caused by UV radiation (sunburn). It was previously thought that erythema was only caused by radiation components in the UV-B range of wavelengths. Present opinion is that UV-A plays a part in causing erythema because there is so much more of it present. Medical investigations have shown that intensive exposure to UV in leisure time and at work increases the risk of skin cancer. Children in particular should be protected from strong UV radiation since the skin stores the information about the UV dose received in the first years of life, and this can be a leading factor in the development of skin tumors in later years.

Sunburns occur in fair-skinned people (skin type 2) with a UV dose of as little as 250 J/m². Our table (according to F. Greiter: Sonne und Gesundheit, (Sun and Health), published by Gustav Fischer Verlag 1984) lists the various exposure duration's for minimal skin reddening for different skin types.

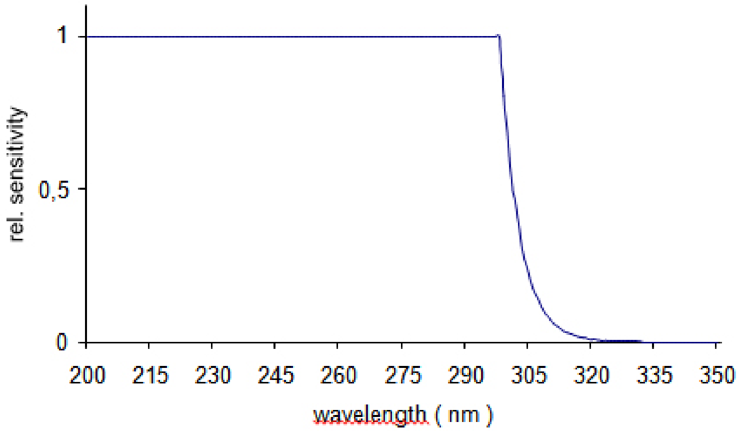

Fig. 7: Erythemal spectral function

Skin type	Description	Identification	Reaction to the sun	Sunburn Tanning	Exposure duration (min)
I	• Skin: noticeably light	Celtic type (2 %)	Only very painful	No reddening, white,	5 to 10

	• Freckles: strong • Hair: reddish • Eyes: blue, rarely brown • Nipples: very pale			after one to two days skin peels	
II	• Skin: somewhat darker than I • Freckles: rarely • Hair: blonde to brown • Eyes: blue, green and grey • Nipples: light	Light skinned European (12 %)	Only very painful	Skin peels hardly	10 to 20
III	• Skin: light to light brown, fresh • Freckles: none • Hair: dark blonde, brown • Eyes: grey, brown • Nipples: darker	Dark skinned European (78 %)	Moderate	Average	20 to 30
IV	• Skin: light brown, olive • Freckles: none • Hair: dark brown • Eyes: dark • Nipples: dark	Mediterranean type (8 %)	Hardly	Fast and deep	40

Tab. 1: Skin type categories

Phototherapy UV-A, UV-B and UV-B_{311} Phototherapy

UV is widely used by dermatologists in the treatment of certain skin diseases like Psoriasis and Vitiligo. Whole body exposure booths as well as hand and foot units that use light sources which emit broadband UV-A, UV-B, narrowband 311 nm UVB and combinations of UV-A and UV-B are used to irradiate the patient.

In PUVA phototherapy, also called photochemotherapy, UV-A is applied in combination with a photosensitizing agent. The photosensitizing agent is taken in pill form or applied topically to the skin. This medication is called psoralen, hence the acronym PUVA, and makes the skin more sensitive and responsive to the UV-A (315 nm – 400 nm) wavelengths.

Due to the risks of premature skin ageing and skin cancer from prolonged exposures, also with consideration to skin type, PUVA is only recommended for moderate to severe cases of Psoriasis. As a side note, psoralen is currently also used as a photosensitizer in UV sterilization of blood.

UV-B broadband treatment is normally administered without a photosensitizing agent. It is considered safer than UV-A for wavelengths between approx. 290 nm to 315 nm since it does not penetrate as deeply into the skin and is more energetic thus allowing for shorter exposure times. However, it is generally accepted that wavelengths below 290 nm produce more erythema, which can actually inhibit the therapeutic effects of the longer wavelengths.

As a result, narrowband UV-B sources emitting predominantly at 311 nm – 312 nm have been developed. They emit right in the wavelength zone that is most effective while producing lesser erythemal interference than broadband UV-B sources.

This is generally known as a TL-01 source. A TL-12 UV-B source with a slightly wider band of emittance between 280 nm – 350 nm, peaking at about 305 nm, is also used. For more information, contact the National Psoriasis Foundation and the American and European Academies of Dermatology.

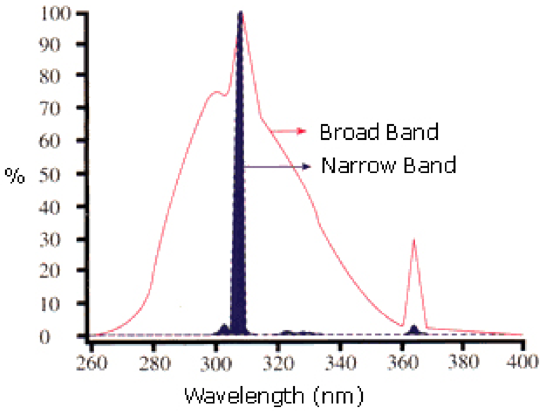

Fig. 8: Narrowband 311 nm and broadband UV-B source spectra

Dose, used here as irradiance accumulated over time, is normally measured in phototherapy applications.

$$\text{joules} / \text{cm}^2 = \text{watts} / \text{cm}^2 \times \text{seconds}$$

$$\text{dose} / \text{energy} = \text{irradiance} \times \text{time}$$

In the research and development stage or field service, direct irradiance may be monitored to discern any variation in output through lamp or delivery system degradation. Most of today’s phototherapy instruments are howevery equipped with sensors and electronics that enable delivery of pre-selected UV doses.

Third party checks of these internal dosimeters using qualified UV radiometers is recommended to ensure proper dosimetry and safety.

Bilirubin Phototherapy

Newborn jaundice or neonatal hyperbilirubinemia, a yellowish appearance of the skin and whites of the eyes, is present to some degree in almost all newborn infants. This is caused by an elevated level of bilirubin molecules in the blood, which is as a result of immature liver function combined with the destruction of the present red blood cells present. When these levels are very high, one method of clearing the jaundice is by exposing the newborn to light in the blue spectral region between 400 nm and 550 nm. The light interacts with the bilirubin, converts it to a substance that is excreted back into the bloodstream before being excreted with feces. The naked newborn is placed in a 'bilibed' or protected Isolette and exposed to fluorescent lights designed or filtered to emit in the blue spectrum. A recent development is the 'biliblanket' that delivers blue light through fiber optics and can be wrapped around the infant. Radiometric measurements of bili-lights are important in order to ensure proper dosimetry.

Efforts to standardize an action spectral function and measurement procedures for bilirubin are in process. Due to early work in this field, the units of microwatts/cm^2/nm were wrongly adopted for radiometric measurement of bili-lights. For technical correctness, the units of watts/cm^2 should be used.

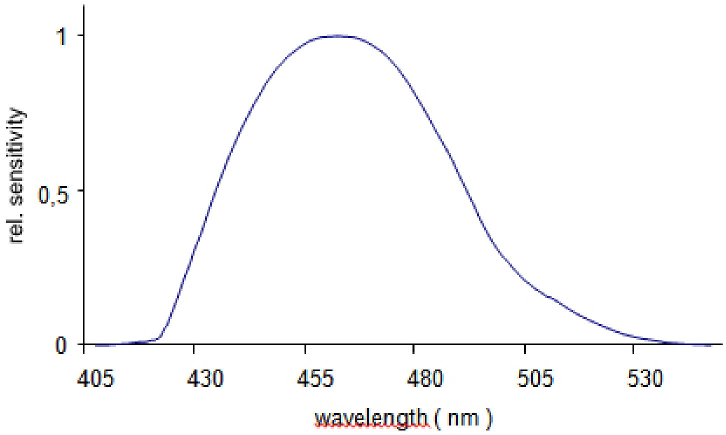

Fig. 9: Bilirubin spectral function

7.2 Plant physiology

The study and understanding of the interrelation of optical radiation and plants, seeds and soil is critically important for our existence. Research and control of biochemical factors require a precise and predictable measurement technology. The absorption of optical radiation in the range of wavelengths between 300 nm and 930 nm initiates photochemical reactions in plants that are essential for plant growth. The three most important reactions of plants to optical radiation are: Photosynthesis, Phototropism, Photomorphogenesis

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Photosynthesis

Photosynthesis is one of the most important biochemical processes on the planet. In the process of photosynthesis, green plants absorb carbon dioxide from the atmosphere and water from the soil, combining them with the aid of radiation energy to build sugar, releasing oxygen and water into the atmosphere. This process can be described by the following assimilation formula:

The occurrence of photosynthesis in plants is characterized by the green color of their leaves. This is due to chlorophyll which is absorbed with the photosynthetically active radiation. Absorption of the radiation energy quanta in the chlorophyll molecules hence raises the electrons to a higher energy state. As they return to their initial state, the released energy is converted into chemical energy.

