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Introduction, Properties and Concepts of Light and Color

I. Introduction

Light, or the visible part of the electromagnetic radiation spectrum, is the medium through which human beings receive a major portion of environmental information. Evolution has optimized the human eye into a highly sophisticated sensor for electromagnetic radiation. Joint performance between the human eye and visual cortex, a large part of the human brain, dwarfs recent technical and scientific developments in image processing and pattern recognition. In fact a major part 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 not only encompasses visible 'light' but radiation invisible to the human eye as well. The term optical is used because this radiation follows the laws of geometrical optics.

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

This tutorial is an introduction to the basic nature of light and color, radiometric, photometric, colorimetric, reflection and transmission principles, quantities, symbols and units. 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 these tutorials. Many international organizations including the CIE (Commission Internationale de l'Eclairage) have adopted this system of units exclusively. The terminology used follows that of the CIE *International Lighting Vocabulary*.

II. 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 (figure II.1.), as long as the variation of wavelength is limited to the range between 400 nm and 800 nm (1 nm = 1 nanometer = 10^{-9} m). In the optical range of the electromagnetic spectrum, wavelength is sometimes also given in Ångstrøm (Å= 10^{-10} m). Outside this range, our eye is insensitive to electromagnetic radiation and thus we have no perception of ultraviolet (UV, below 400 nm) and infrared (IR, above 800 nm) radiation.

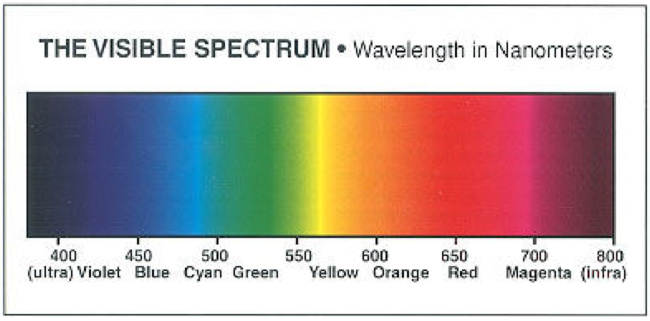


Fig. II.1. Monochromatic electromagnetic radiation of different wavelengths between 400 nm and 800 nm causes the impression of different colors. Outside this wavelength range, the human eye is insensitive.

II.1. The wavelength range of optical radiation

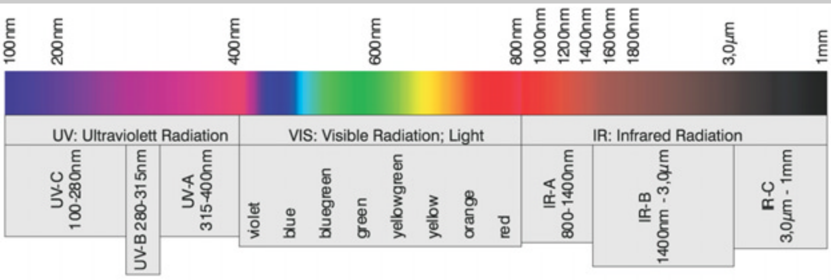
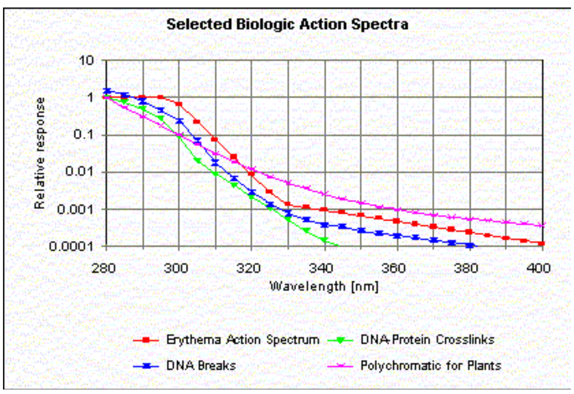


Fig. II.2. Wavelength ranges of electromagnetic radiation.

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. Similarly, **infrared (IR) radiation** covers the wavelength range above 800 nm and is subdivided in IR-A, IR-B and IR-C ranges (DIN 5031, part 7).

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 and thus causes melanoma and other types of skin cancer. As the strength of radiation effects on matter does not change abruptly with wavelength, different authors define UVA and UVB ranges slightly different. As an example, the US Food and Drug Administration (FDA) and the US Environmental Protection Agency (EPA) define the UV-A range between 320 nm and 400 nm. However, two of the main standardization authorities, the CIE and the DIN, agree with their definition of the UVA range 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, such as DNA damage, formation of erythema (sunburn) and of non-melanoma skin cancer, tanning of the human skin and the photosynthesis process in green plants, have been studied and quantified by spectral sensitivity functions (Fig.). Especially when related to certain biological reactions, the term "action spectrum" is often used instead of "spectral sensitivity".



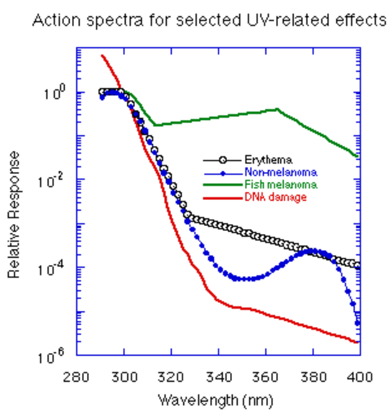


Fig. II.3. Action spectra for various biological reactions to UV radiation

II.2. Velocity, amplitude, wavelength, and frequency - the measures of a wave

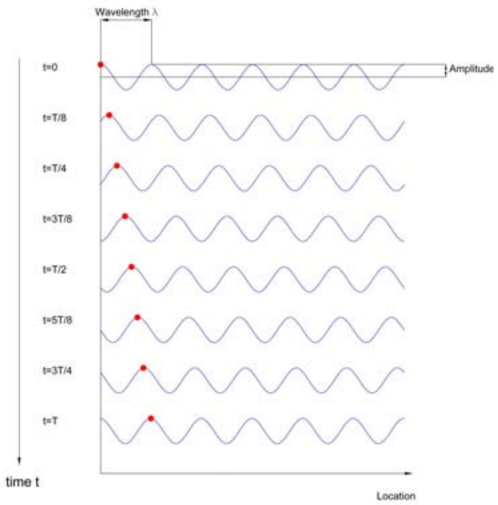
Like all other waves (waves in a string, water waves, sound, earthquake waves ...), light and electromagnetic radiation in general can be described as a vibration (more general: a periodical change of a certain physical quantity) that propagates into space (Fig. II.4.a). The propagation is caused by 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. II.4.b).

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 still can 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 nature of the wave and on the medium (see Table II.Ibelow).
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 (Fig. II.4.a), this value is identical with half of the vertical distance between the wave's crest and its trough. In the case of a pressure wave in air („sound", Fig. II.4.b), the amplitude is half of the pressure difference between rarefaction and compression.
- 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** ν 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

$$\nu = 1 / T$$

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:



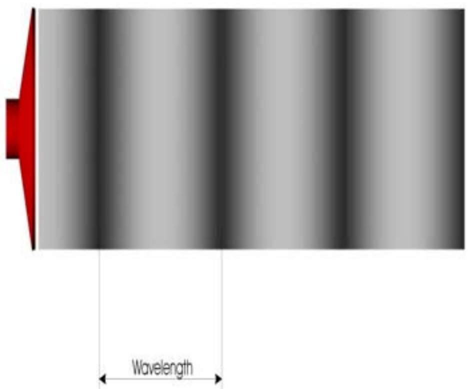


Fig. II.4 (a) Formation and propagation of a wave in a string. (b) Formation and propagation of a compression wave in air, a phenomenon colloquially called sound

During the time span a crest needs to travel the distance of one wavelength λ from location X to location Y (Fig. II.4.a), the next crest arrives at location X. Thus, this time span is identical with the wave's period T. But when a crest needs the time span T to travel the distance λ, its velocity c amounts to

$$c = \lambda / T = \lambda \cdot \nu \qquad \text{Equ. II.1}$$

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 of equation II.1..

As 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 for which medium the actual wavelength value is given. According to CIE regulations, which are also 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 relation

$$\lambda_{Medium} = \lambda_{Vacuum} / n_{Medium} = \lambda_{Air} \cdot n_{Air} / n_{Medium}$$

with

$$n_{Air} = c_{Vacuum} / c_{Air} \text{ and } n_{Medium} = c_{Vacuum} / c_{Medium}$$

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}.

	Sound	Optical (electromagnetic) radiation		
		at λ= 434 nm	at λ= 589 nm	at λ= 656 nm
in vacuum	-	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	299708 km/s (n = 1.340)	224900 km/s (n = 1.333)	225238 km/s (n = 1.331)

Table II.I Velocities of sound and light in air and in water. For optical radiation, the respective index of refraction is given in parenthesis

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II.3. Spectra of various light sources

A spectrum generally describes the variation of a certain physical quantity as a function of wavelength. The term “spectrum” without any further specifications refers to the quantification of the monochromatic intensity as a function of wavelength (the term “spectrum” is also used for other (physical) quantities apart of intensity, but is then always used with a specific prefix. As an example, the strength of a biological reaction (for example erythema – see § VI.1) to light with different wavelengths is described by an “action spectrum”). As an example, the next figure shows spectra of an incandescent bulb, natural sunlight and two types of discharge lamps.

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 are direct and diffuse sunlight and 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. II.5.).

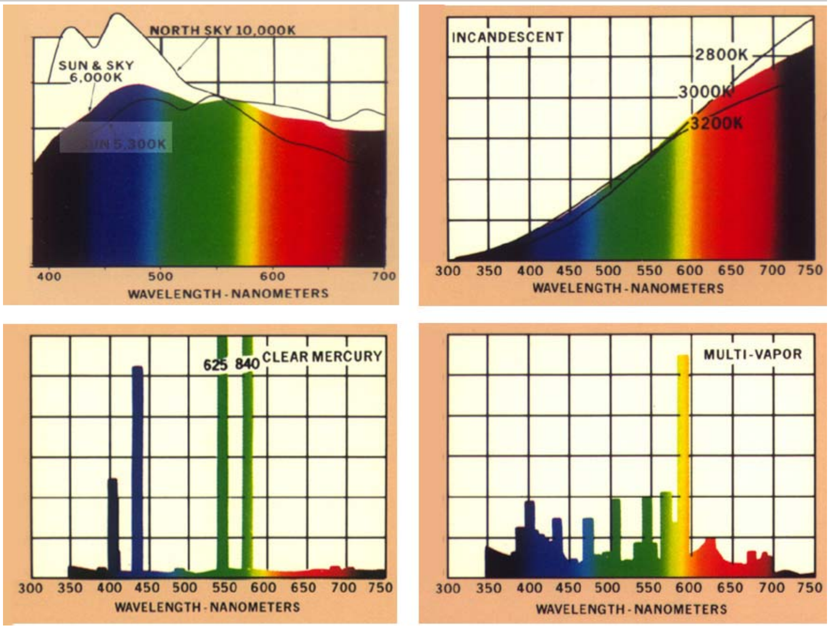

Fig. II.5. Emission spectra of natural light from the sun and the sky and of artificial light from incandescent bulbs at different temperatures, from a mercury vapor lamp and from a multi-vapor lamp.

II.4. Basic radiometric quantities

The whole discipline of optical measurement techniques can be roughly subdivided into the two areas of **photometry** and **radiometry**. Whereas the central problem of photometry is the determination of optical quantities closely related to the sensitivity of the human eye (see § II.6.), 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 labeled 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 purpose 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. In paragraph II.5., the concept of differential quantities and integral calculus is briefly explained for spectral radiometric quantities.

II.4.a. 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 arbitrary radius r (see Fig.II.). Then, a certain part of this full visual field defines an area A on the sphere’s surface and the solid angle Ω is defined by

$$\Omega = A / r^2$$

Equ. II.2

As 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.II.area A is the area of a spherical calotte. However, as the solid angle is not only defined for conical parts of the full visual field, area A can be any arbitrary shape on the sphere’s surface.

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

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

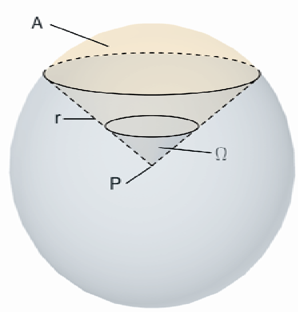

Fig.II.6. The solid angle Ω quantifies a certain part of the visual field, seen by an observer located at P

II.4.b. Radiant power or radiant flux Φ_e

Radiant power Φ_e is defined by 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.

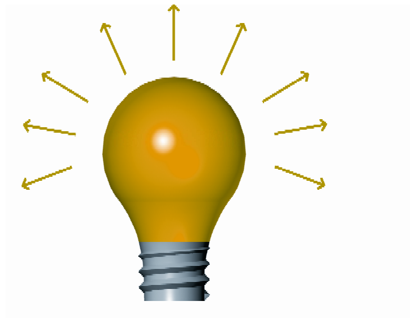

Fig. II.7. The radiant power of Φ_e of a light source is given by its total emitted radiation.

II.4.c. 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**.

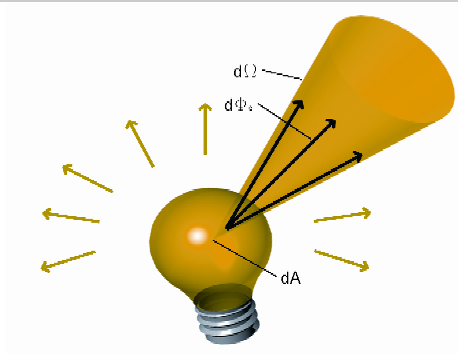

Fig. II.8. Typical directional distribution of radiant intensity for an incandescent bulb.

II.4.d. Radiance L_e

Radiance L_e describes 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. Within the frame of this tutorial, the most relevant application of radiance describing the spatial emission characteristics of a source is discussed). The radiant power $d\Phi_e$ emitted by a (differential) surface element dA in the direction of the (differential) solid angle element $d\Omega$ is given by

$$d\Phi_e = L_e \cos(\vartheta) \, dA \, d\Omega$$

Equ.II3

In this relation, ϑ is the angle between the direction of the solid angle element $d\Omega$ 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,

$$I_e = \int_{\text{emitting surface}} L_e \cdot \cos(\vartheta) dA$$

Equ.II.4

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/(m²·sr)**.

II.4.e. Irradiance E_e

Irradiance E_e describes 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 maximised when the surface element is perpendicular to the beam:

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

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

$$E_e = E_{e,normal} \cos(\vartheta) \qquad \text{Equ.II.5}$$

The unit of irradiance is **W/m²**.

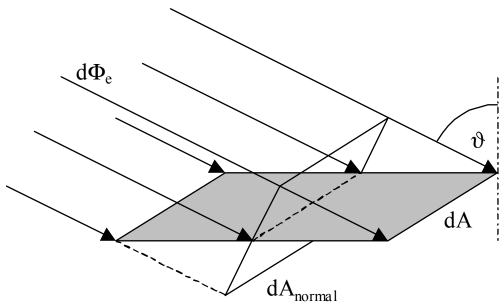

Fig. II.9 – Irradiance is defined as incident radiant power $d\Phi_e$ per surface area element dA.at P

Gigahertz-Optik

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II.4.f. Radiant exitance M_e

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

$$d\Phi_e = M_e\, dA$$

From the definition of radiance follows that the (differential) amount radiant exitance dM_e emitted or reflected by a certain location on a surface in the direction of the (differential) solid angle element $d\Omega$ is given by

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

and consequently

$$M_e = \int_{2\pi\, sr} L_e \cos(\vartheta)\, d\Omega \qquad \text{Equ.II6}$$

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 § II.8.a).

II.4.g. 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 quantify not only the absolute amount of these quantities but also the contribution of light from different wavelengths, the respective **spectral** quantities are defined.

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 $\lambda+d\lambda$ is given by

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

This equation can be visualised geometrically (see Fig. II.10.). As $d\lambda$ is infinitesimally small, spectral radiant power $\Phi_\lambda(\lambda)$ is approximately constant in the interval between λ and $\lambda+d\lambda$. Thus, the product $\Phi_\lambda(\lambda)\, d\lambda$ equals the area under the graph of $\Phi_\lambda(\lambda)$ in the interval between λ and $\lambda+d\lambda$. 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 (see Table VII.IV and Table VII.V).

