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Optical Radiation Metrology and Uncertainty

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Additional information is available at the end of the chapter

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Abstract

Metrology is the science of measurement. The chapter contains introductory material, terminology and units used in the optical radiation metrology. Optical radiation metrology provides an applied understanding of essential optical measurement concepts, techniques and procedures. In this chapter, we focus on electromagnetic radiation with wavelengths from approximately 100 to 2500 nm. We describe the principles used to measure photometry and radiometry quantities such as total flux, intensity, illuminance, luminance, radiance, exitance and irradiance. Measurement results should be expressed in terms of estimated value and an associated uncertainty, we provide an explanation to how to estimate and build the uncertainty budget of measurements. Metrology is based on measurements and comparisons. The unit is a unique name we assign to the measures of that quantity. Base standards must be both accessible and invariable. The metrological traceability chain is the sequence of measurement standards and calibrations that were used to relate the measurement result to the reference. The uncertainty budgets for photometric and radiometric quantities are represented in this chapter.

Keywords: photometry, radiometry, illuminance, luminance, total flux, radiance, irradiance intensity, luminous intensity, irradiance, traceability, accreditation laboratory, uncertainty

1. Introduction

Optical radiation metrology is the radiometry and photometry science of measurements. Optical radiation metrology provides an applied understanding of essential optical measurement concepts, techniques and procedures. In this chapter, we focus on electromagnetic

radiations with wavelengths from approximately 100 to 2500 nm. We describe the principles used to measure photometry and radiometry quantities such as total flux, intensity, illuminance, luminance, radiance, exitance and irradiance. Measurement results should be expressed in terms of estimated value and an associated uncertainty, we provide an explanation how to estimate and build the uncertainty budget of measurements. Metrology is based on measurements and comparisons. We measure each quantity in its own units, by comparison with a standard. The unit is a unique name we assign to the measures of that quantity. Base standards must be both accessible and invariable. The metrological traceability chain is the sequence of measurement standards and calibrations that were used to relate the measurement result to the reference.

Optical radiations bathe the world in which we live [1]. Very early in our history, it was observed that light can be produced by different means depending upon the daily rotation of the earth. New ways of using light were discovered to effect changes upon many of the materials we found in the world around us. In this chapter, we discuss some of the procedures and equipment necessary to obtain accurate measurements of the amount of optical radiation that will act on our activities. The principal purpose of the science of photometry is to evaluate visible radiation or light, so the results match as closely as possible with a normal human observer exposed to that radiation. In order to achieve this aim, one must take into account the light stimulus, the radiation entering the eye and the characteristics of the visual organ that produce the relevant sensation of light [2]. Light is essential for vision, the world is only visible when light reflected or emitted by objects reaches our eye. Light is a kind of energy and is portion of a broad range of the electromagnetic spectrum. The visible light spectrum is a little part of this spectrum, between 380 and 760 nm (see **Figure 1**). The total light energy emitted from a source or falling on a surface can be measured. This total energy can cover a part of the visible spectrum, including ultraviolet and infrared energy. The branch of science in which we study light measurement is known as photometry and a subset of the broader field is radiometry.

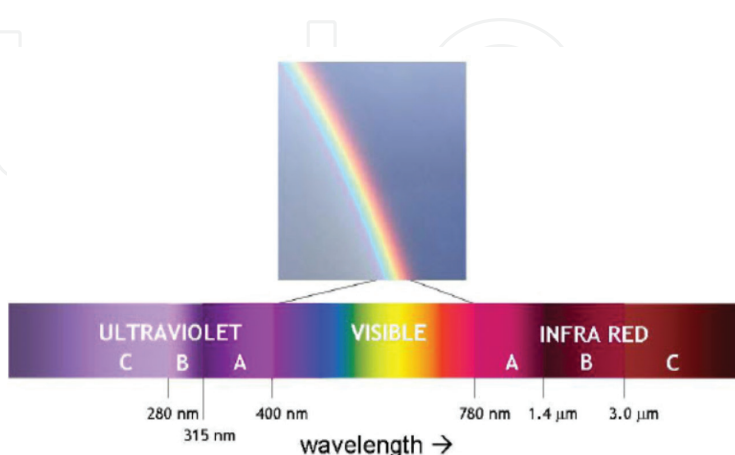


Figure 1. Electromagnetic radiation spectrum [3].

2. Optical radiation quantities

To understand the measurement of several basic optical radiation quantities used to determine absolute amounts of optical radiation, it is useful to study the two aspects of quantitative optical radiation measurements: the geometrical optical radiation that we wish to measure and the spectral components of this special geometrical compound of radiation [1]. Our discussion concentrates on electromagnetic radiation with wavelengths from approximately 100 to 2500 nm, which is an extension from the visible wavelength range, which is approximately from 380 to 760 nm.