In general plant physiology, the term **P**hotosynthetically **A**ctive **R**adiation **(PAR)** refers to the radiation in the range of wavelengths between 400 nm and 720 nm. This is the energy that is absorbed by the assimilation pigments in blue-green algae, green algae and higher order plants. The wavelengths for the lower limit (400 nm) and an upper limit (720 nm) are not entirely rigid. Photosynthetic reactions have, for example, been established in some algae at wavelengths shorter than 400 nm. In general, the lower limit depends on the structure and thickness of the leaf as well as on the chlorophyll content. Some research projects have shown 700 nm as the upper wavelength limit.

DIN 5031, Part 10 (currently in the draft phase) defines the spectral response function for photosynthesis as illustrated in the diagram below. For plant physiology, this range can be further subdivided into three narrower bands:

- 400 nm to 510 nm: strong light absorption by chlorophyll, high morphogenetic effect
- 510 nm to 610 nm: weak light absorption by chlorophyll, no morphogenetic effect
- 610 nm to 720 nm: strong light absorption by chlorophyll, high morphogenetic and ontogenetic effect

This response function can be considered as a mean spectral response function. A number of different investigations have shown that the spectral absorption spectra of various plant types can be very different. These differences can also occur in a single plant e. g. in leaves of different ages or with different thicknesses, chlorophyll content, etc. It should also be noted that the spectral response function for photosynthesis is defined with avoidance of mutual cell shading, based on experimentation with a young, thin leaf or thin layer of algae suspension.

The spectral distribution of the response function for photosynthesis might give the impression that visible radiation in the green range centered around 550 nm contributes very little to the photosynthetic process, and therefore is of minor importance. Experiments have however proven that the opposite is true. This green radiation yields the greatest productivity and efficiency in densely populated arrangements of plants or in thick suspensions of micro-organisms.

This discovery is important for studies on plant yields in the lower layers of wooded areas or greenhouse stocks, or in deep water (e. g. in sea plants).

Classical investigations into plant physiology have indicated that photosynthetic bacteria possess special pigments with strong absorption bands in vivo at 750 nm (chlorobium chlorophyll in the green chlorobacteria) or at 800 nm, 850 nm, 870 nm and 890 nm. In contrast to the blue-green algae, green algae and the higher plants, the absorption spectrum of the photosynthetic bacteria also extends into the UV region as far as about 300 nm.

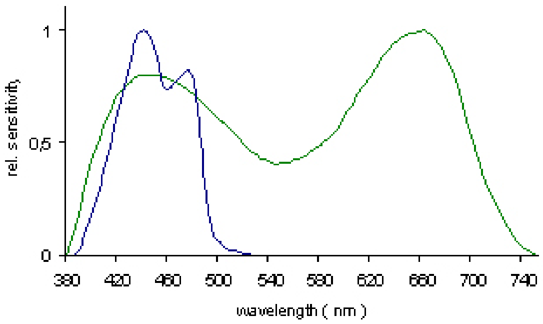

Fig. 1: Phototropism (blue) and photosynthesis (green)

Ultraviolet Radiation Effects

The weakening of the ozone layer has been discussed in public for more than a decade. It presents a serious challenge to plant physiology. For instance above Europe, a 3 – 6 % reduction in the total amount of ozone per decade (since 1978) has been established. This corresponds to UV-B radiation increase of up to 7% in high alpine areas with clean air. In March 1993, a 15 % disappearance of ozone was observed. As a result, a general increase in UV-B radiation must be expected.

UV-B radiation penetrates the tissues and leads to molecular changes in DNA, proteins, lipids and phytohormones. At high levels of UV radiation, oxygen radicals are formed leading to oxidation of proteins and lipids. The result of this is that growth, photosynthesis productivity and yield are impaired. Some field trials have shown that with an ozone reduction of 25 %, the UV-sensitive soy bean variety Essex, unlike the insensitive Williams variety, undergoes a reduction in photosynthesis leading to fall in yields by up to 25 %. This effect of UV-B radiation (280 nm – 313.3 nm) is internationally known as “generalized plant damage”, and is evaluated using the UV-B response function according to Caldwell. This GPD response function incorporates the degree of damage, linear growth, the cell division rate and other factors. Thus, in plant physiology and crop cultivation, it is necessary not to only investigate the positive photosynthetic effects of optical radiation, but also the negative effects that are mostly due to UV radiation if the activity and protection mechanisms of plants are to be understood and manipulated.

Phototropism

Phototropism is the effect of optical radiation on the direction of plant growth. The regions of maximum effect lie in the blue range between 380 nm and 520 nm (see Fig. 1). Radiation can also cause parts of plants to move.

Photomorphogenesis

Photomorphogenesis is the way in which plants are formed under the influence of optical radiation. Radiation in the red region of the spectrum encourages linear growth, while blue radiation yields small, strong plants. To be more precise, the ratio of the radiation intensities in the range of wavelengths from 690 nm to 780 nm (long wavelength red) to the range of wavelengths from 560 nm to 680 nm (short wavelength red) is of great importance for the plant's biological processes.

Measurement Aim, Measurement Methods

The photochemical processes involved in plant physiology are understood as quantum processes. Associated measuring techniques should also treat them as such. The most important measurements for plant physiology are:

- Analysis of the efficiency of energy conversions in photosynthesis
- Determination of the rate of photosynthesis (yield factor) when exposed to radiation sources with different emission spectra
- Comparison of the rate of photosynthesis in various plant types cultivated under various radiation conditions
- Determination of the protective mechanism and the stress processes of plants in relation to UV radiation and high levels of heat radiation (infrared radiation)

The effect of radiation of various wavelengths on the growth processes taking place within plants can be represented in a number of ways. The rate of photosynthesis is defined as the ratio of the quantity of assimilated carbon dioxide (CO_2) molecules to a suitable radiation input quantity. These quantities are:

- the irradiance in W/m^2, i. e. the radiant power per unit area of the irradiated object
- or alternatively, the photosynthetic photon irradiance $E_{p,sy}$. This magnitude is also frequently referred to as the quantum flux density.

Photosynthetic Photon Irradiance $E_{p,sy}$

The radiation conditions used in determining the rate of photosynthesis and the photosynthetic potential of various plant or algae types are not the same in all research institutions. Results obtained under very different radiation conditions, using detector heads with non-uniform rectangular (radiometric) characteristics, and then relating them to one another, may lead to false conclusions. This is because the varying spectra of the radiation sources in use are ignored in obtaining the measurement.

The solution is to evaluate the irradiance with a sensor that has an appropriate spectral response function. It is presently assumed that the number of light quanta absorbed is responsible for plant growth, which implies that it is quantum magnitudes effective in plant biology that need to be measured. The most important magnitude is the photosynthetic photon irradiance $E_{p,sy}$.

The photosynthetic photon irradiance $E_{p,sy}$ is defined as follows:

$$E_{p,sy} = \int E_{p,\lambda}(\lambda)\, d\lambda = \frac{1}{hc} \times \int E_{\lambda}(\lambda)\, \lambda\, d\lambda$$

where:
$E(\lambda)$ is the spectral irradiance of the light source
λ is the wavelength of the radiation
$E_{p,sy}(\lambda)$ is the spectral photon irradiance
λ is the number of photons per second, per unit area and wavelength
h is the Planck's constant
c is the velocity of light

The unit of photosynthetic photon irradiance, $E_{p,sy}$, is defined as follows:

$[E_{p,sy}] = 1\ E\ s^{-1}\ m^{-2} = 1\ Mol\ s^{-1}\ m^{-2}$

where
$1\ E = 1\ Mol = 6.02 \times 10^{23}$ photons
(the most commonly used unit is $\mu Mol\ s^{-1}\ m^{-2}$).

The integration limits need to be specified according to the formula. For example, if the photosynthetic photon irradiance is to be measured in the range of wavelengths between 400 nm and 700 nm, 320 nm and 500 nm, and 590 nm to 900 nm, the integration is carried out in the corresponding spectral segments. This numerical integration can be performed implicitly by means of an integral measuring head. Such a measuring head must also satisfy two important conditions:

- The incident radiation must be evaluated in accordance with the cosine of the angle of incidence, i. e. using a cosine diffuser
- The spectral sensitivity of the measuring head must be adapted to the l/l_r function. l_r is the reference wavelength. The upper limit wavelength, i. e. 700 nm, 500 nm and 900 nm, is always taken respectively for the ranges between 400 nm – 700 nm, 320 nm – 500 nm, and 590 nm – 900 nm.