Generally, a radiant quantity can be calculated from the respective spectral quantity by integration over wavelength from $\lambda=0$ to $\lambda=\infty$. However, this integration is often restricted to a certain wavelength range, which is indicated by the respective prefix. For instance, UVA irradiance is defined as

$$E_{e,UVA} = \int_{315\,nm}^{400\,nm} E_\lambda(\lambda)\, d\lambda$$

as the UVA range is defined from $\lambda = 315$ nm to $\lambda = 400$ nm.

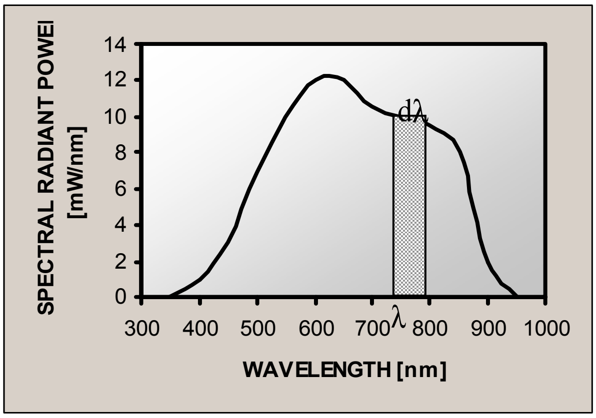


Fig.II.10. Relation between spectral radiant power $\Phi_\lambda(\lambda)$ and radiant power Φ_e visualized at a hypothetical example. Radiant power emitted in the wavelength interval between λ and $\lambda+d\lambda$ is given by the area of the shaded rectangle, which amounts to $\Phi_\lambda(\lambda)\, d\lambda$. 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.

II.5. Calculation of radiometric quantities - Examples

II.5.a. 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 in 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/ As the source emits light symmetrical in all directions, its radiant intensity is equal for all directions and amounts to $I_e = \Phi_{e,source} / 4\pi$ sr = 10 W / 4π sr = <u>0.796 W / sr</u>.

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

$$d\Omega = dA / r^2$$

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

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

Thus, the irradiance at distance r amounts to

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

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 $4r^2\pi$. As 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 / area of this surface = $\Phi_{e,source} / 4\pi r^2$

which is identical with the result above.

Remark: The fact that E is proportional to r^2 is generally known under the name "*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, and then the "inverse square law" still holds true when distance r is measured from this virtual point source (see Example 2). However, when the source cannot be assumed point like and every point of the source emits light in more than a single direction , the "inverse square law" no longer holds true. As an example, this is the case for fluorescent tubes.

II.5.b. 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 figure below). Assuming that the mirror reflects without any losses and uniform distribution of power over the cone,

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

a/ In 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 radius of 0.05 m. If we assume that irradiance is constant all over this circle and we neglect the fact that the surface is not everywhere strictly perpendicular to the beam, we can calculate the irradiance at a distance of 25 cm from the flashlight's front window:

E = radiant power impinging upon a surface / area of this surface
== $0.2 / 0.05^2 \pi$ W / m²
E ≈ <u>25 W / m²</u>

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 by the area of a circle with a radius of 5 cm (= 0.05 m), we get

$$\Omega = A_{Circle} / r^2$$

with r describing the distance of the circle form the cone's vertex.

From Fig. II.11, we get

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

and

$$x / x{+}0.25 = 0.03 / 0.10$$

from which we calculate

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

and

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

Thus, the cone defines a solid angle given by

$$\Omega = A_{Circle} / r^2 = 0.05^2\,\pi / 0.357^2 = 0.0616 \text{ sr}$$

and the flashlight's radiant intensity amounts to

$$I = \Phi / \Omega = 0.2 / 0.0616 \text{ W / sr} = \underline{3.25 \text{ W / sr}}.$$

Remark: As 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" holds true for this configuration. However, the distance r which the law relates to has to be measured from the position of the virtual point source.

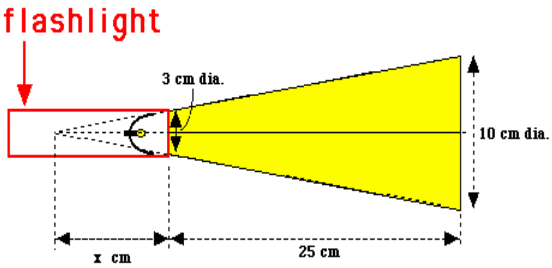


Fig. II.11 - Calculating the irradiance caused by a flashlight.

II.5.c. Example 3: The Lambertian surface

By definition, a **Lambertian surface** either emits or reflects radiation into all directions of a hemisphere with constant radiance L_e (Fig.II.12). From Equ.II.4 in paragraph II.4.d. follows that the directional distribution of radiant intensity is given by

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

with

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

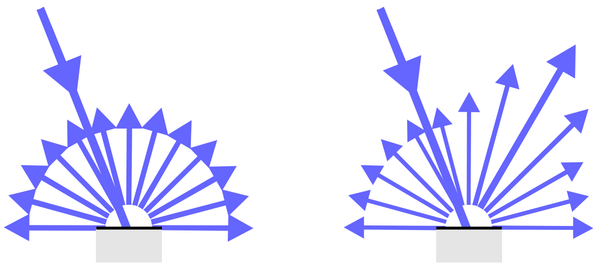
whereby $I_{e,0}$ denotes radiant intensity emitted in the direction perpendicular to the surface and $I_e(\vartheta)$ denotes radiant intensity emitted in a direction enclosing the angle ϑ with the surface's normal. Calculating the surface's exitance M_e from Equ.II.6 in paragraph II.4.f. by use of the relation $d\Omega = \sin(\vartheta)\, d\vartheta\, d\varphi$, we get

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

Equ.II7

The respective relations for photometric quantities (see § II.6.) characterizing a Lambertian surface can be derived by replacing the index "e" by the index "v".

Reflecting Lambertian surfaces are widely used in light measurement for well defined, perfectly diffuse scattering fully independent of the direction of the incoming beams. Thus, the radiance reflected from a certain location on the surface in a certain direction 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 by an integration over all directions of a solid angle of 4π or 2π. Lambertian reflection is especially desired for the coating of integrating spheres, which are widely used for detector input optics or for output optics of radiance or luminance standards.



Ideal diffuse reflection (lambertian surface)   Diffuse reflection with directional components

Fig.II.12. Constant spatial distribution of radiance L_e after ideal diffuse reflection at a Lambertian surface

II.6. Spectral sensitivity of the human eye

The sensitivity of the human eye to light of a certain intensity varies strongly over the wavelength range between 380 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, the spectral sensitivity of the human eye under dark adapted conditions (scotopic vision), defined by the spectral luminous efficiency function V'(λ), becomes 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.

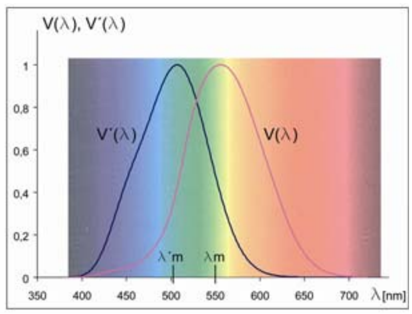


Fig. II.13. Spectral luminous efficiency functions V (λ) for photopic vision and V'(λ) for scotopic vision, as defined by the CIE.

II.7. Basic photometric quantities

One of the central problems of optical measurements is the quantification of light sources and lightning 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, which differ from the respective radiometric quantities only in 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 the scotopic spectral luminous efficiency function (see § II.6). 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", and photometric quantities relating to scotopic vision are denoted by an additional prime, for example Φ_v'. The following explanations are given for the case of photopic vision, which describes the eye's sensitivity under daylight conditions, thus being relevant 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 takes place in the range in between, no spectral luminous efficiency function has been defined yet). However, the respective relations for scotopic vision can be easily derived when replacing V(λ) by V'(λ) and replacing K_m (= 683 lm / W) by K'_m (= 1700 lm / W) (see definition in § VII.2).

As the definition of photometric quantities closely follows the corresponding definitions of radiometric quantities, the corresponding equations hold true – the index "e" just 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.

II.7.a. 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 unit of luminous flux is lumen (lm), and 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 by the symbol K_m (the value of K_m = 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 II.7.f.

II.7.b. 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 radiometric quantity "radiant intensity" I_e. 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

$$d\Phi_v = I_v \cdot d\Omega$$

and thus

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

The unit of luminous intensity is lumen per steradian (lm / sr), which is abbreviated with the expression "candela" (**cd**):

$$1 \text{ cd} = 1 \text{ lm / sr}$$

II.7.c. 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. Within the frame of this tutorial, 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

$$d\Phi_v = L_v \cos(\theta) \cdot dA \cdot d\Omega$$

with θ denoting the angle between the direction of the solid angle element d Ω and the normal of the emitting or reflecting surface element dA.

The unit of luminance is

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

II.7.d. 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

$$d\Phi_v = E_v \cdot dA$$

Generally, the surface element can be oriented at any angle towards the direction of the beam. Similar to the respective relation for irradiance, 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)**, and

II.7.e. Luminous exitance M_v

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

$$d\Phi_v = M_v \cdot dA$$

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.

II.7.f. 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,

$$X_v = X_e * V(\lambda) * 683 \text{ lm / W}$$

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

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

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

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

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 with K_m = 683 lm / W, so

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

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

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

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

II.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. II.14). When no diffusion occurs, reflection or transmission of an unidirectional beam results in an unidirectional beam according to the laws of geometrical optics (Fig. II.15). In this case, we speak about **regular reflection** (or **specular 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.

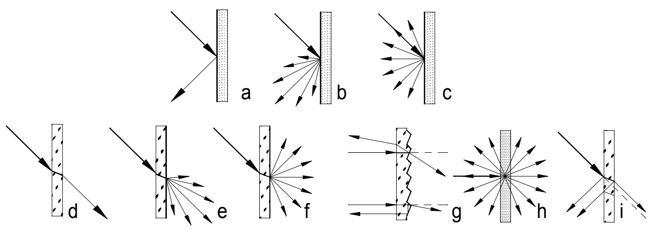


Fig. II.14 - a-c: Direct, mixed and diffuse reflection d-f: direct, mixed and diffuse transmission

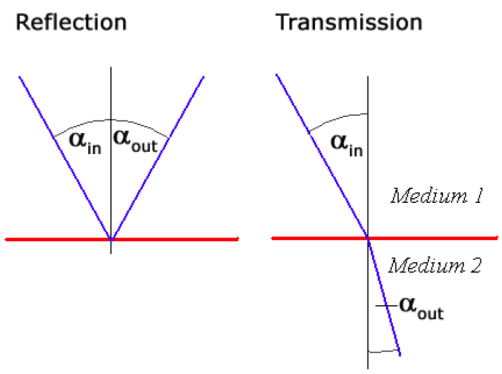


Fig. II.15 - When directly reflected or directly transmitted, an unidirectional beam follows the laws of geometrical optics: direct reflection (left): $\alpha_{in} = \alpha_{out}$, direct transmission (right): $n_1 \cdot \sin(\alpha_{in}) = n_2 \cdot \sin(\alpha_{out})$ with n_1 and n_2 denoting the respective medium's index of refraction

II.8.a. 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

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

and 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,

$$\rho = \frac{d\Phi_{e,reflected}}{d\Phi_{e,incident}} = \frac{M_e \cdot dA}{E_e \cdot dA} = \frac{M_e}{E_e}$$

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

Properties and Concepts of Light and Color

Quantities such as reflectance and transmittance are used to describe the optical properties of materials. The quantities can apply to either complex radiation or to 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 paragraph III.1.f below.

II.8.b. 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 thus 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.). 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

$$dL_e = BRDF \cdot dE_e$$

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 generally is 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 by the Greek letter ρ, which bears the danger of mixing the BRDF up with reflectance (see foregoing paragraph).

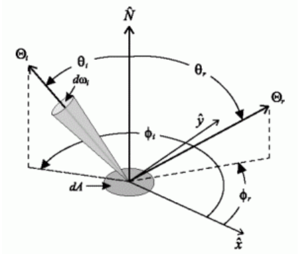


*Fig. II.16 - Geometry used for the definition of the bidirectional reflectance distribution function (BRDF). The BRDF depends on the directions of incident **and** reflected radiation, which are given by the angles ϑ_i and ϑ_r, which are measured relative to the reflecting surface's normal, and the azimuth angles φ_i and φ_r, which are measured in the plane of the reflecting surface.*

II.9. The perception of color

Color sensations are human sensory perceptions, and color measurement technology must express them in descriptive and comprehensible quantities. DIN 5033, Part 1, 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 neighbouring 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 the term "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, the 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 into nervous stimulation, which is in turn transmitted to the appropriate part of the brain, where it is experienced as color. The sensation of color depends not 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 amongst the contributory factors.
Color manifests itself in the form of light from self-emitting light sources, surface colors (of non-self emitting light sources) and in the intermediate form of the luminescent colors of dyestuffs such as optical brightening agents and dayglow 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.

II.9.a. 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 wavelength of light (Fig. II.17.). As an example, light with a wavelength of 650 nm wavelength is perceived as „red" and light with a wavelength of 550 nm is perceived as „green". However, there are colors, such as purple, which 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. As 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, which is shown in Fig. for the average normal sighted human eye. If monochromatic radiation irradiates the eye, as it 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 exclusively 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 - in the absence of a signal from the other cones - as the color „red". Therefore, these cones are called „red cones". Similarly, the two other types of cones are called „blue cones" and "green cones".

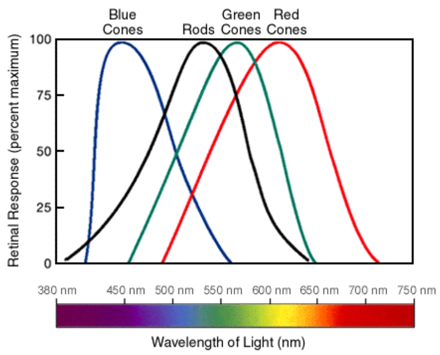


Fig. II.17 - Relative spectral sensitivity of all four types of the human eyes retinal light receptors. The three types of cones are responsible for photopic vision, whereas the rods are responsible for scotopic (night) vision

II.9.b. Color addition

As discussed above, monochromatic light of a certain wavelength might predominately 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. Red and green cones, for instance, are both excited by monochromatic light of 580 nm, and a signal from these two types of cones – with the simultaneous absence of a signal from blue cones – produces the color perception of "yellow".
However, our visual system cannot discriminate 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 comparably stimulated and blue cones are not stimulated at all. Similarly, 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. II.17). 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 (Figure II.18). 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 by color addition forms the **RGB color space**, as they are based on the three (additive) primary colors red, green and blue.

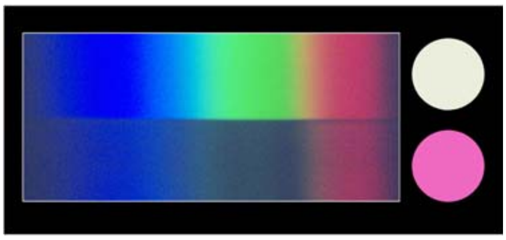


Fig. II.18 - The effect of color addition demonstrated with white light from an overhead projector before (top) and after (bottom) passing through a magenta filter. To the left, the respective spectral decomposition is shown, whereas the circle to the right shows the resulting color impressions. It can be clearly seen that the filter strongly absorbs light from the green part of the visual spectrum, whereas blue and red light pass 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.

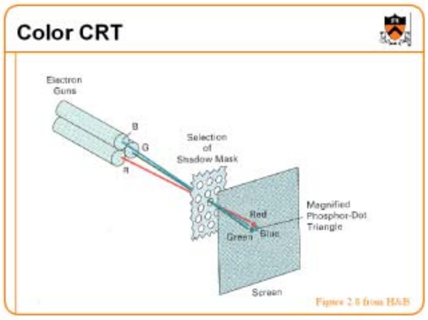


Fig. II.19 - An RGB monitor consists of tiny red, green and blue spots. Variation of their brightness produces the impression of different colorsby color addition.

II.9.c. 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 transmits only 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 about 500 nm and reflecting wavelengths above appears yellow when irradiated with white light. So, 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. As the effect of filters on transmitted light is the same as the effect 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. So, 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, in reality the absorption properties of these pigments are never ideal, thus four-color-printing uses a black pigment in addition. Colors produced by a combination of **c**yan, **y**ellow, **m**agenta and blac**k** form the so called **CYMK color space**.

Fig. II-20 - 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.

II.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 characterised, $\varphi_\lambda(\lambda)$ 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 characterised, $\varphi_\lambda(\lambda)$ 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. As 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 D_{56} is representative of average daylight with a correlated color temperature of 6500 K (for the definition of color temperature, see below).