2.1. Solid angle (ω)

A solid angle (ω) is defined by the surface area of a sphere subtended by the lines and by the radius of that sphere, as shown in **Figure 2**. The dimensionless unit of solid angle is the steradian, with 4π steradians in a full sphere [4].

2.2. Radiometry

Radiometry is the science of electromagnetic (EM) radiation measurement. The spectrum covered by the science of radiometry is the range from 100 to 2500 nm.

2.2.1. Radiant flux (Φ_e)

Radiant flux is defined as power emitted, transmitted or received in the form of radiation as shown in **Figure 3** [4]. The International System of Units (SI unit) of radiant flux is Watt.

2.2.2. Radiant intensity (I_e)

Quotient of the radiant flux ($d\Phi_e$) leaving the source and propagated in the element of solid angle ($d\omega$) containing the given direction divided by the element of solid angle. The SI unit for radiant intensity is Watt/steradian (Watt/sr) as shown in **Figure 4** [4].

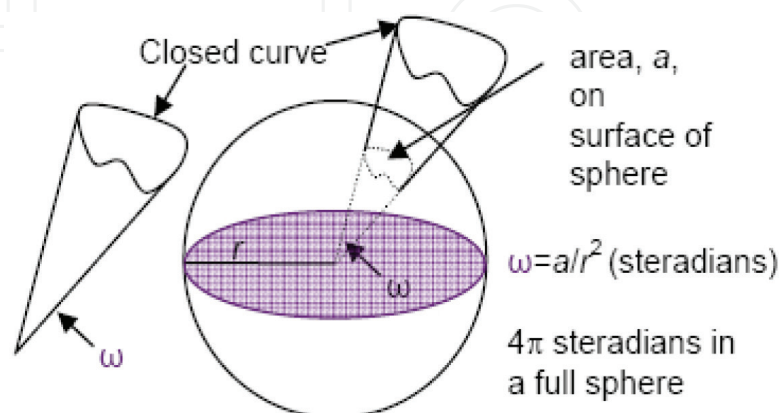


Figure 2. Solid angle [5].



Figure 3. Radiant flux [6].

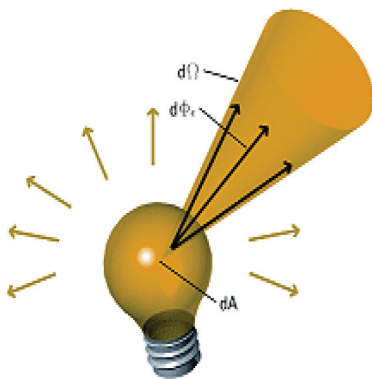


Figure 4. Radiant intensity [6].

$$I_e = \frac{d\Phi_e}{d\omega} \tag{1}$$

2.2.3. Radiance (L_e)

Quotient of the radiant flux (Φ_e) leaving, arriving at or passing through an element of surface at this point and propagated in directions defined by an elementary cone containing [7]:

$$L_e = \frac{d^2\Phi_e}{d\omega \cdot dA \cdot \cos \varepsilon} \tag{2}$$

where ε is the angle between the normal of the surface element and the direction of propagation under question. The SI unit for radiance is Watt/square meter steradian (Watt/m² sr), as shown in **Figure 5**.

2.2.4. Irradiance (E_e)

Flux per unit area passing through a plane from all directions in one hemisphere [7].

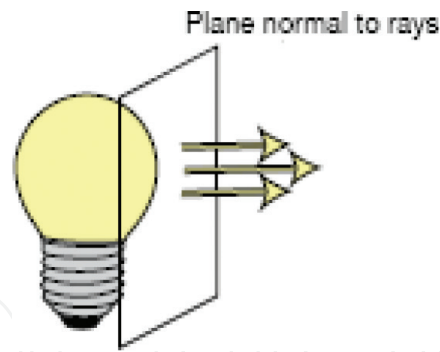


Figure 5. Radiance.

$$\begin{aligned}
 E_e &= \int_{2\pi} L_e(\varepsilon, \varphi) \cos \varepsilon d\omega(\varepsilon, \varphi) \\
 &= \int_{\varphi=0}^{2\pi} \int_{\varepsilon=0}^{2\pi} L_e(\varepsilon, \varphi) \cos \varepsilon \sin \varepsilon d\varepsilon d\varphi \omega_0
 \end{aligned} \tag{3}$$

$\omega_0 = 1$ sr unit of solid angle.

where the angles ε and φ are as shown in **Figure 6**.