The spectral sensitivity of the sensor should be zero outside the responsive spectral zone of interest.

7.3 UV-Disinfection and Lamp Control

UV radiation can have harmful effects on human skin and eyes, especially during indoor application of high-energy UV irradiators. There is however a positive aspect to UV's hazardous effect on living organisms. Ultraviolet treatment of drinking and wastewater is a well-established, economical and efficient method for killing germs, bacteria, mold and fungus. It is increasingly being used in the place of conventional water treatment techniques, which use chlorine and ozone, due to cost and environmental reasons.

Fig. 1: UV treatment of wastewater

Source (valid as of 2002): http://www.mindfully.org/Water/UV-Disinfection-Wastewater.htm

Recently, a field study performed in homeless shelters in New York, Birmingham and New Orleans (TB UV Shelter Study, TUSS) has shown that UV treatment of room air with upper room irradiators leads to a drastic reduction of tuberculosis infection rate.

Fig. 2: Upper room UV irradiators help lower tuberculosis infection rates

Source (valid as of 2002): http://www.news.ucf.edu/FY2001-02/011205.html

The CIE divides ultraviolet optical radiation into three ranges:

- UV-A: 315 nm to 400 nm (skin pigmentation)
- UV-B: 280 nm to 315 nm (vitamin D synthesis, erythema)
- UV-C: 200 nm to 280 nm (germicidal action, absorption maximum of DNA). Below 230 nm, UV radiation has enough energy to break chemical bonds.

Short–wavelength, high-energy ultraviolet radiation in the UV-C spectral range from 100 nm to 280 nm is used in germicidal/bactericidal sterilization of air and water. UV-C at 253.7 nm is also used in EPROM erasure as well as to clean sensitive surfaces in the semiconductor industry. UV curing is another area where UV-C is used.

UV-C Light Sources

Due to its high and pre-dominantly monochromatic output at 253.7 nm, low pressure mercury is the preferred light source in these applications. Medium and high pressure Hg as well as metal halide and other broadband UV sources are also used, particularly in UV curing.

Light Source Life-time

The useful lifetime of high power UV-C sources is limited. UV-C intensity must be monitored to ensure process control.

7.4 UV Curing and UV Processing

UV curing is a process in which photo-curable chemicals applied to substrates are irradiated with high energy UV or visible radiation for curing. This energy accelerates polymerization (cross-linking) and consequently the hardening or drying process. The irradiated energy needs to be controlled since too low a dose will not cure the product, whereas too high a dose will damage it.

In the curing application, a dose refers to the amount of energy delivered to the target product. It is defined as radiant exposure (energy per unit area) and typically measured as irradiance over time.

$$J/cm^2 = W/cm^2 \times \text{seconds}$$

High-power UV sources are used in this process. Because of non-linear ageing, UV output needs to be continuously monitored and controlled.

These high UV levels place special demands on the measurement devices used in this application.

That component of ultraviolet energy useful for curing makes up only a small part of the spectral bandwidth within the lamp’s total emission spectrum and the bare detector‘s spectral sensitivity.

Optical bandpass filters are therefore used to limit the detector‘s sensitivity to the spectral range of interest.

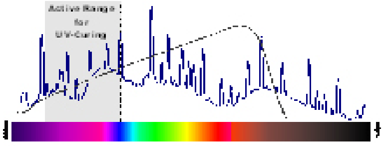

Fig. 1: UV curing spectral region

Conventionally designed UV irradiation detectors show drift and instability over time due to the hostile ambient conditions found in the UV-curing process. Solarization, ’fogging” effects and even delamination of the filter elements and other optical components can occur. In addition to altering the detector’s absolute sensitivity, these effects can also change its spectral sensitivity. On recalibration, a change in absolute sensitivity may be noted and adjusted but unless a complete spectral test is performed, a change in spectral sensitivity can go undetected. What is thought to be a newly recalibrated detector will often produce erroneous readings when returned to the end user.

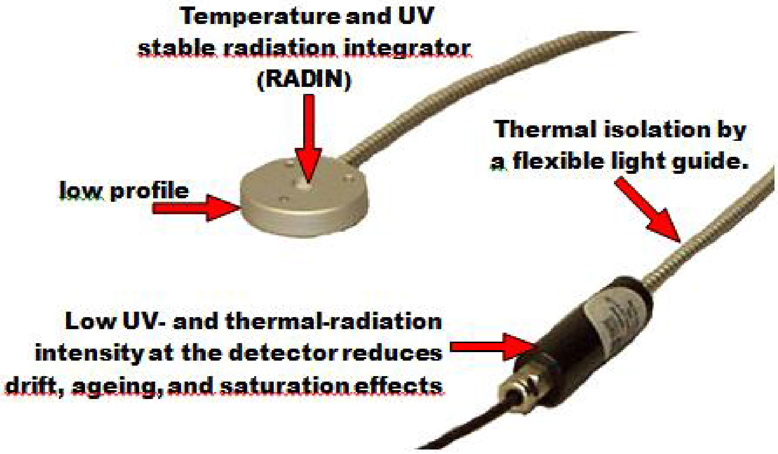

Fig. 2: UV curing detector

A new detector design has been developed based on the integrating element, RADIN™, which is not only able to withstand the high UV and temperature conditions of the UV-curing process, but can also maintain stability and measurement accuracy over long term use. Critical components in the detector are only exposed to a fraction of the direct irradiation.

RADIN is a trade name of Gigahertz-Optik.

The detector's response which best matches the absorption spectrum of the photo-curable chemical in use is selected. This way, the detector spectrally emulates the product to be cured.

The lamp(s) used in the system are selected by the equipment manufacturer for optimal curing within this active bandpass.

When lamp replacement becomes necessary, the replacement lamps should have similar spectral and absolute output as the old ones so as not to invalidate the established process parameters.

It should be noted that in order to properly 'frame' the results, information on the spectral response function of the detector in use should be provided along with any statement of measured magnitude. UV detectors from different manufacturers can have very different spectral responses. This means that they will not read the same under the same test conditions.

Due to the many errors involved with UV measurement, even two detectors from the same manufacturer can have very different readings.

Normally in the field, readings within ±10 % are considered acceptable in the UV-A range.

Uncertainties get progressively worse as you move to shorter wavelengths.

It is important to remember that the UV meter is after all a scientific instrument which is expected to perform reliably and repeatedly in very hostile environments.

Maintaining calibration cycles at the intervals recommended by the manufacturer is necessary. If unacceptable levels of change are seen on recalibration, the cycle time should be shortened (staircase method). This way you end up with a recalibration program tailored to your specific requirements.

It is also recommended to have a second instrument on hand that should be used only for an in-house calibration check of the working production unit(s).

7.5 Colorimetry

Color is the attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, grey, black, etc., and qualified by bright, dim, light, dark or by combinations of such names.

Perceived color depends on the spectral distribution of the color stimulus as well as on the size, shape, structure and surroundings of the stimulus area, on the state of adaptation of the observer's visual system, and on the person's experience of prevailing and similar sight situations. More details about colorimetry.

Color and Illuminance Measurement

In many applications involving the measurement of color or color temperature of self-emitting light sources, the same measurement geometry is used as for illuminance. Appropriate absolute calibration of the measuring system allows the illuminance of a reference plane in **lux (lx)** to be determined in addition to the colorimetric parameters. If the incident light is diffuse, this measurement requires the measuring system to have a field of view adapted to the cosine function. Only in this way can the laws for the incidence of diffuse radiation from one or more sources of radiation be satisfied. Detectors used to determine absolute illuminance must therefore have a cosine spatial function as their measurement geometry. If the incident radiation is not parallel, the accuracy of the cosine function is critically important to the result of the measurement. In Germany, DIN 5032, Part 7 classifies the quality of devices for measuring illuminance (luxmeters/photometers) according to the accuracy of their measurement into:

- Devices under class A, with a total measurement uncertainty of 7.5 % for precise measurements.
- Devices of class B, with a total measurement uncertainty of 10 % for operating measurements.

Since there are no equivalent regulations for colorimeters, some of the regulations in DIN-5032 can also be used in illuminance measuring colorimeters.

Fig 1: Color and illuminance meter

Color and Luminous Flux Measurement

Luminous flux is the quantity used to define all of the emitted radiation in all directions by a light source in the photometric unit, **lumens (lm)**. One of its purposes is to reference the efficiency of incandescent lamps, arc lamps, light emitting diodes, etc., as it is derived from the relationship between the input electrical power and the luminous flux.