II.10.a. 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 which 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 standardised **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** $\bar{x}(\lambda)$ $\bar{y}(\lambda)\bar{z}(\lambda)$ These colour 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 field of view of 10°, the CIE specifies another set of colour matching $\bar{x}_{10}(\lambda)$ $\bar{y}_{10}(\lambda)$ $\bar{z}_{10}(\lambda)$ functions

This set defines the **CIE 1964 supplementary standard colorimetric observer**, which has to be used for fields of view larger than 4°.

Although RGB and XYZ color matching functions can be equally used to define three parameters which numbers uniquely describe a certain color perception, the XYZ color matching functions are preferred as $\bar{y}(\lambda)$ they have positive values for all wavelengths (Fig. II.21). In addition, is equal to the CIE spectral luminous efficiency function V(λ) for photopic vision.

The XYZ tristimulus values of a certain spectral color

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

$$Y = k \int_\lambda \varphi_\lambda(\lambda) \cdot \bar{y}(\lambda) d\lambda$$

$$Z = k \int_\lambda \varphi_\lambda(\lambda) \cdot \bar{z}(\lambda) d\lambda$$

stimulus function $\varphi_\lambda(\lambda)$ are calculated by

The choice of the normalisation constant k depends on the colorimetric task:

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

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

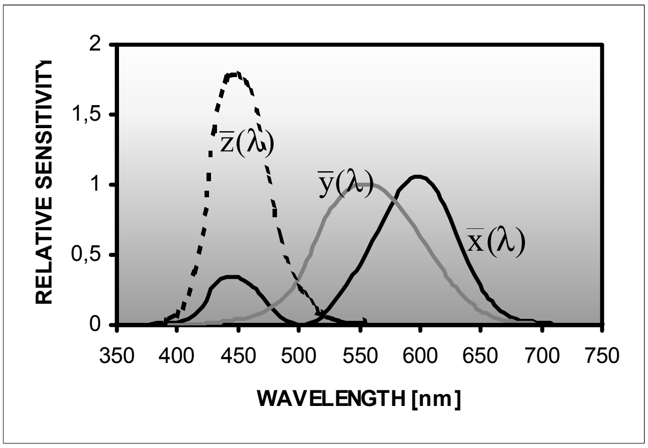


Fig. II.21 - XYZ color matching functions as defined by the CIE 1931 standard colorimetric observer. $\bar{x}(\lambda)$ (solid black line) consists of a short- and a long-wavelength $\bar{y}(\lambda)$ part, and (solid gray line) is identical with the CIE spectral luminous efficiency function V(λ).

II.10.b. The (x,y)- and (u',v')-chromaticity diagrams

Although the XYZ tristimulus values define a three-dimensional color space representing all possible color perceptions, for most applications the representation of color in a two-dimensional plane is sufficient. One possibility for a two-dimensional 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:

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

Although widely used, the (x, y) chromaticity diagram has a major disadvantage of non-uniformity as geometric distances in the (x, y) chromaticity diagram do not correspond to perceived color differences. Thus, in 1976 the CIE defined the **uniform (u', v') chromaticity scale (UCS) diagram**, with its coordinates defined by

$$u' = \frac{4X}{X+15Y+3Z} \qquad v' = \frac{9Y}{X+15Y+3Z}$$

Although this definition of the coordinates u' and v' 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.

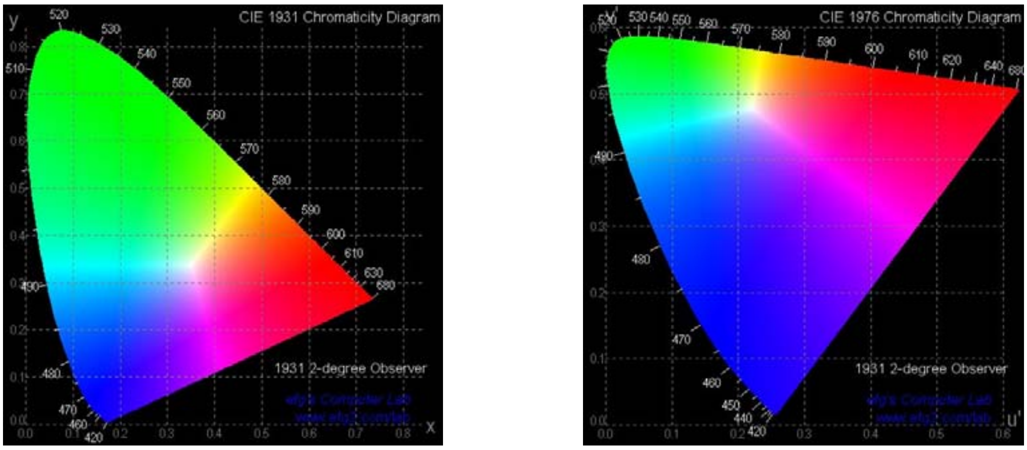


Fig. II.22 - The CIE 1931 (x,y) chromaticity diagram and the CIE 1976 (u', v') chromaticity diagram.

II.10.c. Correlated color temperature

The **correlated color temperature** is used to characterize the spectral distribution of optical radiation emitted by a light source. This characterisation corresponds to the projection of a two-dimensional chromaticity diagram onto a one-dimensional scale and thus is 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 to 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 with dominated by short (bluish) wavelengths correspond to a high correlated color temperature.

As an 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.

III. 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 impinging upon a surface. Obtaining this information has its price: Spectroradiometers are highly sophisticated optical measurement devices and in general, their proper calibration, operation and maintenance is rather time consuming. However, for the vast majority of applications, integral detectors (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, multiplied with the detector's spectral sensitivity (see § III.2)) offer an economical and user friendly alternative: In most cases, it is not necessary to determine the exact spectral distribution of the measured quantity, and it is sufficient to use a detector especially 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), and detectors for solar UV irradiance potentially harmful to the human skin are matched to the CIE erythema action spectrum.
As integral detectors provide just a single output signal (usually voltage or photocurrent), they are much easier to characterise than spectroradiometers. The main parameters determining the usability and the quality of an integral detector are

- The detector's input optics, which determines its directional sensitivity
- The detector's spectral sensitivity
- The dynamic range, over which the detector's output is proportional to the input signal's intensity
- The detector's time behaviour

Refer to § III.5. for more info about calibration laboratory. More information is also available about our calibration services and calibration standards as well as Uniform Light Sources.

III.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 an integrating sphere with the light source placed either inside the sphere or directly at the sphere's entrance port. Refer also to § III.1.b.
- The determination of irradiance and illuminance requires a detector's directional sensitivity proportional to the cosine of the angle of incidence, which can be achieved either by a flat field detector or by the entrance port of an integrating sphere. Refer also to § III.1.c.
- Radiant and luminous intensity, radiance and luminance are quantities which are defined as a function of solid angle, and therefore the detector's field of view has to be limited to a small angle. This can be achieved by baffles and/or lenses arranged in a tube.

Refer also to § III.1.d and III.1.e.

III.1.a. Integrating spheres used with integral detectors

In an ideal case, the inner surface of an integrating is a perfect diffuse Lambertian reflector (see § II.4.c). Thus, the directional distribution of reflected radiation is independent from the directional distribution of incident radiation, and no specular reflection occurs.

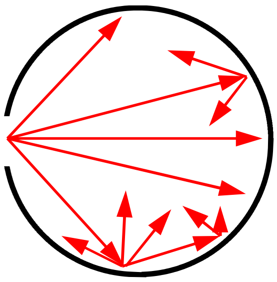


Fig. III.1. Ideal multiple Lambertian reflections inside an integrating sphere

Due to its geometry, an ideal integrating sphere is characterised by constant irradiance (or illuminance)) at all locations of it's inner surface. Furthermore, the level of this irradiance (illuminance solely depends on the total amount of radiant power (luminous flux) entering the sphere and is independent from its directional distribution.
However, real surfaces do not show perfect Lambertian reflection properties. Although minimised 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, at the input and exit ports, where the coating material is missing, radiation is far from being ideally reflected. For these reasons, the quality of measurements performed with integrating spheres strongly depends on the sphere's coating material, on the exact position of baffles and on 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 for the determination of radiometric and photometric quantities, defining the arrangement of the sphere's entrance and exit ports and internal baffles (see § III.1.b. to III.1.f).
Apart from their directional sensitivity, integrating spheres offer additional advantages:

- The high number of internal reflections generally eliminates a detector's sensitivity to the polarisation of incident radiation.
- For the characterisation of powerful light sources, an integrating sphere can be used for attenuation in order to prevent saturation effects of the detector. As this attenuation results in an increase of internal temperature, the light source's maximum power is limited by the sphere's temperature range of operation.
- In general, geometric alignment of source and integrating sphere is not very critical, which simplifies calibration and measurement procedures.

For more detailed information about the theory and application of integrating spheres, see chapter V.

III.1.b. Measurement of radiant power and luminous flux

<u>Radiant power and luminous flux of lasers and spot sources</u>

Lasers, LEDs, spot lamps, endoscopes, optical fibres 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 does thus 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.

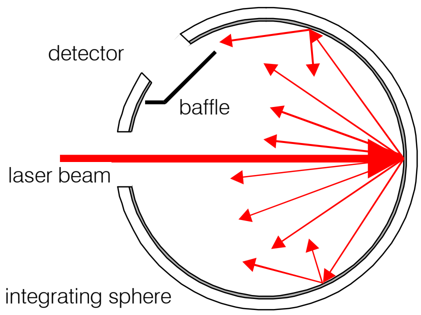


Fig. III.2. Integrating sphere used for laser power measurements

Measurement of Light

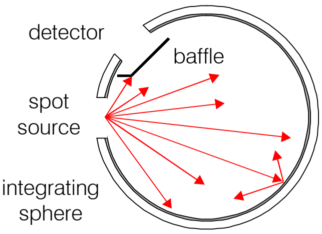


Fig. III.2. Integrating sphere used for radiant power and luminous flux

As an alternative, radiant power and luminous flux of collimated (parallel) beams can be directly measured by flat field detectors as long as the detector's active area exceeds 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 be possibly sensitive to the beam's polarisation.
- The detector's active area might be possibly inhomogeneous in its sensitivity. In this case, it is important to ensure equal illumination during calibration and measurement.
- Alignment of the detector relative 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. Therefore, a lamp has to 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 and thus causes a source of measurement error, which can be accounted for by use of an auxiliary lamp (see below).

Integrating spheres used to measure the radiant power or luminous flux of lamps must be well suited for the lamp under test to reduce measurement uncertainty. 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 set-up to measure the luminous flux of fluorescent lamps with 120 cm (47 in) length should be at least 2 m (79 in) in diameter. Furthermore, the diameter of the sphere limits the maximum power of the lamp.

In actual measurements, the lamp must be placed in the centre 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. To get the lamp in the centre position, hinged integrating spheres that open and 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 in the centre of the sphere. The port is normally closed with a cap during the measurement. The port cap's inside surface 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.

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) and for arc lamps about 100 hours (IEC 81) is recommended.

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

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

- 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)
- Y_{HX} : measurement signal of the auxiliary lamp (with test lamp switched off)

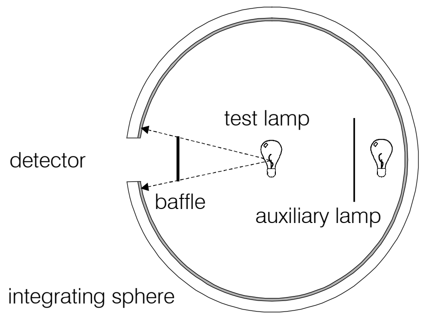


Fig. III.3. Experimental setup for radiant power and luminous flux measurements of a lamp. The auxiliary lamp is used to reduce measurement uncertainties caused by the interference of the lamp under test and its accessories with the sphere's internally reflected radiation.

III.1.c. Measurement of irradiance and illuminance

According to Equ.II.5 in paragraph II.4.e., a detector for irradiance or illuminance of a surface has to weight the incident radiation according to the cosine of its angle of incidence. This can be either achieved by

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

In both cases, the ideal directional cosine response can only be approximately achieved. 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

Light Source	Approximate Average Illuminance (lx)
overcast night	0,0001
full moon	0,1
office light	500
clear bright sky	70000 - 85000

Table III.1 – Some avarage illuminance values

$$\cos ineerror(\vartheta) = \frac{\frac{S(\vartheta)}{S(0)} - \cos(\vartheta)}{\cos(\vartheta)} = \frac{S(\vartheta) - S(0)\cos(\vartheta)}{S(0)\cos(\vartheta)}$$

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. II.9). S(0) denotes the detector's signal caused by the same ray of light impinging vertically upon the detector's entrance optics.

Fig. III.5 - Irradiance detector heads with cosine diffuser and waterproof version for underwater and outdoor use

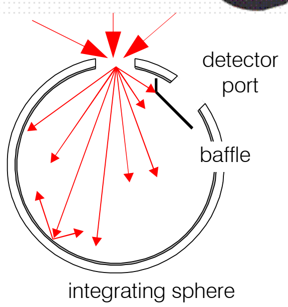


Fig. III.4. Integrating sphere design for measurement of irradiance or illuminance of a horizontal surface. The baffle prevents direct illumination of the detector, and the knife edges at the sphere's entrance port prevent shading by the sphere's wall, which would distort the detector's cosine response.sources.

III.1.d. 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. As the source's directional characteristics often depends on its internal temperature distribution and thus on its position relative to the vertical, for accurate measurements of radiant and luminous intensity it is not recommended to rotate the source around a horizontal axis.

As radiant and luminous intensity are defined by the surface integral of radiance and luminance (see Equ. II.4), the emitting source has to be completely 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, the use of additional baffles and the reduction of the detector's field of view are proper precautions.

III.1.e. 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 with 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 (Fig. III.6).

Light Source	Approximate Average Luminance (cd/m²)
self-luminous paints	$0{,}02\ 10^{-3}$
Candle flame	1
computer screen	100
overcast daytime sky	1000
clear bright sky	5000-6000

Table III.2 – Some average luminance values

III.1.f. Measurement of reflection and transmission properties

Reflectance ρ (for incident radiation of given spectral composition, polarization and geometrical distribution) is used to describe the optical properties of materials (see § II.8).
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:

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

I(X): signal with sample irradiation
I(N): signal with standard irradiation

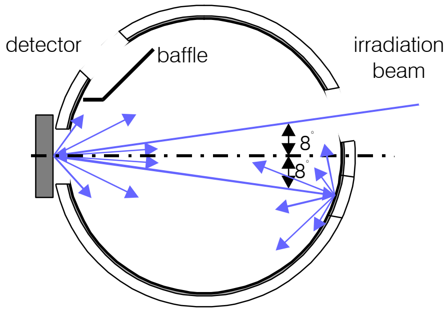


Fig. III.7. Integrating Sphere Total Reflection Measurement Set-up

Diffuse Reflectance r_d is used to describe the optical properties of materials (see § II.8).
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 r_N) with a collimated or conical radiation beam.
The signals of the detector will be calculated as follow:

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

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

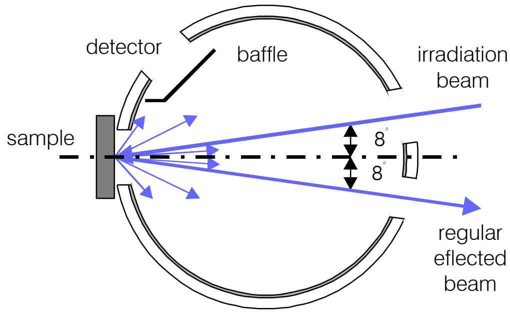


Fig. III.8. Integrating Sphere Diffuse Reflectance Measurement Set-up

Transmittance τ (for incident radiation of given spectral composition, polarization and geometrical distribution) is used to describe the optical properties of materials (see § II.8).

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 will be calculated as follow:

$\tau = I(X) / I(open)$

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

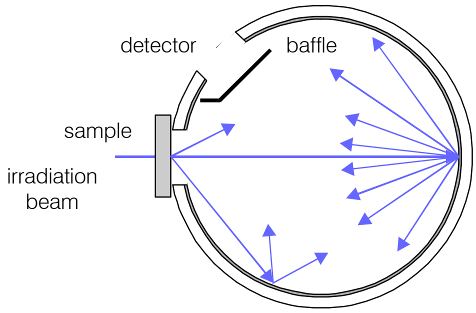


Fig. III.9. Integrating Sphere Total Transmittance Measurement Set-up

Diffuse Transmittance τ_d is used to describe the optical properties of materials (see § II.8).