The amount of incident radiant flux per unit area of a plane surface in Watt/square meter (Watt/m²), as shown in **Figure 7**.

2.2.5. Exitance (M) [4]

It is the radiant flux emitted by a surface per unit area. The SI unit of radiant exitance is the amount of radiant flux per unit area leaving a plane surface in W/m², as shown in **Figure 8**.

2.3. Photometry

Photometry has a unique position in the science of physics. It is influenced by vision science and is a branch of optical radiometry. The science of photometry has been developed to quantify light and its properties accurately [9, 10]. The human eye reacts to electromagnetic

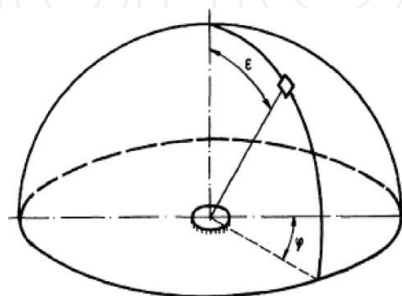


Figure 6. Illustrating the definition of the irradiance produced on a plane by a distributed source [7].

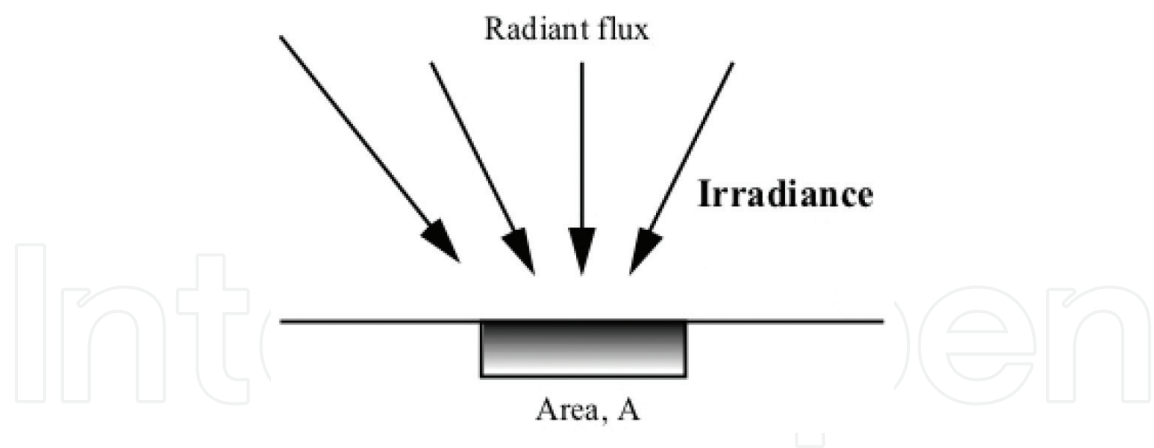


Figure 7. Irradiance [8].

radiation only in a certain part of the spectrum, that is, to a limited range of wavelengths or frequencies. The radiation of sufficient power within a wavelength range of approximately 380–830 nm only can stimulate the eye, and it is called light. Light enters the human eye through the cornea, a tough transparent membrane on the front of the eye as shown in **Figure 9**. It is refracted by the cornea and lens to form an image on the retina at the back of the eye. The sensitivity of the human eye to radiation is not the same for each of the wavelengths. This subjective nature of the visual system sets photometric quantities apart from purely physical quantities.

2.3.1. Photopic and scotopic vision

The human eye adapts to the changes in brightness and color conditions, but a lux meter does not. [12]. CIE measured the light-adapted eyes of a sizeable sample group and compiled the data into the CIE standard luminosity function. During the daytime, the cones of the eye are the primary receptors and the response is called photopic vision, . During the nighttime, the rods become the primary receptors, and the eye’s response changes to scotopic vision,. Relative spectral sensitivity here means the ratio of the perceived optical stimulus to the