In cases where the light source emits in an approximately parallel beam, it is possible to measure the luminous flux with a photodetector assuming that the diameter of the beam is less than that of the detector measurement aperture. If the light beam is highly divergent or if a 4π radiation characteristic must be considered, measurement geometry that ensures the evaluation of all radiated light, regardless of the direction in which it is emitted, must be used. The measurement geometry most often used for highly divergent sources is a hollow body, ideally formed as a hollow sphere, with a diffusely reflecting interior wall. Such ”integrating spheres” are known in Germany as Ulbricht spheres. The figure below illustrates the construction principle of Ulbricht spheres.

Color and Luminous Intensity Measurement

The quantity of luminous intensity specifies the light flux emitted by a light source in a particular direction within a specified solid angle in the photometric units of **Candela (cd)**. One field in which this applies is when lamps and projectors are used in imaging systems (lens systems, reflectors) and the subsequent distribution of luminous intensity from the illumination or spotlight system must be calculated.

In order to measure luminous intensity, the field of view of the color detector must be restricted to the desired solid angle. This is usually accomplished using steradian adapter tubes that limit the detector head’s field of view. It is important that the inner walls of these tubes be designed to exhibit low reflectance. Steradian tubes that attach to the front end of the detector can be used for this purpose.

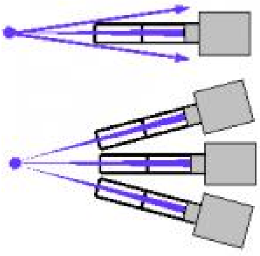

Fig. 2: Typical measurement geometries

Color and Luminance Measurement

The quantity of luminance is used to evaluate the intensity of light from surface emitters in the photometric units of **Candela / square meter (cd/m^2)**. A defined angular field of view for the color measuring device is needed in order to measure the luminance. This can be accomplished using either steradian tubes or lens systems.

Color Temperature Measurement

Color temperature is a simplified way of characterizing the spectral properties of a light source. While in reality the color of light is determined by how much each point on the spectral curve contributes to its output, the result can still be summarized on a linear scale.

Low color temperature implies warmer (more yellow / red) light while high color temperature implies a colder (more blue) light. Daylight has a rather low color temperature near dawn, and a higher one during the day. Therefore it can be useful to install an electrical lighting system that can supply cooler light to supplement daylight when needed, and fill in with warmer light at night. This also correlates with human feelings towards the warm colors of light coming from candles or an open fireplace at night.

Standard unit for color temperature is **Kelvin (K)**.

The Kelvin unit is the basis of all temperature measurements, starting with 0 K (= -273.16 °C) at the absolute zero temperature. A temperature interval of one kelvin has the same size as the interval of one degree Celsius, and is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water, which positions 0° Celsius at 273.16 K.

Light sources are sometimes described by their correlated color temperatures (CCT). The correlated color temperature of a source is the temperature of a black body radiator that is most similar to the source. A blackbody radiator is an ideal surface that absorbs all energy impinging on it and then re-emits it all. The spectral output distribution of an incandescent (tungsten) lamp approximates a blackbody at the same temperature. Correlated color temperature is typically presented using the absolute centigrade scale, degrees Kelvin (K).

Some typical color temperatures are:

- 1500 K: candlelight
- 3000 K: 200 W incandescent lamp
- 3200 K: sunrise / sunset
- 3400 K: tungsten lamp
- 5500 K: sunny daylight around noon

For many color measurement tasks, it is important to determine the color temperature of luminous objects. According to DIN 5031-P.5, the color temperature t_c of a radiator requiring characterization is the temperature of a Planckian radiator at which it emits radiation of the same color type as that of the radiator being characterized. The color temperature is calculated and displayed by the meter. The calculation of color temperature is performed using an algorithm according to Qiu Xinghong, which enables very good research results for the color temperature range from 1667 K to 25000 K to be obtained.

7.6 Photo-stability

The current *ICH (International Conference for Harmonization)* guidelines specify that drug and drug products must be photo-tested to ensure that exposure to light does not cause photochemical degradation of the product or packaging. The product under test must receive a measured dose of both UV-A (200 watt-hours per square meter) and Visible (1.2 million lux-hours) optical radiation exposure. This requires both radiometric and photometric measurements in terms of illuminance in lux and UV-A (315 nm to 400 nm) irradiance in W/m^2 multiplied by exposure time in hours.

It is important to note that total or absolute UV-A is implied. No effective UV-A spectral function is specified. Ideally for total UV-A measurements, the perfect broadband UV-A detector would have a flat square-wave spectral shape starting at 315 nm to 400 nm for 100 % response at each wavelength across this spectrum with no response outside this bandpass. Most currently available UV-A detectors have a 'bell' shaped spectral response which, if uncorrected through calibration or redesign of spectral function, will read > 25 % too low on the UV-A fluorescent source, and > 40 % too low for Xenon and glass ID65 type light sources.

Note that UV-A fluorescent and Xenon or Metal Halide simulated ID65 light sources are the only sources specified in the ICH guidelines.

A closer approximation to an ideal UV-A broadband detector has recently been developed by Gigahertz-Optik for photo-biological and photostability applications. Compared to the ideal UV-A spectral function, the typical detector total area error is 34 % whereas for the Gigahertz-Optik 'flat' UV-A detector, the total area is only 14 %.

The guidelines also state that in order to ensure spectral conformity of the light source(s), a photo tester may rely on the spectral distribution specifications of the manufacturer of the light source. There have been many practical cases where either the spectral data is not available or typical data is not reliable due to ageing effects of the source and other factors. This is another important reason for using photodetectors with the best spectral match to the ideal functions.

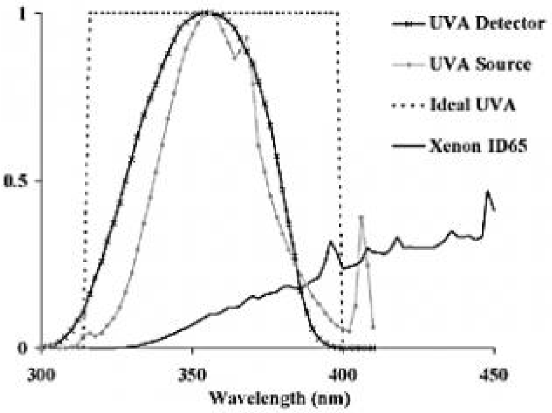

Fig. 1: Typical UV-A spectral function

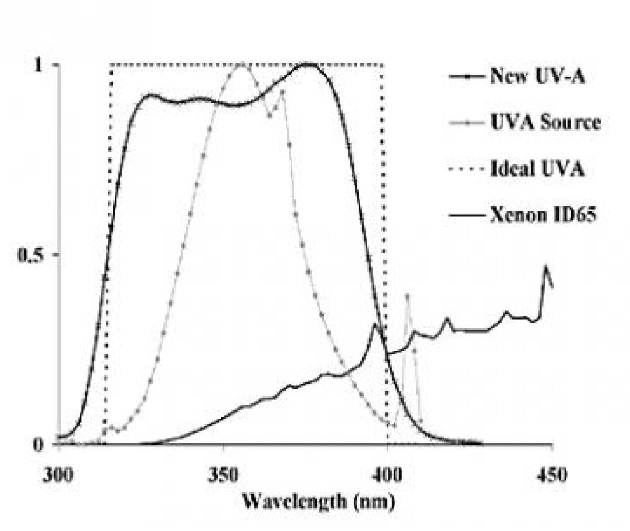

Fig. 2: Flat UV-A spectral function

Most often, the photo-testing is performed in a photo-stability chamber with long fluorescent light sources mounted above the products under test. For larger profile products, light sources may also be mounted along the sides of the chamber to fully immerse the target. Since this is an extended source type of measurement rather than a point source configuration, the detector angular responsivity should be cosine corrected using a diffuser. This way, the incoming light signals are properly weighted according to the cosine of the angle of incidence.

In this case, the detector properly emulates the target in the way the light signal is received.

Profiling the photo-stability chamber for uniformity over the exposure plane is an important procedure since products placed in different areas inside the chamber should be uniformly exposed to the same light levels. Moving the detector or using multiple detectors in multiplex mode maps the exposure levels at various locations across the exposure plane.

Some of the photo-stability chambers manufactured today are equipped with internal light sensors to continuously monitor the light and UV-A output. Maintaining accuracy and reliability in on-line continuous monitoring of UV applications is a daunting challenge.

Without proper protection engineered into the detector, changes due to solarization, temperature effects and ensuing calibration drift can occur. It is advisable to do a third party check using a qualified radiometer/photometer.