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 will be calculated as follow:

$$\tau_d = \frac{I(X) - t.I(stray)}{I(open) - I(stray)}$$

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

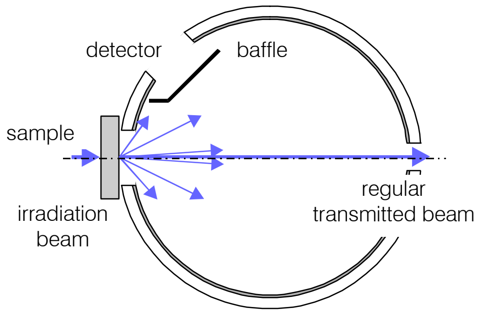


Fig. III.10. Integrating Sphere Diffuse Transmittance Measurement Set-up

III.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 $X_{\lambda 1}(\lambda)$ and Y_2 the detector's response to the input signal $X_{\lambda 2}(\lambda)$. Then, the detector's response to the superimposed input signal $X_{\lambda 1}(\lambda)+X_{\lambda 2}(\lambda)$ 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 $a \cdot X_{\lambda 1}(\lambda)$ is given by $a \cdot Y_1$ (whereby 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 replaced by Y-Y_0, Y_1-Y_0 and Y_2-Y_0.*

Deviations from this behaviour are called **nonlinearities** and cause measurement errors. However, it is possible to experimentally determine a detector's nonlinearities and to correct for them. An example of a nonlinearity effect is the saturation of a detector's output signal at high radiation levels, which poses 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)** by

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

whereby $X_\lambda(\lambda)$ 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

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

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

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

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

$$s_m = \int_\lambda s(\lambda)\, d\lambda$$

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

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

This integral relation is equivalent to the definition of photopic quantities, whereby 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 (see § II.7.f). 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 (see § VI.1).

This correspondence allows the direct determination of photopic quantities or biologically active radiation by an especially 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 especially adapted to the color matching functions defined by the CIE 1931 standard colorimetric observer (see § II.10.a).

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

III.2.a. Monochromatic radiometry

For radiometric characterisation 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. Thus, a photodiode can be used without any spectral correction filters as long it is sensitive at the respective wavelength.

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

- laser power meters equipped with a flat field detector (for lasers with collimated beams) or with an integrating sphere (for lasers with non-collimating beams and LEDs),
- integrating spheres equipped small area photodiodes, whose low capacitance results in a detector time constant in the order of nanoseconds. Thus, these detectors are perfectly suitable for laser pulse analysis with high time resolution.
- detectors equipped with integrating spheres with unique baffle design for measurements in fibre optics telecommunication. Additional adapters for standard fibre optic connectors are available.

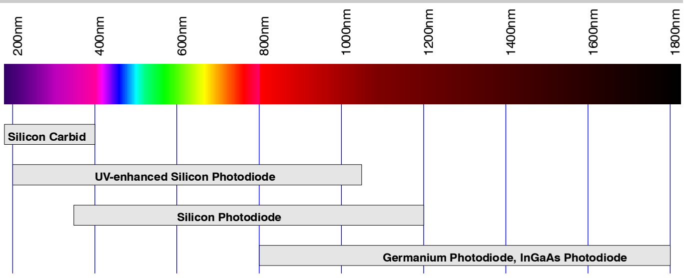


Fig. III.11. Sensitivity ranges of various types of photodiodes

III.2.b. 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.
Gigahertz Optik offers absolutely calibrated irradiance and radiant power meters equipped with a cosine diffuser or an integrating sphere, whose spectral sensitivity is optimised for UVA, UVB, UVC, visible (VIS) and near infrared (NIR) ranges.

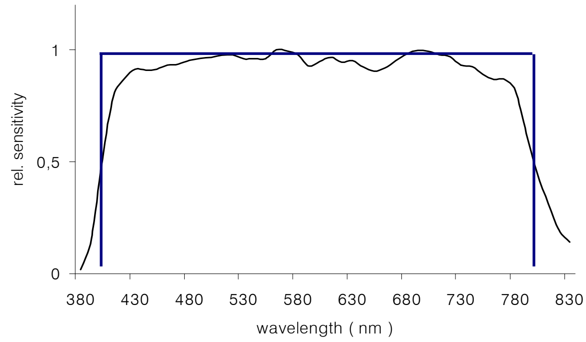


Fig. III.12. Spectral sensitivity of Gigahertz Optik's RW-3703 VISIBLE$_{400\text{-}800\ nm}$ Irradiance detector closely matches the ideal rectangular shape.

III.2.c. Photometry

For photometric measurements, the detector's relative spectral sensitivity $s_r(\lambda)$ has to match the CIE spectral luminous efficiency function V (λ) 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

$$f_1' = \frac{\int_\lambda \left| s_r^*(\lambda) - V(\lambda) \right| d\lambda}{\int_\lambda V(\lambda)\, d\lambda}$$

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

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

where $S_A(\lambda)$ is the spectral distribution of the CIE standard Illuminant A (see § II.10.), which is the recommended photometric calibration source. High quality photometric detectors show a value for f_1' below 3%, whereas a value of f_1' above 8% is considered as poor quality. The DIN 5032, part 7 requires a spectral mismatch of f_1' ≤ 3% for "Class A" instruments and f_1' ≤ 6% for "Class B" instruments. Gigahertz Optik offers high quality illuminance, luminance and luminous flux detectors meeting Class A level (f_1' = 3%) and, as an economical alternative, detectors meeting class B level (f_1' = 5%).

III.2.d. 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 (see § II.10.a). However, as the x(λ) color matching function consists of two separated regions of sensitivity, the X value is often determined by two detectors. In this case, altogether four detectors are needed for the determination of a stimulus' X, Y and Z values. As the color matching function y(λ) is identical with the CIE spectral luminous efficiency function V(λ), the respective detector can be absolutely calibrated for simultaneous photometric measurements.

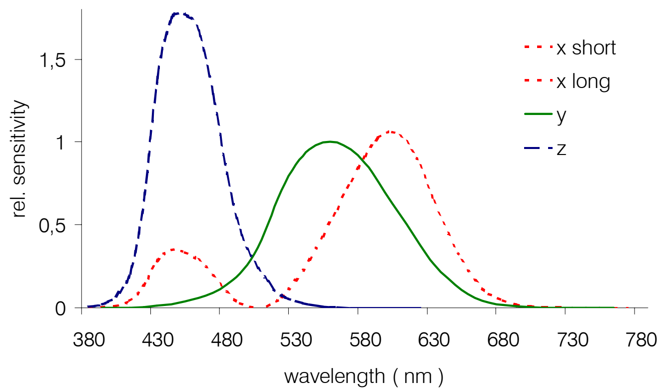


Fig. III.13. Spectral sensitivity functions used for colorimetric measurements with Gigahertz Optik's CT-3701 High Precision

III.3.The detector's time behaviour

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 as well but gradually increases or decreases until it reaches its final value. The detector's **rise time** is defined by 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. Accordingly, **fall time** is defined by 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 exponentially approaches the final value. In that case, the detector's time behaviour is 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 then given by

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

Gigahertz Optik's integral detectors use photodiodes, which are typically characterised by time constants of **µ**s. As 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, especially lasers are often pulsed with a frequency in the order of 10^9 Hz (for example in telecommunication), which corresponds to signals periods in the order of 1 ns. In that case, the relatively slow response of normal photodiodes prevents the accurate characterisation of the laser signal's time characteristics. For this application, Gigahertz Optik offers the LPPA-9901 detector, which uses a photodiode with an especially small capacity. This allows to reduce the LPPA-9901's time constant to a value of 5 ns.

Measurement of Light

III.4. The detector's dynamic range

In general, a detector fulfils the condition of linearity (see § III.2.) only for a limited range of the input signal level. There are two effects which 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 which occurs even when the input signal is constant. The absolute level and the frequency distribution of these variations depends 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 does no longer quantify the physical quantity which should 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. As the shape of the noise signal depends on the temporal resolution that can be achieved of the recording electronics (often characterised by the electronics' time constant), the noise equivalent input is defined for a stated 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 thus the detector no longer fulfils the condition of linearity (see § III.2.). Instead, physical limits of the light sensitive element and / or the electronics cause **saturation** of the output signal, which increases less than proportional to the input signal and finally reaches 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 behaviour and still leads to higher measurement uncertainties at high levels of the input signal.

The detector dynamic range depends on the photodiode type The overall measurement system dynamic range will depend on both the detector and electronic meter's range capabilities. For example, a typical silicon photodiode is capable of measuring more than 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, which are used for industrial UV curing processes.

III. 5. Calibration of integral 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 in 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. But this in itself does not guarantee accuracy or the ability of the lab to meet its calibration uncertainty claims. Since calibration standards are subject to change with age and use, a means to periodically check the calibration of the standards themselves must be in place. Occasionally the standards must be replaced in order to maintain the quality of calibration and traceability. 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 audit. 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. Refer to Appendix VI.6 for more information on national calibration organizations.

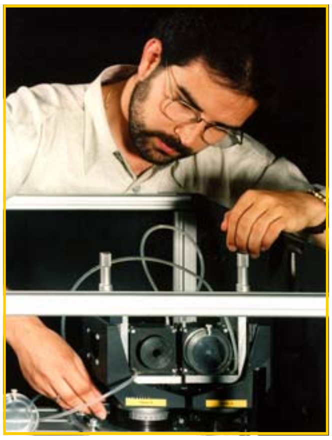


Fig. III.14.
GO Calibration Engineer

III.5.a 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 against 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 cal lab. This work standard is then used to calibrate the final product (D) or device under test. Accordingly, the calibration path is 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.

III.2.b. Polychromatic radiometry

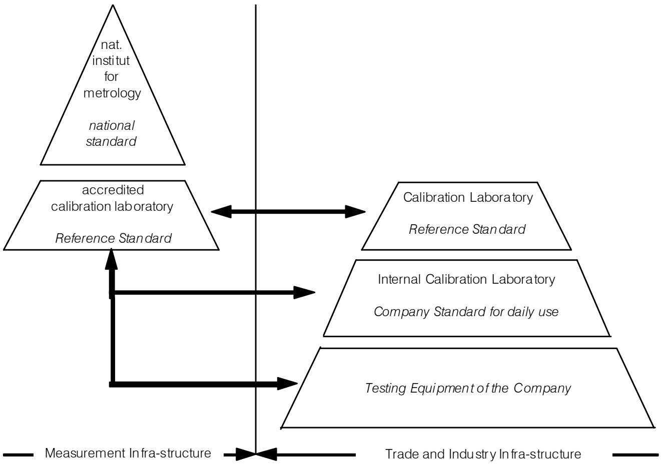


Fig. III.15
Calibration Hierarchy from Primary Standard to Test Equipment

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.

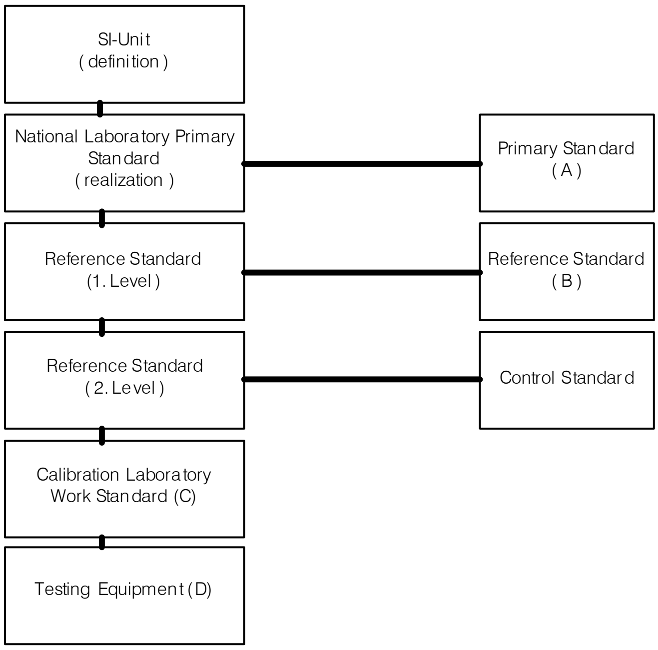


Fig. III.16 - Hierarchy of Standards

III.5.b. ISO/IEC/EN 17025 (formerly ISO Guide 25 and EN45001)

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 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. * Without exception, DKD accredited calibration laboratories fulfill the requirements of the European standard EN 45001 (general criteria to operate a testing laboratory, May 1990). Outside of Europe this standard is not compulsory. Instead of this the ISO/IEC Guide 25 (General requirements on the competence of testing and calibration laboratories, December 1990) is recognized. In content, EN 45001 and ISO/IEC Guide 25, known as ANSI/NCSL Z540-1 in the United States, is identical. This is the basis for the mutual appreciation between the European cooperation for Accreditation (EA) and its extra-European partners. In 1999 ISO/IEC 17025 took the place of EN 45001 and ISO/IEC Guide 25 which eliminated any formal differences.

ISO/IEC/EN 17025 is compatible with A2LA and NVLAP requirements.

*ISO 17025 web page : http://www.fasor.com/iso25

III.5.c Calibration Quantities

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 with a spectral measurement device or spectroradiometer as compared to a reference standard. The spectral range of calibration depends on the source and spectral zone of interest. A typical QH lamp may be spectrally scanned from 200 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 with a spectral measurement system or spectroradiometer equipped with a radiance lens assembly that has been calibrated with an integrating sphere based radiance standard. The spectral range of calibration will depend on the source and the spectral range of interest. A full spectral scan may cover from 350 to 2500 nm.

Spectral Responsivity

Optical radiation detectors, photodetectors, photodiodes, exhibit changes in sensitivity at different wavelengths. This spectral responsivity can be measured as relative responsivity in percent (%) versus wavelength (nm) across the active wavelength bandpass of the photodevice. For example a silicon device scan could cover the wavelength range from 250 to 1100 nm at a set increment. Or a GaAsP photodiode from 250 to 700 nm. The increment setting could span from 1 to 50 nm depending on the required resolution. Also, 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.

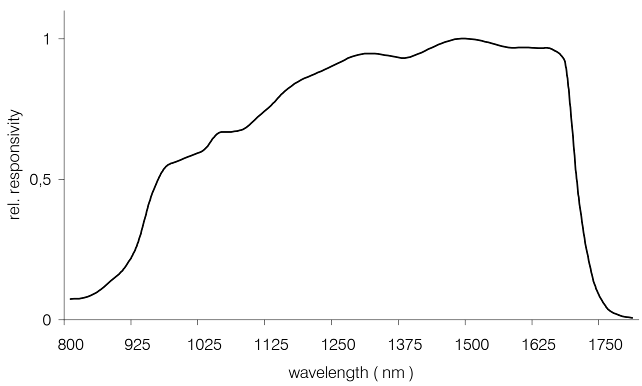


Fig. III.18. InGaAs Detector with sphere. Relative Spectral Response Plot

Gigahertz-Optik

Measurement of Light

Illuminance Sensitivity
lux / foot-candles
Calibration of the illuminance response of photopic detectors is normally performed as a transfer comparison from 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 left to advance radiometry labs. Illuminance sensitivity calibrations allow direct reading of the photopically corrected detector in lux or foot-candles. Very often a tungsten source is used for illuminance calibrations. If the photopic detector spectral response does not match the CIE photopic curve too a high degree, measurement errors will occur when measuring different type sources.

Luminance Sensitivity
cd/m² & fL
Luminance responsivity of photopic detectors equipped with field limiting input optics is accomplished by comparison to a luminance reference standard detector. A uniform field of luminance is produced as the calibration source using an integrating sphere or a source with an optically diffuse material in front of it. 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 to measure in the optical units of candela per square meter and foot-lamberts.

Color Sensitivity
Broadband colorimetric detectors are calibrated by comparison to 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.

Irradiance Sensitivity
W/m² & W/cm²
Broadband irradiance detector calibrations are performed by transfer comparison to reference standards with consideration to the spectral characteristics of the detector to be tested. Reference detectors are calibrated against spectral irradiance measurements using a double monochromator spectroradiometer, itself calibrated using traceable spectral irradiance standards. Irradiance detectors are calibrated to read out in the optical units of watts per square meter or watts per square centimeter over a specific wavelength range.

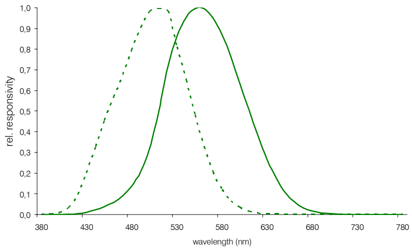


Fig. III.19. CIE Scotopic and Photopic Function

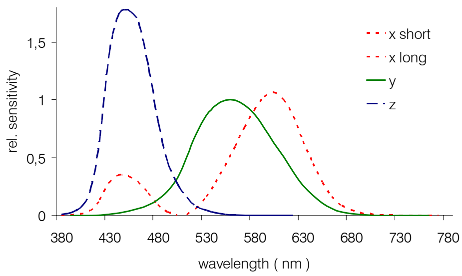


Fig. III.20. Color Detector Tristimulus Functions

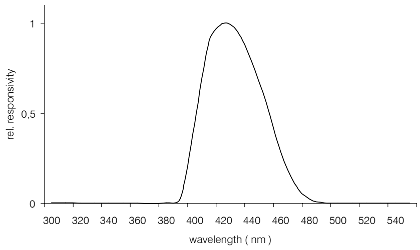


Fig. III.21. BLUE Spectral Response Irradiance Detector

Spectral Reflectance
Calibration of the spectral reflectance of materials is accomplished by comparison to reference reflectance standards which themselves are used to set-up calibration of the spectrophotometric instrument which actually performs the measurement. Single or double beam spectrophotometers can spectrally range from 250 to 2500 nm, with adjustable wavelength increments. When coupled to an integrating sphere; total hemispherical, diffuse and specular reflectance can be separately measured with the spectrophotometer. Without the sphere the in-line set-up of the spectrophotometer measures the normal specular reflectance component only.

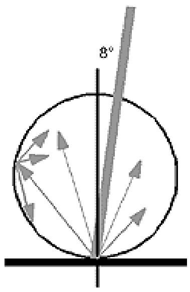


Fig. III.22. 8 Degree Reflectance Measurement Set-up

Spectral Transmittance
Calibration of the spectral transmittance of materials is accomplished by comparison to reference transmission standards which themselves are used to set-up calibration of the spectrophotometric instrument which actually performs the measurement. Single or double beam spectrophotometers can spectrally range from 250 to 2500 nm, with adjustable wavelength increments. When coupled to an integrating sphere; total hemispherical, diffuse and regular (specular) transmittance can be separately measured with the spectrophotometer. Without the sphere the in-line set-up of the spectrophotometer measures the regular reflectance component only. Calibration is performed as percent transmission versus wavelength.

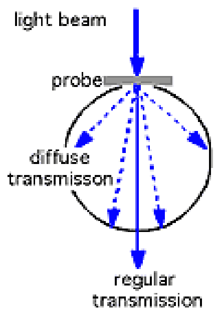


Fig. III.23. Transmission Measurement Set-up

III.5.d 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. From these differences calibration correction factors can be calculated allowing absolute readings when the output signal is corrected by these values. For photometric and radiometric measurement quantities different calibration standards are needed:

Photometric – Radiometric Quantity:
Luminous Flux – Radiant Power
Luminous Intensity – Radiant Intensity
Luminance – Radiance
Illuminance – Irradiance

Equivalent photometric and radiometric quantities exist where the measurement and therefore calibration geometry is 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 lab standard for subsequent transfer to a device under test. For traceable calibrations an unbroken chain of transfer comparisons 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. So light sources with a uniform luminous area are needed to determine the non-uniformity of a lens system or visual imaging detection system

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 handle the calibration:

- The source may 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 may 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 the same 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 in use. Filament position and stability of the tungsten halogen lamp is critical plus it has a limited lifetime. Therefore the lamp should only be operated in the position specified in the calibration certificate. Comparing the lamp output against other in-house reference standard sources or against suitable reference detection systems must be periodically done to check 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, to ensure the stability of the spectral characteristic. The minimum specification for current stability should be held at 10^{-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 during the calibration of the source, must be subsequently used.
In luminance, radiance and imaging uniformity calibrations, tungsten halogen lamps must be fitted with a diffuse screen or placed within an integrating sphere. Sphere based luminance and radiance standards offer higher uniformity and a better diffuse function.
For calibrating luminance and radiance meters with a limited field-of-view, a diffuse transmitting screen can be used at the sphere output. In imaging applications the uniformity and the diffuse function of currently available screen materials are not precise enough so the open output port of the sphere is typically used.
If the intensity of the tungsten halogen lamp is not high enough, which happens especially in the UV range, arc lamps such as xenon lamps may be used. But the increase in intensity can affect calibration uncertainty.

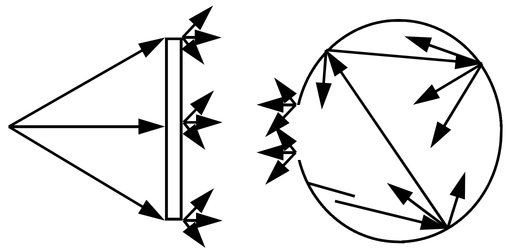


Fig. III.24. Diffuse Screen & Integrating Sphere

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 detector has the advantage of long-term absolute and mechanical stability, especially true of semiconductor detectors. The use of detector-based standards is very common in monochromatic radiometric applications such as the calibration of laser power meters for telecommunication testing. But because of surface reflections, polarization effects, beam misalignment and beam 'bounce-back' errors, the use of detector based calibration standards must be carefully considered.
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 comparison of 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 monchromator 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.
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 a minimum 15-hour burn-in procedure and must display a satisfactory burn-in data trend during this period. The calibrated tungsten reference source provides spectral irradiance data from 250 to 2500 nm covering many typical UV-Vis-IR radiometric and photometric applications.
The lamp is normally provided in a housing and socket made from ceramic or other material which ensures long-term stability and protection. Filament targeting aids may be provided for best measurement accuracy in the calibration laboratory.
Since lifetime is somewhat limited, lamp power supplies with on/off ramping functions are recommended for use with these sources.

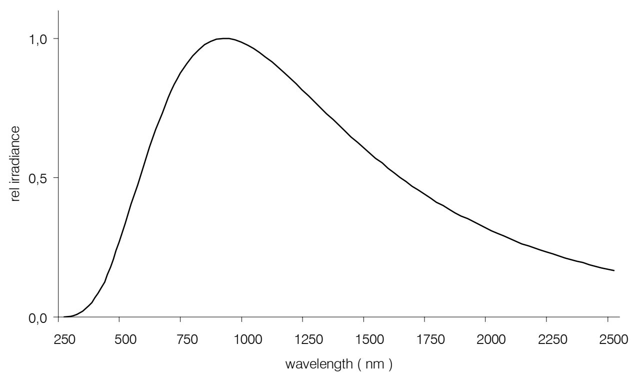


Fig. III.26. Lamp Spectral Distribution

Fig. III.25. FEL Calibration Standard Lamp

Luminance Standards

Reference sources of luminance are used to calibrate the uniformity of imaging systems and the luminance output of luminance meters, spot exposure meters and other photometric equipment.
The standard is constructed around the integrating sphere of various diameters which provide the highly uniform diffuse luminance at the exit port required for these types of calibrations. The spheres may be coated with barium sulfate or machined from 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% the port opening which can be as large as 100 mm in diameter. Angular uniformity of less than ± 5% within ±40° enables luminance output calibration of detection systems with wide acceptance angles. Luminance outputs can range from 0.5 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. III.27. Luminance Standard

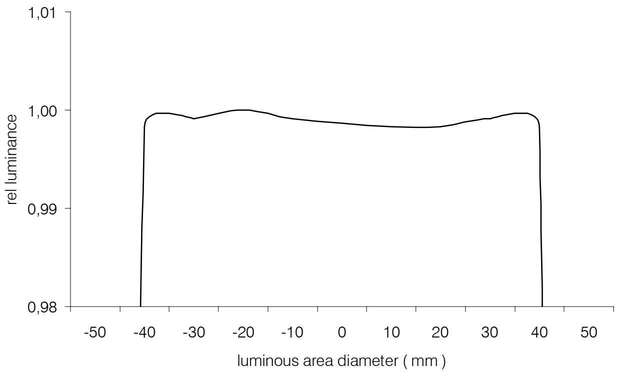


Fig. III.28. Typical Luminance Uniformity Response Plot

Spectral Radiance Standards

Reference sources of radiance are used to calibrate radiance detectors and other radiometric equipment. The standard is constructed around the integrating sphere of various diameters which provide the highly uniform diffuse radiance at the exit port required for these types of calibrations.
The spheres may be coated with barium sulfate or machined from 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% the port opening which can be as large as 100 mm in diameter. Angular uniformity of less than ± 5% 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. III.29. Variable Radiance Standard

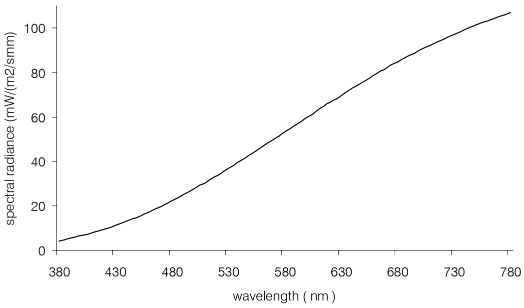


Fig. III.30. Typical Spectral Radiance Plot

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.
These photodiodes with active areas as large as 100 mm^2, are mounted into machined housings to protect and precisely fix the detector in a calibration set-up in concert with targeting aids. Some housings may include an integral temperature sensor to monitor thermal characteristics during test sessions. Or to ensure best measurement uncertainty, temperature stabilization using cooling jackets that maintain the device temperature to within ± 0.5°C are employed. UV enhanced Si devices offer spectral coverage from 250 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. III.31. Detector Calibration Standard

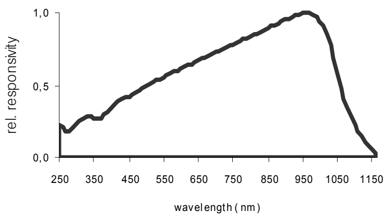


Fig.

Reflectance Standards

White optically diffuse reflectance standards traceably calibrated for spectral reflectance over a spectral range from 250 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 Lambertian diffuse reflectance and up to 98% spectrally neutral reflectance over the spectral range of interest. Processed PTFE machined and 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.
To maintain the quality of a calibrated standard it is normally mounted into a protective housing with a removable lid to keep the material clean and covered when not in use.

IV. 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 down to 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. Selectable averaging calculation of the sampled results from microseconds to seconds provides more measurement flexibility for fast events or low-level signals. Operation of the device can be accomplished through a logical menu structure with user input via front-panel keyboard or through computer control via RS232 or IEEE computer interface.
The quantity or optical unit measured will depend on the detector type, how it's configured in the way of filtering and input optic, and its calibration. Radiometers are available in hand-held mobile or bench-top models for laboratory use. Self-contained 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, datalogging) separate the different models. Usually the application determines what specific capabilities are important to have in the radiometer system. For example, in a UV curing production process where multiple stations must be monitored, a multi-channel radiometer with settable min/max reading feature, RS232 or IEEE interface and remote multiplexed detectors would be desirable.
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 & Features:

CW: Continuous wave is a run of continuous type measurements. The measurement frequency depends on the *integrating time* and the max. *sample rate*. of the meter.
CW Min/Max: CW measurement where the min. or max. value that occurred during the measurement run will be displayed. The min. or max. value can be reset with the RESET switch.
CW Level Check: CW measurement where the measurement values are compared against min.-max. threshold values. The threshold values are entered into the meter by the user.
CW Level Minimium / Maximum: Menu to adjust the threshold values for CW Level Check.
Run/Hold: To freeze a measurement value on the display and stop 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 stored individually in the optometer's memory. Each measurement may be manually or automatically initiated by a preset measurement cycle time. Measurement data can be outputted through 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 most positive sample of one 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 most negative sample of one 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 of the most positive to the most negative sample of one 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 pulse-energy is calculated by integrating the samples. I-Effective 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 0.1s and 0.2s, 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. Minimally configured, 3 pins (of a DB-9 type connector) are used, namely: Ground, Transmit Data and Receive Data. On PCs, the RS-232 ports labeled as "serial" or "asynch" and are either 9 or 25 pin male type.
Remote IEEE488: Interface IEEE488 of the device enabled. IEEE488 is a standard for Parallel Transfer between computer equipment and measurement instruments. Data is transmitted in 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 are allowed to be connected to one USB host computer. The connected devices may be powered by the host computer.
Auto Range: when activated, the measurement range is switched by the device automatically to the optimal value (depending on the input signal).
Manual Range: with autorange disabled, the measurement range can be manually fixed to a certain value. The device is not allowed to switch measurement ranges automatically. Manual range adjustment can be useful in cases where input signals are changing 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. Offset can be set to zero or to the measured CW-value. Offset is useful to compensate for the influence of ambient light or if the measurement value is very small relative to the adjusted measurement range.
Integration Time: Time period for which the input signal is sampled and the average value of the sampled values is 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 50Hz 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 100ms 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.

Specifications:

Slew-rate: 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 ms.
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: 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 1V/10pA to 1V/1mA (depending on the device).
Linearity: The linearity of an optometer can be described as follows: Reading a value of 10nA, with a max. gain error of 1%, the possible error is +/-0.1nA. Together with an additional offset error of 0.05nA, the total measurement uncertainty would be 10nA +/-0.15nA or 1.5%.
At a reading of only 1nA in the same gain range, the gain error would be 1% of 1nA or 0.01nA. The offset error would still be 0.05%. The total measurement uncertainty would be 1nA +/-0.06nA 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 nearly eliminated be using offset compensation.
Some errors cannot be compensated 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 ampflifier 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. But the user should 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.

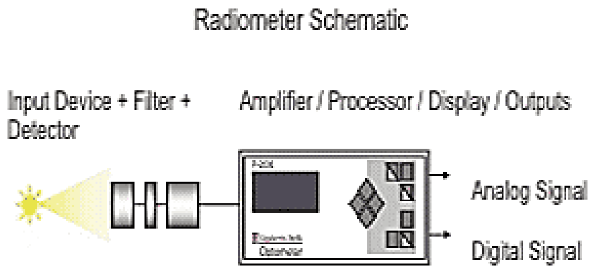


Fig. IV.1. Radiometer Schematic

V. Theory and applications of integrating spheres

Integrating spheres are very versatile optical elements, which are designed to achieve homogenous distribution of optical radiation by means of multiple Lambertian reflections at the sphere's inner surface. The primary radiation source can be located either inside the sphere or in front of the source's entrance port. In the latter case, 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 which 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 especially important when an integrating sphere is used as the input optical element of a detector for radiant power (see § III.1.b).

- 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 as optical radiation leaving the sphere is characterised by homogenous radiance and exitance distributions. This property becomes especially important when a sphere is used as a standard calibration source.

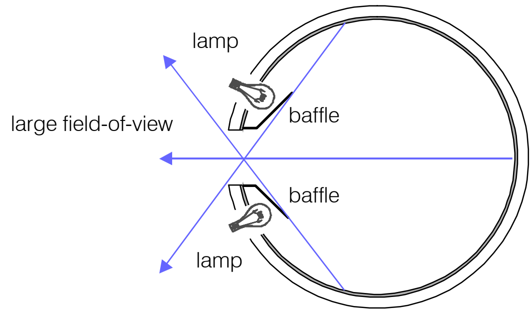


Fig. V.1. Integrating sphere used as a standard source for optical radiation. Multiple Lambertian reflections inside the sphere result in a homogenous radiance and exitance distributions at the sphere's exit port.

V.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 characterised 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 § II.5.c. and III.1.a.

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

$$E_{total} = E_0 + E_1 + E_2 + ...$$

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".

Lets 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.V.2). 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 characterised by a constant directional radiance distribution L. According to Equ. II.7 in paragraph II.5.c, 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,

$$L = \frac{\rho \, E_0}{\pi} \qquad \text{Equ.V.1}$$

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.V.2). 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 seens from dA:

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

with d denoting the distance between dA and dA'.

According to Equ.II.3 in paragraph II.4.d., the radiant power emitted by dA into the solid angle dΩ' and thus impinging upon dA' is given by

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

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:

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

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

In order to obtain the irradiance E_1 at the location of dA', 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:

Formula A

whereby Φ_0 denotes 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 holds true 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 reflec-

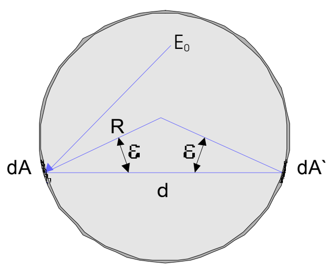


Fig.V.2. Geometry of an ideal integrating sphere of radius R.