7.7 Telecommunication

An ongoing revolution occurring in the field of telecommunications is the development of small laser diodes and high capacity optical fibers. Without telecommunication devices that use optical fiber, the highly convenient availability of huge amounts of information at comparatively low costs, as provided by the Internet, would not be possible.

The measurement of the power output of laser diodes or fibers is a daily routine in the field of telecommunication components testing. Optical power meters using a bare detector have a high sensitivity but at a cost of potential measurement inaccuracies caused by the effects of polarization, local saturation, signal 'bounce-back' and beam misalignment. In addition, the use of large sized photodiodes, which require the reduction of the source-to-detector-misalignment, increases costs.

A welcomed alternative is the integrating sphere. This is able to collect all of the source's optical radiation output independent of beam geometry. In the world of photonics, the integrating sphere is well known for its ability to reliably and accurately measure total flux from fibers, laser diodes, lasers, LEDs, and any other optical radiation or light source. Since the incoming signal is captured as a whole and reflected inside the sphere multiple times before reaching the baffled detector mounted to it, the adverse effects of polarization, local saturation, signal 'bounce-back' and beam misalignment are reduced.

7.8 LED Measurements

Presently, a fast and steady large scale technological change is taking place: The traditional incandescent bulb is increasingly being replaced by special semiconductor devices called light emitting diodes or LEDs. Over the past decade, LEDs have caught up in efficiency and now offer an economical alternative to incandescent bulbs even for bright signal lamps such as traffic and automotive lighting.

An LED can be designed to emit light of only the desired color. Since the emission color depends on the spectral distribution of the LED, there is a certain demand for LEDs with identical specifications. LEDs therefore have to be selected according to their specifications due to the tolerances in the production. This procedure is called binning. In this process, very fast and precise measurements have to be performed. These are achieved through optimized spectral radiometers that use diode arrays.

A typical LED has a lifetime of 100,000 hours (compared to about 1000 hours for incandescent bulbs) thus drastically reducing the need for maintenance, and often leading to significant overall cost reduction when LEDs are used in the place of traditional lighting. As an example, in the late 1990's the city of Denver had replaced some 20000 incandescent bulbs in traffic light signals with LED devices. Calculated for the lifetime of a LED device, they estimated total savings of about $ 300 per signal.

Polychromatic vs. Monochromatic

The laser is the most commonly encountered monochromatic source. Because of its monochromatic and coherent radiation, high power intensity, fast modulation frequency, and beam orientated emission characteristics, the laser is the primary source used in fiber optic communication systems, range finders, interferometers, alignment systems, profile scanners, laser scanning microscopes, and many other optical systems.

Traditional monochromatic radiometric applications are found in the range of optical spectroscopy with narrow band-pass filtered detectors and scanning monochromators used as monochromatic detection systems or monochromatic light sources.

Optical radiation describes the segment of electromagnetic radiation from $\lambda = 100$ nm to $\lambda = 1$ mm. Most lasers used in measurement equipment and fiber optic telecommunication systems work predominantly in the 200 nm to 1800 nm wavelength range.

Because of the monochromatic emission spectrum and fixed output wavelength, detectors used to measure laser power do not need a radiometric broadband characteristic. This means that the typical spectral sensitivity characteristic of Si or InGaAs photodiodes can be used without requiring spectral correction.

For absolute power measurements, the bare detector's spectral response can be calibrated at a single wavelength or over its complete spectral range (typically done in 10 nm increments).

The corresponding calibration factor for that specific wavelength is selected when making the laser power measurement. Some meters offer the capability of selecting a wavelength by menu on the display. The meter then calculates the reading by applying the calibration factor for the wavelength selected and displays the measurement result.

There are two typical measurement strategies for laser power detection:

- Lasers with collimated (parallel) beams are typically measured with a flat-field detector whose active size is larger than the laser beam diameter. Because of the high power of lasers, the responsivity of the detector may have to be reduced by an attenuation filter. However, there is a risk of measurement errors due to polarization effects, surface reflections from optical surfaces in the light path and misalignment of the beam on the detector.

- Lasers with non-collimated (divergent) beams cannot be measured with a flatfield detector because of the different angles of incidence. The power output of these lasers is typically measured using detectors combined with an integrating sphere that collects all incoming radiation independent of the angle of incidence. The following are more unique features offered by the integrating sphere:
    - Through multiple internal reflections, the sphere offers high attenuation for high power measurements. The maximum power is limited by the sphere's upper operating temperature limit.
    - In addition, the multiple internal reflections prevent measurement errors caused by polarization effects with flat-field detectors.
    - The sphere port diameter can be enlarged by increasing the sphere diameter thus enabling measurement of larger diameter beams
- Laser Stray-light: Although very useful, laser radiation can pose a health risk to the human eye. Even stray-light from lasers may be hazardous due to the typically high power levels. The EN 60825 standard describes the risk and measurement methods for risk classification. Laser stray-light can be assessed using a detector head with a 7 mm diameter free aperture to mimic the open pupil.

7.9 Nondestructive testing

The *American Society for Nondestructive Testing* defines NDT as the examination of an object with technology that does not affect the object's future usefulness. The term NDT includes many methods that can:

- detect internal or external imperfections
- determine structure, composition or material properties
- measure geometric characteristics

Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT) and *Visual and Optical Testing (VI)* are test methods used to detect defects in materials with the aid of optical radiation or light. The light levels used in these operations are critical to the integrity of the inspection process. Thus, radiometric and photometric measurements are designed for quality control purposes. *American Society for Testing and Materials (ASTM), MIL* and DIN standard practices exist to help ensure uniformity in these examinations.

Liquid Penetrant Testing

The dye penetration examination process is a widely used method for detection of surface defects in nonporous metal and non-metal materials. Two different methods are hereby used:

Dye Penetration Process

A colored liquid or dye is applied to the surface of the test object which, through capillary action, penetrates into any existing surface defect(s). After removing any excess, an absorptive white layer is applied drawing the colored liquid out of the defect and hence making it visible. Adequate illumination of the test object with white light is critical to create good contrast.

Fluorescent Penetrating Agent

For maximum sensitivity, a fluorescent dye is used as the penetrating liquid and the test is carried out under ultraviolet lighting. UV-A sources known as 'black lights' are most commonly used. In order to perform reliable tests using fluorescent agents, an adequate level of UV-A irradiance containing a very low proportion of white (visible) light must be generated at the object under test.

Magnetic Particle Testing and of course **Visual and Optical Testing** both rely on ensuring adequate light levels for quality control of the examination.

DIN EN 1956, ASTM and MIL Standards have been developed to specify the general conditions and standard practices for the penetrant test examinations, including the procedures to be followed. The minimum requirements for the illumination or irradiation conditions, test procedures to be used for checking these levels, and suitable measurement equipment specifications are also covered.

It is particularly emphasized in these standards that the calibration of the radiometer and photometer used to measure the illuminance and irradiance must be carried out with the aid of calibration standards that can be traced back to national standards. The test certificate must document the calibration testing.

The calibration method must also be considered.

Many of the UV-A radiometers used in this application are calibrated at a single point at the peak of the detector spectral response, typically 360 nm or simply adjusted to some reading on a particular light source. In order to reduce measurement errors due to light sources with different spectral outputs, Gigahertz-Optik uses the integral calibration method where the detector is calibrated to a measured UV-A integrated spectral irradiance standard.

In order to further reduce spectral errors, the Gigahertz-Optik UV-A detector exhibits a nearly flat response across the UV-A bandpass with a sharp cut-off at 400 nm to eliminate visible stray light from contaminating the UV reading.

The spectral response function of the photometric sensor is very important for the same reasons. Spectral errors when measuring lux or foot-candles can occur when testing light sources different from the source used for calibration. A detector that closely matches the CIE photopic function is required for accurate photometry. The spectral function of the photopic sensor from Gigahertz-Optik is within DIN Class B limits (< 6 % mismatch in comparison with the CIE photopic curve).

The detector's spatial response (angular response) is another important factor and potential error source.

Since the detector is fully exposed to light from all directions, including any ambient contribution, it should be cosine corrected using a diffuser. This way, the incoming light signals are weighted properly in accordance with the cosine of the incident angle. The detector receives the light signals in the same way as a flat surface does, so in effect, the detector emulates the sample under test. If the detector's spatial response does not closely match the true cosine function, significant errors in readings will result.