A:

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

B:

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

tions in the same way, we get

Formula B

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 Formula C

In this expression, only E_0 actually depends on the respective location on the sphere's inner surface. As a consequence, E_{total} is independent from the actual location of the sphere's inner surface as long as we assure that $E_0 = 0$ at this location. This means that no direct radiation from the source reaches the location, which can be obtained by 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:

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

As 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.

Formula C:

$$E_{total} = E_0 + E_1 + E_2 + \ldots = E_0 + \sum_{k=0}^{\infty} \frac{\rho^k \Phi_0}{4 \pi R^2} = E_0 + \frac{\Phi_0}{A_{sphere}} \sum_{k=0}^{\infty} \rho^k = E_0 + \frac{\Phi_0}{A_{sphere}} \cdot \frac{\rho}{1-\rho}$$

V.2. Real integrating spheres

Due to the simplifications assumed for an ideal integrating sphere, the relations derived in paragraph IV.1 cannot be directly used in practical applications. Instead, 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. Thus, the relations for the ideal sphere, which have been formulated for radiometric quantities, can no longer directly be applied. Instead, the sphere's behaviour for monochromatic radiation has to be determined by 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, as the radiant power entering or exiting a sphere is proportional to the area of the respective port. As a result, these ports might considerably reduce the amount of light reflected at the sphere's inner surface, which can be accounted for by a modified sphere multiplier:

$$E_{total} = \frac{\Phi_0}{A_{sphere}} \cdot \frac{\rho}{[1-\rho(1-a)]} = \frac{\Phi_0}{A_{sphere}} \cdot K$$

with

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

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

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

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

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 (see paragraph III.1.b).
- Baffles inside the sphere and deviations of the coating material's reflectance properties from perfect Lambertian reflection cause further deviations of the sphere's behaviour from the relations derived in chapter 0. 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. Especially 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 especially 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.

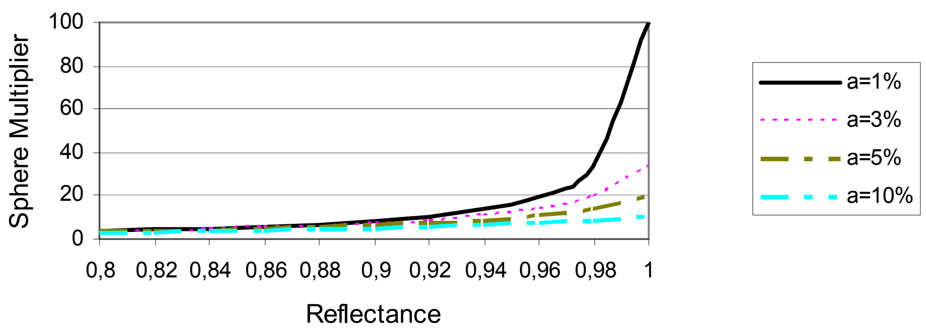


Fig. V.3. Dependence of the sphere multiplier K on reflectance ρ for different values of the share of non-reflecting areas on the sphere's total inner surface.

VI. Applications for Light Measurement in Medicine, Technology, 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 (see § III.5).

VI.1. Phototherapy and Radiation Protection

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

The photobiological effects of optical radiation, especially in the ultraviolet and blue (400 to 500nm) 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 dose (J/m^2) delivered by UV sources in phototherapy processes need to be monitored and controlled through accurate measurements. These measurements are typically performed with 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, photokeratitis (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.
Photobiologists, 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 so datalogging over some time period is commonly employed.
Because 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 highest available level. The CIE, Commission Internationale de l'Eclairage, is 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.

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 others 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 then doubled. As a similar development can be found for other countries, national and supranational networks of solar UV detectors have been established recently to monitor solar UV levels and the World Meteorological Organization is currently preparing guidelines for their characterization, calibration and maintenance.

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 being afforded increasing attention. The reasons for this are to be found 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.

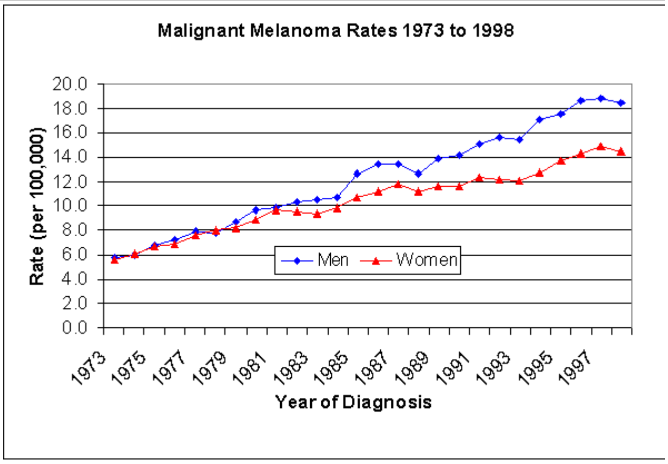


Fig.VI.1. Incidence rates of malignant melanoma in the US since 1973.

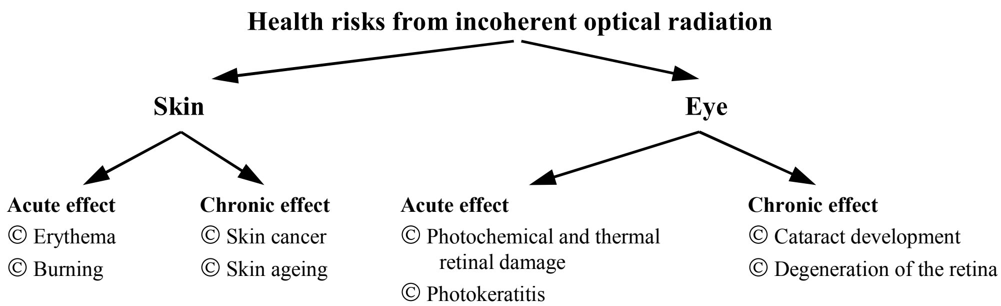


Fig.VI.2. Optical Radiation Health Risks

Light Measurement Applications

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, whereas for the skin, cornea and lens of the eye the critical quantity is the effective irradiance (or the exposure, also known as the dose) that can, for instance, arise at a workplace or in some other location where time is spent.

Photobiologically effective radiance (W/(m^2 sr))

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

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

Photobiologically effective irradiance (W/m^2)

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

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

Photobiologically effective exposure (dose, J/m^2)

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

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

If exposure limits are given in guidelines as effective radiance, Limit, or as effective irradiance, E_{limit}, then the following conditions should be maintained:

$$E_{biol} \le E_{limit} \text{ or } L_{biol} \le L_{limit}$$

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

$$t = L_i / L_{biol} \quad \text{or } t = H / E_{biol}$$

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-Ionising 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 photokeratoconjunctivitis (corneal inflammation). The range of wavelengths from 315 to 400 nm (UV-A) corresponds to a rectangle function representing total UV-A. Threshold Limit Values given for the maximum permissible exposure of the skin define the range of wavelengths as 200 (180) to 400 nm in reference to the ACGIH-ICNIRP function. The limits of maximum permissible exposure for the eye in the range 200 (180) to 400 nm and 315 to 400 nm (UV-A) are defined separately. By definition ACGIH-ICNIRP 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.

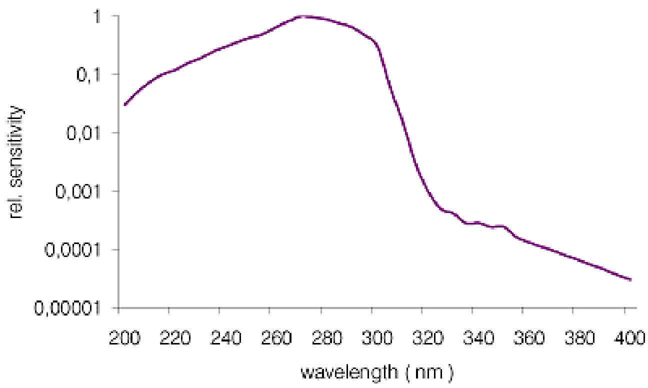


Fig. VI.3. ACGIH Spectral Function

Blue-Light Hazard Photochemical Risks to the Retina

If optical radiation with wavelengths between 380 and 1400 nm of sufficient intensity reaches the retina it can cause photochemical and thermal injury. Radiation in the "blue" part of the spectrum from 380 to 700 nm (effectively 380 to 550 nm) triggers photochemical reactions, if the photon energy in the radiation is high enough, converting chemically unstable molecules into one or more other molecule types. 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:

$L_{BLH} * t \le 100$ J*cm^{-2} * sr^{-1} for t ≤ 10.000s
$L_{BLH} \le 10$ mW * cm^{-2} * sr^{-1} for t > 10.000s
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.

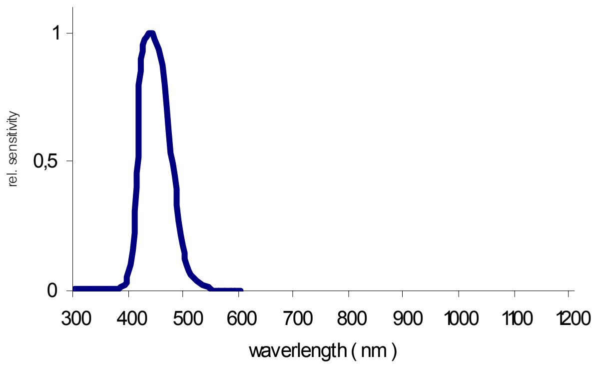


Fig. VI.4. Blue Light Hazard Spectral Function

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

If the retina is exposed during short periods to high radiation intensities, a temperature rise to 45°C leads to hyperthermia, to 60°C causes coagulation, and to over 100°C results in vaporization. Removing the heat depends for the most part 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 and 500 nm, the effect of the RTH function is larger than the BLH function by a factor of 10. Whereas the latter rapidly falls to zero above 500 nm, the thermal function continues on to 1400 nm. Since no industrially useable radiation sensors with spectral sensitivity from 380 to 1400 nm exist, an acceptable simulated match using silicon photodiodes is in use. In this context it is quite adequate to measure the range up to 1200 nm, since various light sources exhibit no more than 4% difference in the integrated totals 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 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

$$10\mu \leq t \leq 10s$$

$L_{haz} \leq 50/(\alpha * t^{0,25})$ (kW*m^{-2}*sr^{-1})
L_{haz} = effective radiance for the RTH function,
a = size of the light source expressed in radians
For t < 10 µs the limit must not be any greater than L_{haz} for t= 10 µs.
For t > 10 µs the limit must not be any greater 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<10s an α of 1.7mrad [1)];
t=10s...100s an α of 11mrad [2)]
t= 100s...10000s an α of 1.1*t^{0,5} [2)];
t> 10000s an α of 100mrad [2)]

[1)] Dominance of thermal damage to the retina
[2)] Dominance of blue light hazard

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 (0,38µm to 3 µm) (September 1997)(0,38µm to 3 µm) (September 1997)

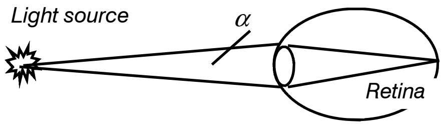


Fig. VI.5. Light Source - Subtended Angle – Retina

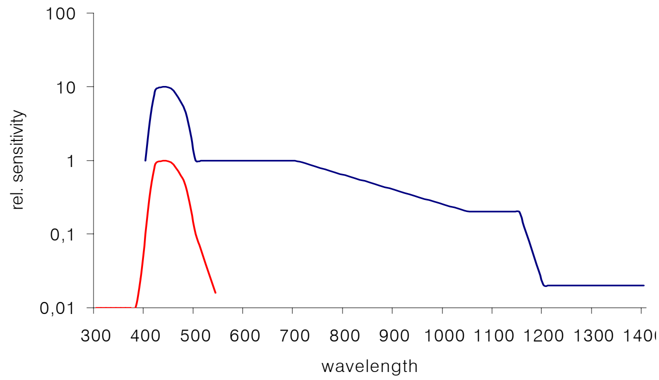


Fig. VI.6. Retinal Thermal & Blue Light Hazard Spectral Functions

UV-Erythema

The typical symptom of UV erythema is acute skin inflammation caused by UV radiation (sunburn). It used to be 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, as the skin stores the information about the UV dose received in the first years of life, and this can be an important factor in the development of skin tumors in later years.
Sunburn occurs in fair-skinned people (skin type 2) with a UV dose of as little as 250 J/m². Our table (following 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.

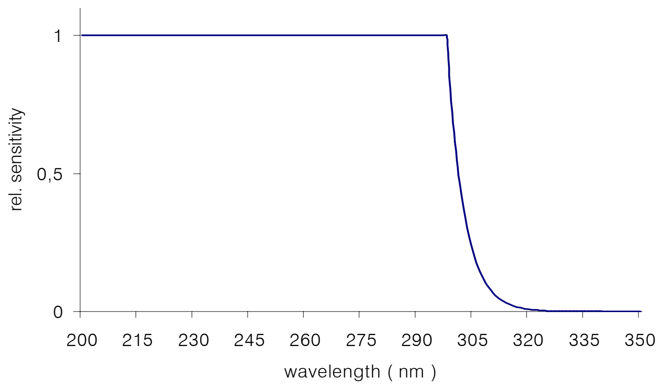


Fig. VI.7. Erythemal Spectral Function

Skin type	Description	Identification	Reaction to the sun		Exposure duration (min)
			Sunburn	Tanning	
I	Skin: noticeably light; Freckles: strong; Hair: reddish; Eyes: blue, rarely brown; Nipples: very pale	Celtic type(2 percent)	Only very painful	No reddeningwhite after 1 to two days, skin peels	5 to 10
II	Skin: somewhat darker than I Freckles: rarely; Hair: blonde to brown; Eyes: blue, green and grey; Nipples: light	Light skinned European (12 percent)	Only very painful	HardlySkin peels	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 percent)	Moderate	Average	20 to 30
IV	Skin: light brown, olive; Freckles: none; Hair: dark brown; Eyes: dark; Nipples: dark	Mediterranean type (8 percent)	Hardly	Fast and deep	40

Table VI.1. Skin Type Categories

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Light Measurement Applications

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 and hand and foot units employing light sources which emit broadband UV-A, UV-B, narrowband 311nm 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 which is taken in pill form or applied topically to the skin. This medication called psoralen, giving rise to the acronym PUVA, makes the skin more sensitive and responsive to the UV-A (315-400nm) 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 also being 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 to 315 nm, since it does not penetrate as deeply into the skin and is more energetic allowing shorter overall 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 at predominantly 311-312 nm, have been developed. They emit right in the wavelength zone of most effectiveness while producing less 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 280-350 nm, peaking at about 305 nm is also in use. For more information contact the National Psoriasis Foundation and the American and European Academies of Dermatology.

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

joules/cm² = watts/cm² x seconds

(dose/energy) = irradiance x time

In the research & development stage or field service, direct irradiance may be monitored to discern any variation in output through lamp or delivery system degradation but most of today's phototherapy equipment is equipped with sensors and electronics which allow delivery of pre-selected doses of UV.

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

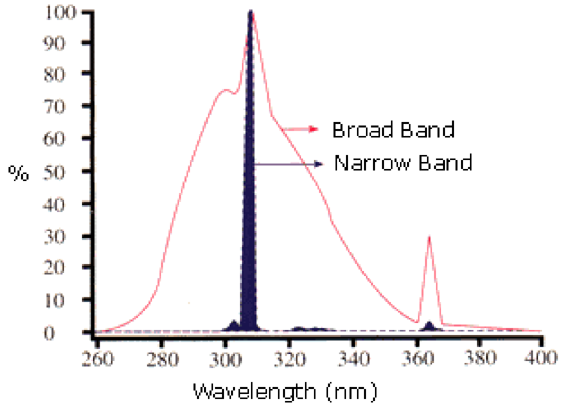


Fig. VI.8. Narrowband 311nm & Broadband UV-B Source Spectra

Bilirubin Phototherapy

Newborn jaundice or neonatal hyperbilirubinaemia, 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 molecule in the blood which results from immaturity of the liver function combined with the destruction of 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 to 550 nm. The light interacts with the bilirubin, converts it to a substance excreted back into the bloodstream which can then be excreted in the feces. The newborn is placed nude 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 bililights 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/cm²/nm were wrongly adopted for radiometric measurement of bililights. To be technically correct the units of watts/cm² should apply.

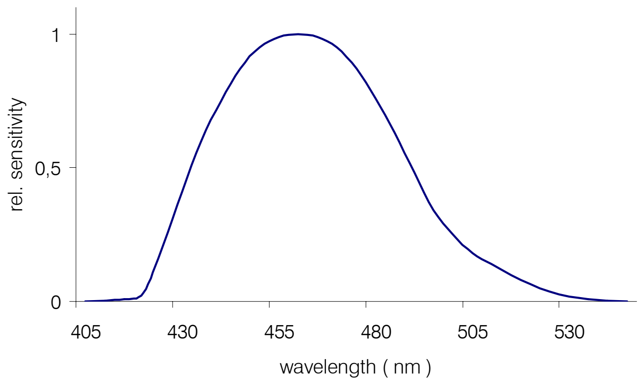


Fig. VI.9. Bilirubin Spectral Function

VI.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

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 bedescribed by the following assimilation formula:

$$6CO_2 + 12H_2O \xrightarrow[674\,kal]{h.v} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

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. Accordingly, the absorption of the quanta of radiation energy in the chlorophyll molecules raises the electrons to a higher energy state. As they return to their initial state, the energy released is converted into chemical energy.

Photosynthesis

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 the thickness of the leaf as well as on the chlorophyll content. Some research projects have shown 700 nm as the upper wavelength limit.

In DIN 5031, Part 10 (currently in the draft phase) the spectral response function for photosynthesis is defined, and this is illustrated graphically below. For plant physiology, this range can be divided 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, experimenting with a young, thin leaf or with a 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. Just the contrary has been demonstrated by experiment. It is precisely this green radiation that yields the greatest productivity and efficiency in densely populated arrangements of plants or in thick suspensions of micro-organisms. This discovery is important for investigations into the yields of plants in the lower layers of wooded areas or of 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, 850, 870 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.

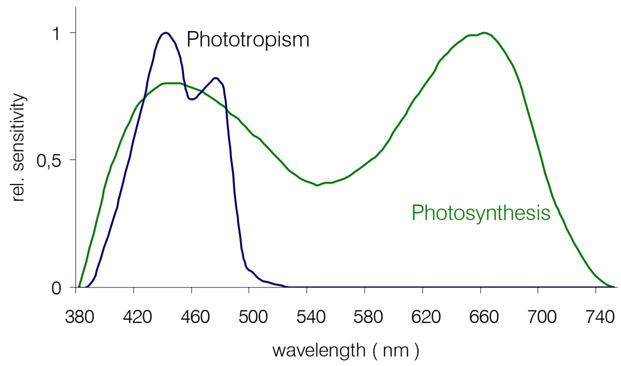


Fig. VI.10. Phototropism (blue) & Photosynthesis (green)

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. Even above Europe, a reduction in the total amount of ozone of 3-6% per decade (since 1978) has been established, which correlates with a measured increase of up to 7% in the level of UV-B radiation in high alpine areas with clean air. In March of 1993 a 15% disappearance of ozone was observed, so that in general an 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, and finally productivity and yield are impaired. Some field trials have provided evidence that in the presence of an ozone reduction of 25%, the UV-sensitive soy bean variety Essex, unlike the insensitive Williams variety, undergoes a reduction in photosynthesis, and therefore of yield, of 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. So in the fields of plant physiology and crop cultivation it is necessary not only to investigate the positive photosynthetic effects of optical radiation, but also the negative effects, mostly due to UV radiation, if the activity and protection mechanisms of plants are to be understood and manipulated.

Phototropism

Phototropism describes 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.VI.10). Radiation can have the effect of causing parts of plants to move.

Photomorphogenesis

Photomorphogenesis describes 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 having 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.

Gigahertz-Optik

Light Measurement Applications

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 with 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:
where:

$$E_{p,sy} = \int E_{p,\lambda}(\lambda) d\lambda = \frac{1}{h.c} \int E(\lambda).\lambda.d\lambda$$

$E(\lambda)$ is the spectral irradiance of the light source
λ is the wavelength of the radiation
$E_{p,sy}(\lambda)$ is the spectral photon irradiance = number of photons per second, per unit area and wavelength.
h is 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* 10^{23} photons (the most commonly used unit is $\mu Mol\ s^{-1}m^{-2}$).
The limits of integration need to be specified for integration according to the formula. If, for example, 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, however, 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, and for the 400-700 nm, 320-500 nm and 590-900 nm ranges it is always the upper limit wavelength, i.e. 700 nm, 500 nm and 900 nm.

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

VI.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. Its use is becoming more widespread than traditional water treatment techniques employing chlorine and ozone for reasons of cost and environmental factors.

Fig. VI.11.
UV treatment of wastewater

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.

The CIE divides ultraviolet optical radiation into three ranges:

- UV-A: 315 to 400 nm (skin pigmentation)
- UV-B: 280 to 315 nm (vitamin D synthesis, erythema)
- UV-C: 200 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 to 280 nm is used in the germicidal/ bactericidal sterilization of air and water. UV-C at 253.7 nm is also employed in eprom erasure and the cleaning of sensitive surfaces in the semiconductor industry. UV curing is another area where UV-C is applied.
UV-C Light Sources
Due to its high and pre-dominantly monochromatic output at 253.7 nm, low pressure mercury is the light source of choice in these applications. Medium and high pressure Hg as well as metal halide and other broadband UV sources are also used, especially 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.

Fig.VI.12.
Upper room UV irradiators help lower tuberculosis infection rates.

VI.4. UV Curing and UV Processing

UV curing is a process in which photocureable 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, dose is used to describe 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/cm² = W/cm² x 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.
Therefore, optical bandpass filters are used to limit the detector's sensitivity to the spectral range of interest.
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. These effects not only can change the detector's absolute sensitivity but 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 perfomed a change in spectral sensitivity can go undetected. So what is thought to be a newly recalibrated detector very often will produce erroneous readings when returned to the end user.
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 also maintain stability and measurement accuracy over long term use. Critical components in the detector are not exposed to direct irradiation but only see a fraction of it.
RADIN is a trade name of Gigahertz-Optik.

The detector response which best matches the absorption spectrum of the photocureable chemical in use is selected. This way the detector spectrally emulates the product to be cured.
The lamp(s) used in the system were selected by the equipment manufacturer for optimal curing within this active bandpass.
When lamp replacement becomes necessary the replacement lamps should be the same in spectral and absolute output as the old ones so that the established process parameters are not invalidated.

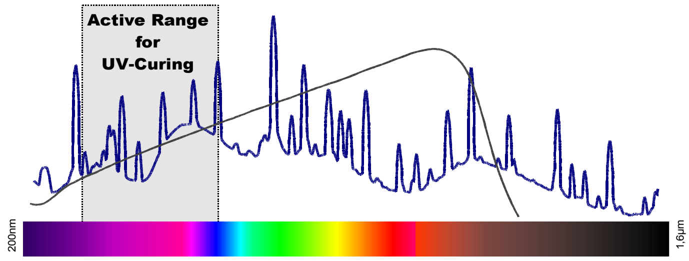


Fig. VI.13. UV Curing Spectral Region

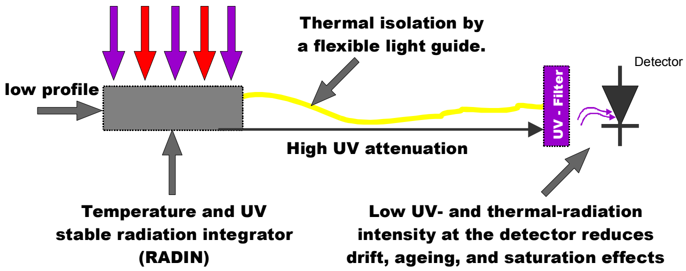


Fig. VI.14. Horizontal UV Detector Design

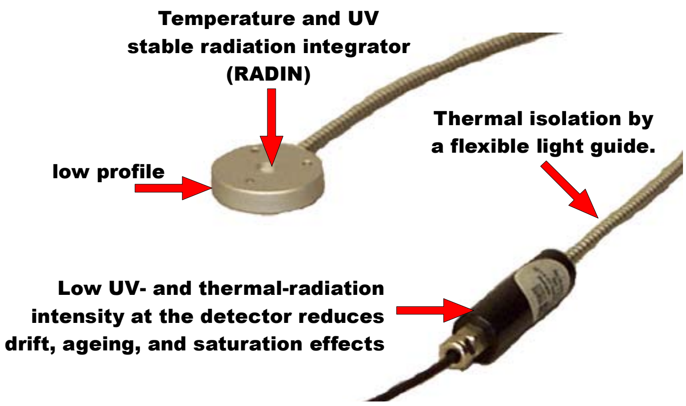


Fig. VI.15. UV Curing Detector

It should be noted that information on the spectral response function of the detector in use should be provided along with any statement of measured magnitude to properly 'frame' the results. 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 read much differently.
Normally in the field, readings within ± 10% are considered acceptable in the UV-A range.
Uncertainties get progressively worse as you move to the shorter wavelengths.

It is important to remember that the UV meter is after all a scientific instrument which is asked to perform reliably and repeatably in very hostile environments.
Maintaining calibration cycles at the manufacturer recommended interval 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.
Also consider having a second instrument on hand which is used only for an in-house calibration check of the working production unit(s).

VI.5. Colorimetry

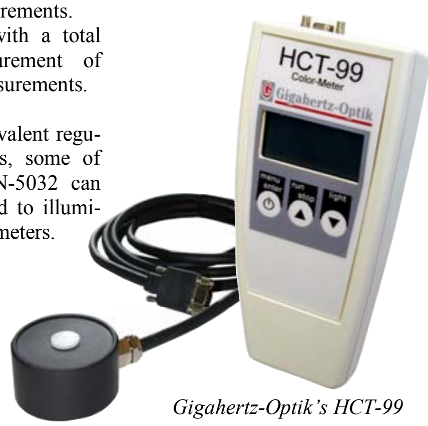
Color is the attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, grey, black, etc., and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

Perceived color depends on the spectral distribution of the color stimulus, 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 situations of observation. For more details about theory, see paragraph II.9 of this tutorials.

Color and Illuminance Measurement

In many applications involving the measurement of color or of the 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 falling diffusely, 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 of class A, with a total uncertainty of measurement of 7.5 % for precise measurements.
Devices of class B, with a total uncertainty of measurement of 10 % for operating measurements.

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



Gigahertz-Optik's HCT-99

Light Measurement Applications

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 this 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, a measurement geometry must be used that ensures that all of the radiated light is evaluated, regardless of the direction in which it is emitted.
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 principle of its construction.

Fig. VI.16. Color and Luminous Flux Measurement Instrument with a 150 mm Integrating Sphere

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 area where it is applicable 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 are designed to exhibit low reflectance. Steradian tubes that attach to the front end of the detector can be used for this purpose.

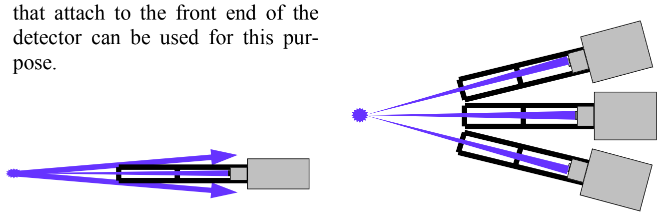


Fig. VI.17. Typical Measurement Geometries

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 metre (cd/m^2). A defined angular field of view for the color measuring device is needed in order to measure luminance. This can be accomplished using either steradian tubes or lens systems.

Fig. VI.18. Color Detector Head for Measurement of Luminous Intensity and Luminance,

Color Temperature Measurement

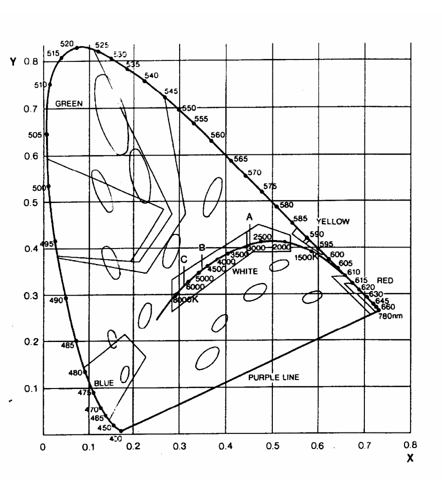
Color temperature is a simplified way to characterize the spectral properties of a light source. While in reality the color of light is determined by how much each point on the spectral curve contributes to its output, the result can still be summarized on a linear scale.
Low color temperature implies 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 measurement, starting with 0 K (= -273.16° C) at the absolute zero temperature. The "size" of one kelvin is the same as that 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 incident upon it, and re-emits all this energy. 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.



VI.6. Photostability

The current ICH (International Conference for Harmonization) guidelines specify that drug and drug products must be phototested 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 to 400 nm) irradiance in W/m² 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 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 + 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 for photobiological and photostability applications by Gigahertz-Optik. Compared to the ideal UV-A spectral function the typical detector total area error is 34% while the Gigahertz-Optik 'flat' UV-A detector is only 14%.

The guidelines also state that to ensure spectral conformity of the light source(s) a phototester 'may rely on the spectral distribution specifications of the light source manufacturer'. It has been found in actual practice that 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.

Most often the phototesting is performed in a photostability 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.

Then the detector properly emulates the target in the way the light signal is received.

Profiling the photostability 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 photostability 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.

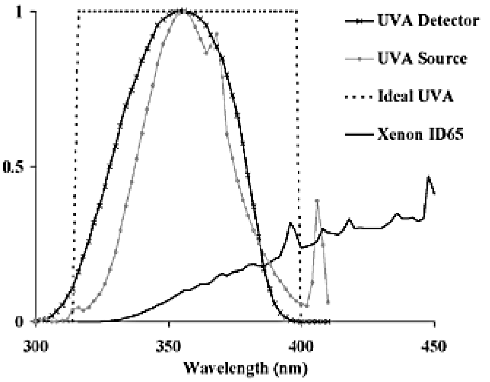


Fig. VI.19. Typical UV-A Spectral Function

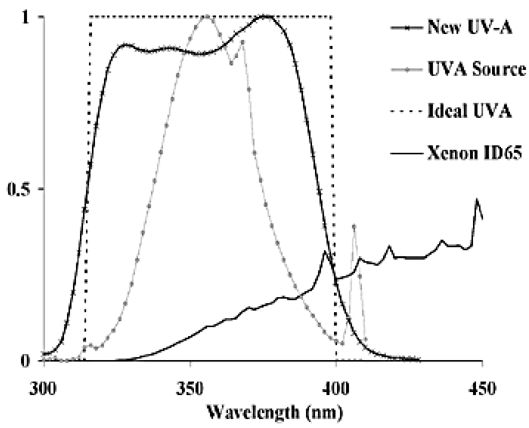


Fig. VI.20. Flat UV-A Spectral Function

VI.7. Telecommunication

An ongoing revolution occurring in the field of telecommunications is the development of small laser diodes and high capacity optical fibres. Without optical fibre telecommunication devices 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 claim high sensitivity but at a cost of potential measurement inaccuracies caused by the effects of polarization, local saturation, signal 'bounce-back' and beam misalignment. Also, the use of large size photodiodes required to reduce source to detector misalignment, increases cost.

A welcome alternative is the integrating sphere which is able to collect all of the source 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 all of the incoming signal is captured 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.

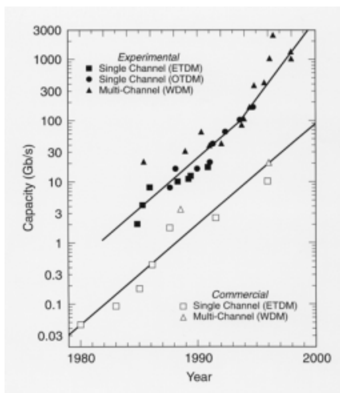


Fig. VI.21. During the last two decades, optical fibre capacity has increased by a factor of about 1000. For comparison, commercial state of the art wire connections range in the region of about 0.1 Gigabit per second (Gb/s).

VI.8. LEDs Measurements

Presently, a slow but steady large scale technological change is taking place: The traditional incandescent bulb is being replaced more and more 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. A high percentage of an incandescent bulb's total light output is lost when passed through a coloured filter. In contrast, an LED emits light of only the desired color, thus no filtering is necessary and consumption of electrical energy can be reduced by up to 90%. Low power consumption and a typical LED lifetime of 100,000 hours (compared to about 1000 hours for incandescent bulbs), drastically reducing maintenance, often equates to significant overall cost reduction when LEDs replace traditional lighting. As an example, the city of Denver, which recently has replaced some 20000 incandescent bulbs in traffic light signals with LED devices, estimates the total savings to about $300 per signal, calculated for the lifetime of an LED device.
At the current level of technology, the broad application of LED devices as sources of artificial light is restricted by comparatively high production costs. However, the LEDs high-energy efficiency and low operating voltage leads to their use when power consumption is a critical parameter as when batteries or solar cells must be used to power the lamps.