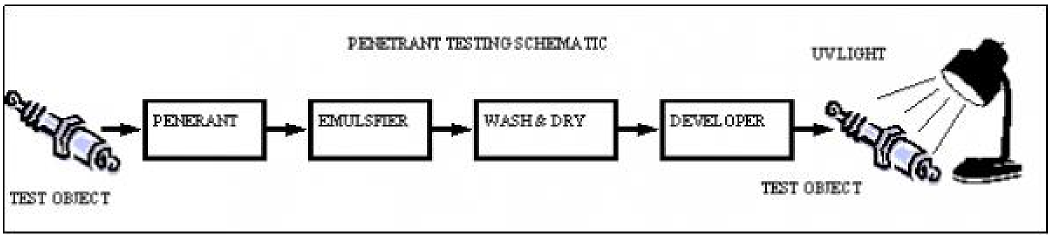

Fig. 1: Penetrant testing schematic

UV sources pose a potential health hazard risk to the skin and eye. UV-A sources used in PT emit some levels of the most harmful UV-C and UV-B rays. The UV-A rays are considered less of a risk, but the ACGIH / ICNIRP guidelines do state threshold limit values (TLV) for UV-A at 1 mW/cm^2 for an eight-hour exposure period. For UV-B, the TLV is much smaller at 0.1 Effective W/cm^2. So UV exposure of workers in PT environments should be tested in order to ensure safety as well as for quality control reasons.

7.10 Transmission and Reflection

“Measurement with Light” refers to the use of optical radiation as a tool for performing a measurement task. Reflectance and transmittance meters employ both light sources and a detection system. A spectrophotometer is a good example of this type of instrument.

Light is defined as optical radiation visible to the human eye over the wavelength range from 380 nm to 780 nm. The eye’s sensitivity to light varies over this spectral range, with the peak at 555 nm. The photometric action function V(λ) defined by the CIE applies to any application where light must be evaluated for visual purposes including reflection and transmission.

DIN 5036 part 3 and CIE 130-1998 recommend an integrating sphere with a minimum diameter of 50 cm for the measurement of photometric material properties such as light transmittance / reflectance, diffuse transmittance / reflectance and regular transmittance / reflectance.

8 Appendix

The appendix offers more information on:

- Relevant quantities, their symbols and units
- Summary of radiometric and photometric quantities
- National Calibration Laboratories
- Most relevant CIE, DIN and ISO publications and regulations

8.1 Relevant quantities, their symbols and units

Quantity	Symbol	Unit(s)
Wavelength	λ	1 nanometer = 1 nm = 10^{-9} m 1 Ångstrøm = 1 Å = 10^{-10} m
Power	P	1 Watt = 1 W
Solid angle	Ω	1 steradian = 1 sr
Radiant power or radiant flux	Φ_e	1 Watt = 1 W
Radiant intensity	I_e	1 W sr^{-1}
Radiance	L_e	1 W sr^{-1} m^{-2}
Irradiance	E_e	1 W m^{-2}
Radiant exitance	M_e	1 W m^{-2}
	E_e	1 W m^{-2}
Luminous flux	Φ_v	1 lumen = 1 lm photopic: 1 lm corresponds to Φ_e = 1 / 683 W at λ_m = 555 nm skotopic: 1 lm corresponds to Φ_e = 1 / 1700 W at λ'_m = 507 nm
Luminous intensity	I_v	1 candela = 1 cd = 1 lm / sr
Luminance	L_v	1 lm sr^{-1} m^{-2} = 1 cd m^{-2} = *1 nit* *1 stilb = 1 sb = 1 cd m^{-2}* *1 apostilb = 1 asb = 1 / π cd m^{-2}* *1 lambert = 1 L = 104 / π cd m^{-2}* *1 foot-lambert = 1 fl = 3.426 cd m^{-2}*
Illuminance	E_v	1 lux = 1 lx = 1 lm m^{-2} *1 phot = 1 ph = 10^{4} lx* *1 foot-candle = 1 fc = 1 lm ft^{-2} = 10.764 lx*
Luminous exitance	M_v	1 lm m^{-2}
	E_e	1 W m^{-2}
Spectral radiant power	$\Phi_\lambda(\lambda)$	1 W nm^{-1}
Spectral radiant intensity	$I_\lambda(\lambda)$	1 W sr^{-}1 nm^{-1}
Spectral radiance	$L_\lambda(\lambda)$	1 W sr^{-1} m^{-2} nm^{-1}
Spectral irradiance	$E_\lambda(\lambda)$	1 W m^{-2} nm^{-1}
Spectral radiant exitance	$M_\lambda(\lambda)$	1 W m^{-2}

E_e	1 W m^{-2}

Please note: Units in italics are not SI units, not consistent with CIE regulations and **should not be used!**

8.2 Summary of radiometric and photometric quantities

Quantification of electromagnetic radiation ...	Radiometric quantity	Spectral quantity	Photometric quantity	Quantity depends on
emitted by a source in total	radiant power Φ_e W	spectral radiant power $\Phi_\lambda(\lambda)$ W nm^{-1}	luminous flux Φ_v lm (lumen)	–
emitted in a certain direction	radiant intensity I_e W sr^{-1}	spectral radiant intensity $I_\lambda(\lambda)$ W sr^{-1} nm^{-1}	luminous intensity I_v lm / sr = cd	direction
emitted by a location on a surface	radiant exitance M_e W m^{-2}	spectral radiant exitance $M_\lambda(\lambda)$ W m^{-2} nm^{-1}	luminous exitance M_v lm m^{-2}	position on source’s surface
emitted by a location on a surface in a certain direction	radiance L_e W sr^{-1} m^{-2}	spectral radiance $L_\lambda(\lambda)$ W sr^{-1} m^{-2} nm^{-1}	luminance L_v lm sr^{-1} m^{-2} = cd m^{-2}	direction and position on source’s surface
impinging upon a surface	irradiance E_e W m^{-2}	spectral irradiance $E_\lambda(\lambda)$ W m^{-2} nm^{-1}	illuminance E_v lm m^{-2} = lx	position on irradiated surface

Tab. 1: Radiometric and photometric quantities

Radiometric quantities

In the following relations, X has to be replaced with one of the symbols Φ, I, L or E:

$$X_e = \int_0^\infty X_\lambda(\lambda)\,d\lambda$$

or

$$X_{e,range} = \int_{\lambda_1}^{\lambda_2} X_\lambda(\lambda)\,d\lambda$$

with λ_1 and λ_2 denoting the lower and the upper limit of the respective wavelength range (for instance, UV-A).

Photometric quantities

In the following relations, X has to be replaced with one of the symbols Φ, I, L or E:

Photopic vision

$$X_v = K_m \times \int_0^{\infty} X_\lambda(\lambda) \times V(\lambda)d\lambda \text{ with } K_m = 683 \text{ lm / W}$$

Scotopic vision

$$X_v = K'_m \times \int_0^{\infty} X_\lambda(\lambda) \times V'(\lambda)d\lambda \text{ with } K'_m = 1700 \text{ lm / W}$$

Basic integral relations between radiometric and photometric quantities

In the following, x has to be replaced either with e (denoting radiometric quantities) or v (denoting photometric quantities).

$$\Phi_x = \int_{4\pi} I_x \, d\Omega$$

$$I_x = \int_{\text{emitting surface}} L_x \cos(\vartheta) \, dA$$

$$M_x = \int_{2\pi} L_x \cos(\vartheta) \, d\Omega$$

8.3 National Calibration Laboratories

DKD – German Accreditation Institution

The German accreditation institution *DKD (Deutscher Kalibrierdienst)* was founded by German trade and industry and the German state represented by the *Physikalisch-Technische Bundesanstalt (PTB)*, the German national standards laboratory. The basic idea of the DKD is to transfer as many PTB responsibilities to the industry as possible, including the calibration of measurement and testing equipment. The DKD ensures traceability of measurement and testing equipment to national standards through accreditation and continuous auditing of industrial calibration laboratories. Therefore, calibrations carried out by DKD accredited laboratories offer a secured traceable and well-documented link to national calibration standards. An uninterrupted traceable chain of calibration links to national standards is absolutely necessary for acceptance of measurement devices by any quality management system. The qualification of the traceability to national standards is the job of the *Physikalisch-Technische Bundesanstalt (PTB)*, the German national standards laboratory. The PTB defines, effects, maintains and transmits the physical quantities of the SI-system, such as a meter, a second, a kilogram, a candela, etc. In order to ensure objective results, equal standards must be used. The calibration of measurement and testing setups based on SI-units is a basis for correct, comparable, recognizable and therefore measurable values that can be audited. Within the DIN ISO 9000 ff. standard, the relationship between quality management and calibration is partially interconnected for continuous control of measurement and testing equipment. DKD accredited calibration laboratories fulfill the requirements of the European standard EN 45001 (general criteria to operate a testing laboratory, May 1990) without exception. Outside of Europe, this standard is not compulsory. The ISO/IEC Guide 25 (General requirements on the competence of testing and calibration laboratories, December 1990) is recognized instead. EN 45001 and ISO/IEC Guide 25 are identical in terms of content. This is the basis for the mutual appreciation between the *European cooperation for Accreditation (EA)* and its partners outside Europe. In 1999 ISO/IEC 17025 took the place of EN 45001 and ISO/IEC Guide 25 thus eliminating any formal differences.

Existing DKD calibration laboratories automatically qualify for ISO/IEC/EN 17025 conformance.

More information on the DKD: http://www.dkd.eu

The European position of the DKD is noted by its membership in the *European Cooperation for Accreditation of Laboratories (EAL)* in Rotterdam, which was founded out of the *Western European Calibration Cooperation (WECC)* and the *Western European Laboratory Accreditation Cooperation (WELAC)* in 1994. Within the EAL, different national accreditation institutes cooperate with common goal being international acceptance of calibration certificates of the EAL-calibration laboratories. In November 2000, 34 accreditation institutions from 28 countries, including the PTB, the accreditation institution of the DKD, signed a *Mutual Recognition Arrangement (MRA)* of the *International Laboratory Accreditation Cooperation (ILAC).*

More information about this arrangement and the participating countries is available at http://www.ilac.org

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PTB – Physikalisch Technische-Bundesanstalt

The *Physikalisch-Technische Bundesanstalt (PTB)* is the highest technical authority for metrology in Germany. The PTB defines, effects, maintains and transmits the physical quantities of the SI-system, such as a meter, a second, a kilogram, a candela, etc. The PTB is the official accreditation institution for DKD calibration laboratories for optical radiation measurement quantities. Gigahertz-Optik operates one such calibration laboratory. The PTB is also actively working on bilateral acceptance on national standards. Because of their activities in 1995, a *Statement of Intent on Traceability of Measurement Standards* was signed between the *Physikalisch-Technische Bundesanstalt (PTB)* and the *American National Institute of Standards and Technology (NIST)*. The Equivalence of the National Standards of NIST and PTB for the SI Units of Luminous Intensity and Luminous Flux was officially recognized in April 1999.

More information on the PTB: http://www.ptb.de

NIST – U.S. National Institute of Standards and Technology

The Optical Technology Division of NIST's Physics Laboratory has the mandate to provide a high quality national measurement infrastructure to support industry, government and academia who rely on optical technologies for competitiveness and success. As a part of this mandate, the Division has the institutional responsibility to maintain two SI base units: the unit for temperature, the kelvin, above 1234.96 K and the unit of luminous intensity, the candela. As part of its responsibilities, the Division develops, improves and maintains the national standards for radiation thermometry, spectroradiometry, photometry, colorimetry and spectrophotometry. It also provides National measurement standards and support services to advance the use and application of optical technologies that are ideal for the ultraviolet range to microwave spectral regions for diverse industrial, governmental and scientific uses. The Division also disseminates these standards by providing measurement services to customers requiring calibrations of the highest accuracy and contributes to the intellectual reservoir of technical expertise by publishing descriptions of NIST developed advances in appropriate scientific journals and books. It also conducts basic, long-term theoretical and experimental research in photo-physical and photochemical properties of materials, in radiometric and spectroscopic techniques and instrumentation, in application of optical technologies in nanotechnology, biotechnology, optoelectronics, and in diverse industries reliant upon optical techniques.

More information on the NIST Physics Laboratory Optical Technology Division: http://www.nist.gov/optical-technology-portal.cfm

NRC – National Research Council Canada

The NRC’s Institute for National Measurement Standards Photometry and Radiometry Group maintains photometric, radiometric, spectrophotometric and colorimetric standards, and provides associated high-accuracy measurement services to companies, universities and government clients involved with lighting, transportation, manufacturing, telecommunications, public health and safety, as well as the environment.

More information on the NRC INMS Photometry and Radiometry: http://www.nrc-cnrc.gc.ca/eng/rd/mss

NPL – National Physical Laboratory UK

The NPL is UK’s National Standards Laboratory for Physical Measurements. NPL's *Optical Radiation Measurement (ORM)* Group provides services which are the backbone for optical radiation measurements in the UK and internationally. Here the UK's Primary Standards and scales are maintained and pioneering research in measurement science carried out. ORM anticipates and responds to industrial and academic measurement requirements for the entire IR, Visible and UV spectra, and provides a comprehensive range of measurement and calibration services, instrumentation products, training and consultancy. Some of the range of measurement and calibration services, which are traceable to national standards include the characterization and calibration of:

- all types of optical radiation sources
- optical radiation detectors and associated devices
- optical properties of materials and components
- aspects of appearance including color, haze and gloss

The development of NPL's primary standards and measurement scales, enables the UK to maintain the most accurate optical measurement references in the world as well as enable the fostering of new ideas and techniques. Areas in which NPL is a recognized world leader include the development of the first cryogenic radiometer and the use of lasers in radiometry.

More information on the NPL's ORM: http://www.npl.co.uk/optical-radiation-photonics

8.4 Most relevant CIE, DIN and ISO publications and regulations

DIN Publications

- **DIN 4512-8, Ausgabe: 1993-01**
  Photographische Sensitometrie; Bestimmung der optischen Dichte; Geometrische Bedingungen für Messungen bei Transmission

- **DIN 4512-9, Ausgabe: 1993-01**
  Photographische Sensitometrie; Bestimmung der optischen Dichte; Spektrale Bedingungen

- **DIN 5030-2, Ausgabe: 1982-09**
  Spektrale Strahlungsmessung; Strahler für spektrale Strahlungsmessungen; Auswahlkriterien

- **DIN 5031 Beiblatt 1, Ausgabe: 1982-11**
  Strahlungsphysik im optischen Bereich und Lichttechnik; Inhaltsverzeichnis über Größen, Formelzeichen und Einheiten sowie Stichwortverzeichnis zu DIN 5031 Teil 1 bis Teil 10

- **DIN 5031-2, Ausgabe: 1982-03**
  Strahlungsphysik im optischen Bereich und Lichttechnik; Strahlungsbewertung durch Empfänger

- **DIN 5033-7, Ausgabe: 1983-07**
  Farbmessung; Meßbedingungen für Körperfarben

- **DIN 5037 Beiblatt 1, Ausgabe: 1992-08**
  Lichttechnische Bewertung von Scheinwerfern; Vereinfachte Nutzlichtbewertung für Film-, Fernseh- und Bühnenscheinwerfer mit rotationssymmetrischer Lichtstärkeverteilung

- **DIN 5037 Beiblatt 2, Ausgabe: 1992-08**
  Lichttechnische Bewertung von Scheinwerfern; Vereinfachte Nutzlichtbewertung für Film-, Fernseh- und Bühnenscheinwerfer mit zu einer oder zwei zueinander senkrechten Ebenen symmetrischer Lichtstärkeverteilung

- **DIN 5039, Ausgabe: 1995-09**
  Licht, Lampen, Leuchten – Begriffe, Einteilung

- **DIN 5042-1, Ausgabe: 1980-10**
  Verbrennungslampen und Gasleuchten; Einteilung, Begriffe

- **DIN 5043-1, Ausgabe: 1973-12**

Radioaktive Leuchtpigmente und Leuchtfarben; Meßbedingungen für die Leuchtdichte und Bezeichnung der Pigmente

- **DIN 19010-1, Ausgabe: 1979-03**
  Lichtelektrische Belichtungsmesser; Skalen, Kalibrieren

- **DIN 58141-5, Ausgabe: 1993-11**
  Prüfung von faseroptischen Elementen; Bestimmung der Faserbruchrate von Licht- und Bildleitern

- **DIN 58141-10, Ausgabe: 1997-02**
  Prüfung von faseroptischen Elementen – Teil 10: Bestimmung der Beleuchtungsstärke und des effektiven Öffnungswinkels von Kaltlichtquellen

- **ISO 31-6, Ausgabe: 1992-09**
  Größen und Einheiten; Teil 6: Licht und verwandte elektromagnetische Strahlung

- **ISO 8599, Ausgabe: 1994-12**
  Optik und optische Instrumente – Kontaktlinsen – Bestimmung des Spektral- und Licht-Transmissionsgrades

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CIE Publications

- 13.3-1995: Verfahren zur Messung und Kennzeichnung der Farbwiedergabe-Eigenschaften von Lichtquellen

- 15.2-1986: Colorimetry, 2. Aufl.

- 15.4-2004: Colorimetry, 4. Aufl.

- 16-1970: Tageslicht

- 17.4-1987: Internationales Wörterbuch der Lichttechnik, 4. Aufl. (gemeinsame Veröffentlichung IEC/CIE)

- 18.2-1983: Grundlagen der physikalischen Photometrie, 2. Aufl.