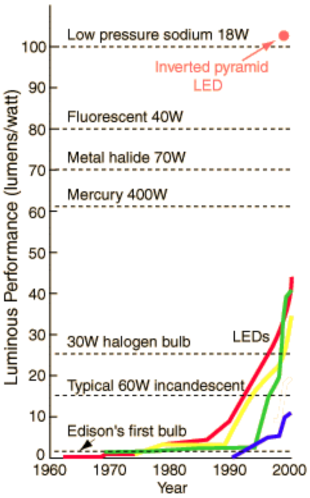


Fig. VI.22. Efficiency of red, green, white and blue LEDs has dramatically increased during the last

V1.9 LASER Measurements

The most commonly encountered monochromatic source is the laser. 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 l=100 nm to l=1 mm. Most lasers used in measurement instrumentation and fiber optic telecommunications systems work predominantly in the 200 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. But 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 flat-field detector because of the different angles of incidence. The power output of these lasers is typically measured with detectors combined with an integrating sphere which collects all incoming radiation independent of the angle of incidence.
- Here are more unique features offered by the integrating sphere: Through multiple internal reflections, the sphere offers high attenuation for high power measurements. The max. power is limited by the sphere's upper operating temperature limit.
Also through multiple internal reflections, measurement errors caused by polarization effects with flat-field detectors do not occur
The sphere port diameter can be enlarged by increasing the sphere diameter which allows 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 found. The EN 60825 standard describes the risk and measurement methods for risk classification. Laser stray-light can be assessed with the use of a detector head with a 7 mm dia. free aperture to mimic the open pupil.

V1.10 Non-Destructive 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 so radiometric and photometric measurements are made 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 using the dye penetration examination process is a widely used method for the detection of surface defects in nonporous metal and non-metal materials. Two different methods are in use:
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 making it visible. Adequate illumination of the test object with white light is critical to create good contrast.
Fluorescent Penetrating Agent:
For highest sensitivity, a fluorescent dye is used as the penetrating liquid and the test is carried out under ultraviolet lighting. UV-A sources known as 'blacklights' are most commonly used. To reliably test with 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 exist that describe 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. 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.
To reduce spectral errors even further, 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 very closely matches the CIE photopic function is required for accurate photometry. The Gigahertz-Optik photopic sensor's spectral function is within DIN Class B limits of <6% fidelity to the CIE photopic curve.
The detector spatial response (angular response) is another important factor and potential error source.
Since the detector is fully immersed in light from all directions, including any ambient contribution, it should be cosine corrected, using a diffuser. This way the incoming light signals are properly weighted according to 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 spatial response does not closely match the true cosine function, significant errors in readings will result

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 for UV-A at 1 mW/cm² for an eight-hour exposure period. For UV-B, the TLV is much less at 0.1 Effective µW/cm². So UV exposure of workers in PT environments should be tested to ensure safety as well as for quality control..

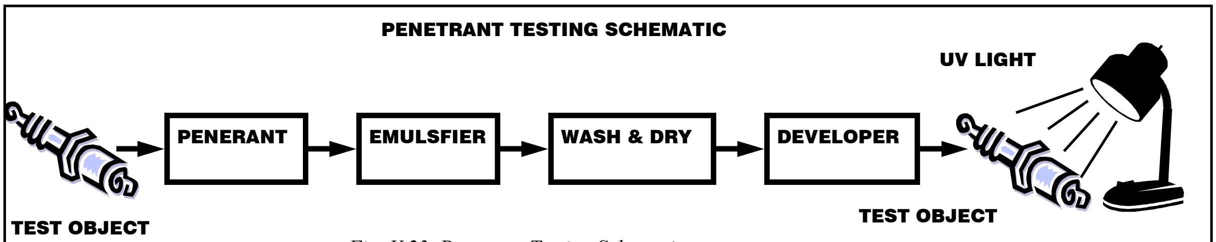


Fig. V.23. Penetrant Testing Schematic

VI.11. Transmission & 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 describes optical radiation visible to the human eye over the wavelength range from 380 to 780 nm. The eye's sensitivity to light varies over this spectral range peaking at 555 nm. This same CIE defined V(λ) photometric action function 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.

VII.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}
Luminous flux	Φ_v	1 lumen = 1 lm photopic: 1 lm corresponds to Φ_e = 1/683 W at λ_m = 555 nm scotopic: 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 =* $10^4/\pi$ *cd* m^{-2} *1 footlambert = 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 footcandle = 1 fc = 1 lm* ft^{-2} *= 10.764 lx*

Appendix

Quantity	Symbol	Unit(s)
Luminous exitance	M_v	1 lm 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} nm^{-1}

Table VII.IV. ***Units in italic*** *are not SI units, not consistent with CIE regulations and* ***should not be used*** *!*

VII.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}	position on source's surface and direction
... 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

Table VII.V – Radiometric and photometric quantities

Radiometric quantities:

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

$$X_e = \int_0^\infty X_\lambda(\lambda)d\lambda \quad \text{or} \quad X_{e,range} = \int_{\lambda_1}^{\lambda_2} X_\lambda(\lambda)d\lambda$$

with λ_1 and λ_2 denoting the lower and the upper limit of the respective wavelength range (for instance, UVA)

Photometric quantities:

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

Photopic vision: $X_v = K_m \cdot \int_0^\infty X_\lambda(\lambda)\cdot V(\lambda)\,d\lambda$ with K_m = 683 lm / W Scotopic vision: $X_v = K'_m \cdot \int_0^\infty X_\lambda(\lambda)\cdot V'(\lambda)\,d\lambda$ with K'_m = 1700 lm / W

Basic integral relations between radiometric and photometric quantities:

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

$$\Phi_x = \int_{4\pi} I_x d\Omega \qquad I_x = \int_{\text{emitting surface}} L_x \cos(\vartheta)\, dA \qquad M_x = \int_{2\pi} L_x \cos(\vartheta)\, d\Omega$$

VII.3. Sources and references for figures

Fig. II.1: http://www.cameraguild.com/technology/colorimetry.htm
Fig. II.3: http://sedac.ciesin.org/ozone/docs/AS.html
Fig. II.5: adapted from http://www.salsburg.com/lightcolor/lightcolor.html
Fig.II.6: adapted from http://whatis.techtarget.com/definition/0,,sid9_gci528813,00.html
Fig. II.11: http://omlc.ogi.edu/classroom/ece532/class1/intensity_flashlight.html
Fig. II.13: adapted from http://www.cameraguild.com/technology/colorimetry.htm
Fig. II.16: http://math.nist.gov/~FHunt/appearance/brdf.html
Fig. II.17: http://lsvl.la.asu.edu/askabiologist/research/seecolor/rodsandcones.html
Fig. II.19: http://www.cs.princeton.edu/courses/archive/fall99/cs426/lectures/raster/img013.gif
Fig. II.22: http://home.wanadoo.nl/paulschils/10.02.htm
Fig. VI.1: http://www.coolibar.com/skin-cancer-in-the-us.html
Fig. VI.11: http://www.mindfully.org/Water/UV-Disinfection-Wastewater.htm
Fig. VI.12: http://www.news.ucf.edu/FY2001-02/011205.html
Fig. VI.22: http://www.bell-labs.com/history/physicscomm/images/br_v_t6w.gif
Fig. VI.23: http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/leds.html

VII.4. Most relevant CIE- DIN- and ISO-publications and regulations

VII.4.a. 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

VII.4.b. CIE Publications

13.3-1995: Method of measuring and specifying colour rendering of light sources New edition (including Disk D008)
15.2-1986: Colorimetry, 2nd ed.
16-1970: Daylight
17.4-1987: International lighting vocabulary, 4th ed. (Joint publication IEC/CIE)
18.2-1983: The basis of physical photometry, 2nd ed.
19.21-1981: An analytic model for describing the influence of lighting parameters upon visual performance, 2nd ed., Vol.1.: Technical foundations
19.22-1981: An analytic model for describing the influence of lighting parameters upon visual performance, 2nd ed., Vol.2.: Summary and application guidelines
38-1977: Radiometric and photometric characteristics of materials and their measurement
39.2-1983: Recommendations for surface colours for visual signalling, 2nd ed.
40-1978: Calculations for interior lighting: Basic method
41-1978: Light as a true visual quantity: Principles of measurement
44-1979: Absolute methods for reflection measurements
46-1979: A review of publications on properties and reflection values of material reflection standards
51.2-1999: A method for assessing the quality of daylight simulators for colorimetry (with supplement 1-1999)
52-1982: Calculations for interior lighting: Applied method
53-1982: Methods of characterizing the performance of radiometers and photometers
55-1983: Discomfort glare in the interior working environment
59-1984: Polarization: Definitions and nomenclature, instrument polarization
60-1984: Vision and the visual display unit work station
63-1984: The spectroradiometric measurement of light sources
64-1984: Determination of the spectral responsivity of optical radiation detectors
65-1985: Electrically calibrated thermal detectors of optical radiation (absolute radiometers)
69-1987: Methods of characterizing illuminance meters and luminance meters: Performance, characteristics and specifications
70-1987: The measurement of absolute luminous intensity distributions
75-1988: Spectral luminous efficiency functions based upon brightness matching for monochromatic point sources, 2° and 10° fields
76-1988: Intercomparison on measurement of (total) spectral radiance factor of luminescent specimens
78-1988: Brightness-luminance relations: Classified bibliography
82-1989: CIE History 1913 - 1988
84-1989: Measurement of luminous flux
85-1989: Solar spectral irradiance
86-1990: CIE 1988 2° spectral luminous efficiency function for photopic vision
87-1990: Colorimetry of self-luminous displays - A bibliography
95-1992: Contrast and visibility
96-1992: Electric light sources - State of the art - 1991
98-1992: Personal dosimetry of UV radiation
101-1993: Parametric effects in colour-difference evaluation
105-1993: Spectroradiometry of pulsed optical radiation sources
106-1993: CIE Collection in photobiology and photochemistry (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: Guide to recommended practice of daylight measurement (including disk)
109-1994: A method of predicting corresponding colours under different chromatic and illuminance adaptations
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: Industrial colour difference evaluation
118-1995: CIE Collection in colour 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 co-ordinated research on evaluation of colour appearance models for reflection print and self-luminous display image comparisons
118/5: Testing colour appearance models: Guidelines for co-ordinated research
118/6: Report on colour difference literature
118/7: CIE guidelines for co-ordinated future work on industrial colour-difference evaluation
121-1996: The photometry and goniophotometry of luminaries
124-1997: CIE Collection in colour and vision, 1997
124/1: Colour notations and colour 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 colour difference evaluation - Report on a colour difference research meeting
125-1997: Standard erythema dose
127-1997: Measurement of LEDs
130-1998: Practical methods for the measurement of reflectance and transmittance
134-1999: CIE Collection in photobiology and photochemistry, 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 Collection in vision and colour and in physical measurement of light and radiation, 1999
135/1: Disability glare
135/2: Colour rendering (TC 1-33 closing remarks)
135/3: Supplement 1-1999 to CIE

Appendix

51-1981: Virtual metamers for assessing the quality of simulators of CIE illuminant D50
135/4: Some recent developments in colour 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 Collection in Photobiology and Photochemistry, 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: The influence of daylight and artificial light on diurnal and seasonal variations in humans - a bibliography (also available as disk)
142-2001: Improvement to industrial colour difference evaluation
148:2002: Action spectroscopy of skin with tunable lasers
149:2002: The use of tungsten filament lamps as secondary standard sources
151:2003: Spectral weighting of solar ultraviolet radiation
CIE Draft Standard DS 010.3-2002: Photometry - The CIE system of physical photometry
CIE Draft Standard DS 012.2:2002: Standard method of assessing the spectral quality of daylight simulators for visual appraisal and measurement of colour
CIE Draft Standard DS 013.2:2002: International standard global UV index
CIE Draft Standard DS 015:2002: Lighting of work places - outdoor work places

VII.5 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 industry as possible, including the calibration of measurement and testing equipment. The DKD ensures the traceability of measurement and testing equipment to national standards by the 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 will define, realize, keep and transmit the physical quantities of the SI-system, such as a meter, a second, a kilogram, a candela, etc. To ensure objective results, equal standards must be used. The calibration of measurement and testing arrangements based on SI-units is a basis for correct, comparable, recognizable and therefore measurable values, which can be audited. Within the DIN ISO 9000 ff. standard the relationship between quality management and calibration are intertwined in part for continuous control of measurement and testing equipment. Without exception, DKD accredited calibration laboratories fulfill the requirements of the European standard EN 45001 (general criteria to operate a testing laboratory, May 1990). Outside of Europe this standard is not compulsory. Instead of this the ISO/IEC Guide 25 (General requirements on the competence of testing and calibration laboratories, December 1990) is recognized. In content, EN 45001 and ISO/IEC Guide 25 are identical. This is the basis for the mutual appreciation between the European cooperation for Accreditation (EA) and its extra-European partners. In 1999 ISO/IEC 17025 took the place of EN 45001 and ISO/IEC Guide 25 which eliminated any formal differences.

Existing DKD calibration laboratories automatically qualify for ISO/IEC/EN 17025 conformance.
DKD homepage: http://www.dkd.info/

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 the goal of 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 online at

http://www.ilac.org.

PTB – Physikalisch-Technische Bundesanstalt

The Physikalisch-Technische Bundesanstalt (PTB) is the highest technical authority for metrology in Germany. The PTB define, realize, keep and transmit 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 such as Gigahertz-Optik. 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 National Institute of Standards and Technology (NIST) USA. 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.

PTB homepage:
http://www.ptb.de/

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 industry, university, and government clients involved with lighting, transportation, manufacturing, telecommunications, public health and safety, and the environment.NRC INMS Photometry & Radiometry Home Page Last Updated: 2001-07-18 (http://www.nrc.ca/inms/phot_rad/prei.html)

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 are reliant upon optical technologies for their competitiveness and success. As a part of this mandate, the Division has the institutional responsibility for maintaining 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; provides National measurement standards and support services to advance the use and application of optical technologies spanning the ultraviolet through microwave spectral regions for diverse industrial, governmental, and scientific uses; 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; conducts basic, long term theoretical and experimental research in photophysical and photochemical properties of materials, in radiometric and spectroscopic techniques and instrumentation, and in application of optical technologies in nanotechnology, biotechnology, optoelectronics, and in diverse industries reliant upon optical techniques. NIST Physics Laboratory Optical Technology Division Home Page, Last updated: April 2002

(http://www.physics.nist.gov/Divisions/Div844/about_otd.html)

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 is carried out. ORM anticipates and responds to industrial and academic measurement requirements throughout the IR, Visible, and UV spectra, providing a comprehensive range of Measurement and Calibration Services, Instrumentation Products, Training and Consultancy.

Some of the range of Measurement and Calibration Services, traceable to national standards, available in this field, includes 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 colour, haze and gloss

The development of NPL's Primary Standards and Measurement Scales, enables the UK to maintain the highest accuracy optical measurement references in the world as well as to 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 for radiometry. NPL ORM Introduction Web Page: http://www.npl.co.uk/optical_radiation/

Appendix

VII.5 National Calibration Laboratories

See chapter Calibration Services in this catalogue or on Gigahertz-Optik's homepage

Deutscher Kalibrierdienst (DKD)
Akkreditierungsstelle bei der
Physikalisch-Technischen Bundesanstalt (PTB)
vertreten im

Deutschen AkkreditierungsRat

Akkreditierung

Die Akkreditierungsstelle des **Deutschen Kalibrierdienstes** akkreditiert hiermit das Kalibrierlaboratorium für optische Strahlungsgrößen

bei

Gigahertz-Optik GmbH
Fischerstraße 4
82178 Puchheim bei München

als Kalibrierlaboratorium nach DIN EN ISO/IEC 17025 für Kalibrierungen in den Bereichen:

spektrale Empfindlichkeit, spektrale Bestrahlungsstärke

Bestandteil der Urkunde ist: Anlage 03 (1 Seite), 2002-10-28

DAR-Registriernummer: DKD-K-10601-03
Akkreditiert im DKD seit: 1993-06-22

Braunschweig, 2002-10-28

Dr.-Ing. Wolfgang Bosch
Leiter der Akkreditierungsstelle

Siehe Hinweise auf der Rückseite