- 19.21-1981: Analytisches Modell zum Erfassen des Einflusses von Beleuchtungsparametern auf das Sehleistungspotential eines Beobachters; Technische Grundlagen

- 19.22-1981: Analytisches Modell zum Erfassen des Einflusses von Beleuchtungsparametern auf das Sehleistungspotential eines Beobachters; Zusammenfassung und Anwendung des Modells

- 38-1977: Strahlungsphysikalische und lichttechnische Stoffkennzahlen und deren Messung

- 39.2-1983: Aufsichtsfarben für visuelle Signalgebung, 2. Aufl.
- 40-1978: Berechnungsverfahren für Innenbeleuchtung (Basisverfahren)
- 41-1978: Licht als visuelle Größe; Meßverfahren
- 44-1979: Absolute Verfahren zur Reflexionsmessung
- 46-1979: Veröffentlichungen über die Eigenschaften und Reflexionswerte von Reflexionsnormalen
- 51.2-1999: Eine Methode zur Gütebewertung von künstlichem Tageslicht für die Farbmessung (mit Zusatz 1-1999)
- 52-1982: Bemessung von Innenbeleuchtung
- 53-1982: Verfahren zur Kennzeichnung von Radiometern und Photometern
- 55-1983: Blendung in Arbeitsräumen
- 59-1984: Polarisation; Begriffe und Polarisation von Instrumenten
- 60-1984: Vision and the visual display unit work station
- 63-1984: Spektroradiometrische Messungen an Lichtquellen
- 64-1984: Determination of the spectral responsivity of optical radiation detectors
- 65-1985: Elektrisch kalibrierte thermische Empfänger optischer Strahlung
- 69-1987: Methods of characterizing illuminance meters and luminance meters: Performance, characteristics and specifications
- 70-1987: Bestimmung der absoluten Lichtstärkeverteilung durch Messung
- 75-1988: Darstellung spektraler Hellempfindlichkeitsfunktionen auf der Grundlage eines Helligkeitsabgleiches für monochrome punktartige Lichtquellen sowie für 2°- und 10°-Gesichtsfelder
- 76-1988: Vergleichsmessung des totalen spektralen Strahldichtefaktors (SRF) an lumineszierenden Werkstoffen
- 78-1988: Zusammenhang zwischen Leuchtdichte und Helligkeit; Literaturverzeichnis
- 82-1989: CIE History 1913 - 1988
- 84-1989: Lichtstrommessung

- 85-1989: Solare spektrale Bestrahlungsstärke
- 86-1990: Modifizierte Funktion des spektralen 2 - Hellempfindlichkeitsgrades für photopisches Sehen (CIE 1988)
- 87-1990: Farbmetrik an selbstleuchtenden Anzeigen; Literaturverzeichnis
- 95-1992: Kontrast und Sichtbarkeit
- 96-1992: Stand der Wissenschaft der elektrischen Lichtquellen - 1991
- 98-1992: Personendosimetrie von UV-Strahlung
- 101-1993: Parametrische Einflüsse auf die Farbabstandsbewertung; Zusammenfassung
- 105-1993: Spektroradiometrische Messung gepulster optischer Strahlung
- 106-1993: CIE-Sammlung Photobiologie und Photochemie (1993)
  - 106/1: Determining ultraviolet action spectra
  - 106/2: Photokeratitis
  - 106/3: Photoconjunctivitis
  - 106/4: A reference action spectrum for ultraviolet induced erythema in human skin
  - 106/5: Photobiological effects in plant growth
  - 106/6: Malignant melanoma and fluorescent lighting
  - 106/7: On the quantification of environmental exposures: limitations of the concept of risk-to-benefit ratio
  - 106/8: Terminology for photosynthetically active radiation for plants
- 108-1994: Richtlinien der empfohlenen Praxis für die Tageslichtmessung (inkl. Disk)
- 109-1994: Eine Methode zur Vorhersage korrespondierender Farben unter verschiedenen Farbumstimmungen und Beleuchtungsstärke-Adaptionen
- 114-1994: CIE Collection in photometry and radiometry
  - 114/1: Survey of reference materials for testing the performance of spectrophotometers and colorimeters

    - 114/2: International intercomparison on transmittance measurement - Report of results and conclusions
    - 114/3: Intercomparison of luminous flux measurements on HPMV lamps
    - 114/4: Distribution temperature and ratio temperature
    - 114/5: Terminology relating to non-selective detectors
    - 114/6: Photometry of thermally sensitive lamps
- 116-1995: Industrielle Farbabstandsbewertung
- 118-1995: CIE Collection in color and vision
    - 118/1: Evaluation of the attribute of appearance called gloss
    - 118/2: Models of heterochromatic brightness matching
    - 118/3: Brightness-luminance relations
    - 118/4: CIE guidelines for coordinated research on evaluation of color appearance models for reflection print and self-luminous display image comparisons
    - 118/5: Testing color appearance models: Guidelines for coordinated research
    - 118/6: Report on color difference literature
    - 118/7: CIE guidelines for coordinated future work on industrial color-difference evaluation
- 121-1996: Photometrie und Goniophotometrie von Leuchten
- 124-1997: CIE collection in color and vision, 1997
    - 124/1: Color notations and color order systems
    - 124/2: On the course of the disability glare function and its attribution to components of ocular scatter
    - 124/3: Next step in industrial color difference evaluation - Report on a color difference research meeting
- 125-1997: Standardisierte Erythemdosis
- 127-1997: Measurement of LEDs

- 130-1998: Praktische Methoden für Reflexions- und Transmissionsmessungen
- 134-1999: CIE-Sammlung Photobiologie und Photochemie 1999
    - 134/1: Standardization of the terms UV-A1, UV-A2 and UV-B
    - 134/2: UV protection of the eye
    - 134/3: Recommendations on photobiological safety of lamps. A review of standards
- 135-1999: CIE-Sammlung 1999 - Sehen und Farbe - Physikalische Messungen von Licht und Strahlung
    - 135/1: Disability glare
    - 135/2: Color rendering (TC 1-33 closing remarks)
    - 135/3: Supplement 1-1999 to CIE 51-1981: Virtual metamers for assessing the quality of simulators of CIE illuminant D50
    - 135/4: Some recent developments in color difference evaluation
    - 135/5: Visual adaptation to complex luminance distribution
    - 135/6: 45°/0° spectral reflectance factors of pressed polytetrafluoroethylene (PTFE) powder
- 138-2000: CIE-Sammlung Photobiologie und Photochemie 2000
    - 138/1: Blue light photochemical retinal hazard
    - 138/2: Action spectrum for photocarcinogenesis (non-melanoma skin cancers)
    - 138/3: Standardized protocols for photocarcinogenesis safety testing
    - 138/4: A proposed global UV index
- 139-2001: Der Einfluß von Tageslicht und künstlichem Licht auf tageszeit- und jahreszeitabhängige Zyklen beim Menschen - Eine Bibliographie
- 142-2001: Verbesserte industrielle Farbabstandsbewertung
- 148-2002: Wirkungsspektroskopie an menschlicher Haut mit durchstimmbaren Lasern
- 149-2002: Der Gebrauch von Wolfram-Glühlampen als Normallampen

- 151-2003: Spektral gewichtete solare ultraviolette Strahlung
- 176-2006: Geometrische Toleranzen für Farbmessungen
- 177-2007: Farbwiedergabe von weißen LED-Lichtquellen
- 198-2011: Determination of Measurement Uncertainties in Photometry
- 205-2013: Bewertung lichttechnischer Gütemerkmale für die Innenraumbeleuchtung mit LED-Beleuchtungssystemen
- 206-2014: Die Auswirkungen der spektralen Lichtverteilung auf die Beleuchtung von Wohngebieten und Fußgängerzonen
- 207-2014: Empfindlichkeit der menschlichen Haut hinsichtlich UV-Strahlung, ausgedrückt als Minimale Erythemdosis (MED)
- 208-2014: Wirkung der Reizgröße auf die Farberscheinung
- 209-2014: Erklärung der Begrifflichkeiten für UV-Dosen und Effekte auf Menschen
- 210-2014: Photometrie mit V(λ)-angepassten Empfängern als Bezugs- und Transfernormale
- 211-2014: Farberscheinung in peripherer Wahrnehmung
- 212-2014: Leitfaden zur optimalen Vorgehensweise bei psychophysischen Verfahren zur Messung relativer räumlicher Helligkeit
- 213-2014: Leitfaden für Protokolle zur Beschreibung der Beleuchtung
- CIE TN 001:2014 CIE (1999), Color rendering (TC 1-33 closing remarks), Publication 135/2, Wien: CIE Central Bureau, ISBN 3-900734-97-6
- CIE (2004), CIE Colorimetric and Color Rendering Tables, Disk D002, Rel 1.3
- DIN 6169-1:1976-01
- ISO CIE 19476 Characterization of the Performance of Illuminance Meters and Luminance Meters
- ISO 23539; CIE S010 Photometrie – Das CIE-System der physikalischen Photometrie