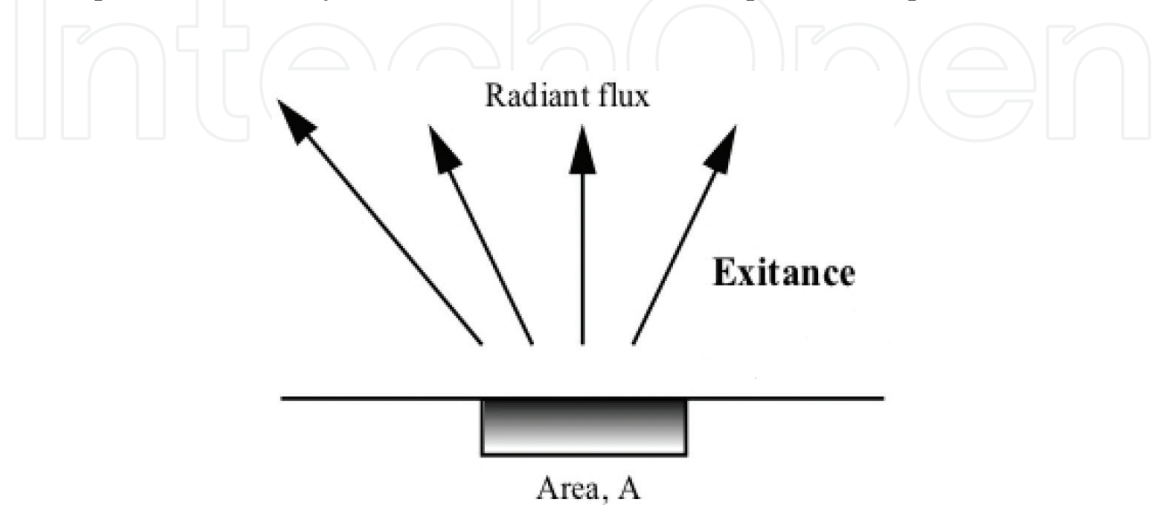


Figure 8. Exitance [8].

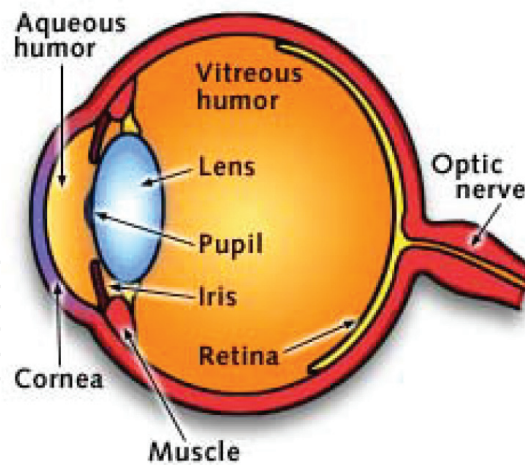


Figure 9. Human eye structure [11].

incident radiant power as a function of wavelength, normalized to unity at the maximum of the function [13] (see **Figure 10**). Special optical filters are used to give photometers nearly the same response as the average eye.

The photometric quantities are related to the corresponding radiometric quantities by the CIE standard luminosity function. We can think of the luminosity function as the transfer function of a filter which approximates the behaviors of the average human eye as shown in **Figure 11**.

2.3.2. Luminous flux (Φ_v)

Quantity derived from radiant flux (Φ_e) by evaluating the radiation according to its action upon the CIE standard photometric observer, as shown in **Figure 12** [4]. The unit is lumen (lm) = $683 \times W \text{ (Watt)} \times V(\lambda)$.

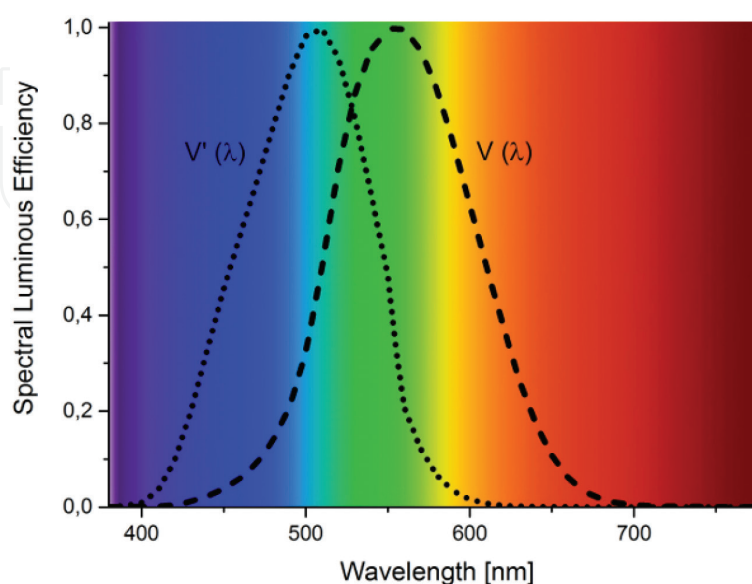


Figure 10. The photopic vision $V(\lambda)$ and the scotopic vision $V'(\lambda)$ functions [14].

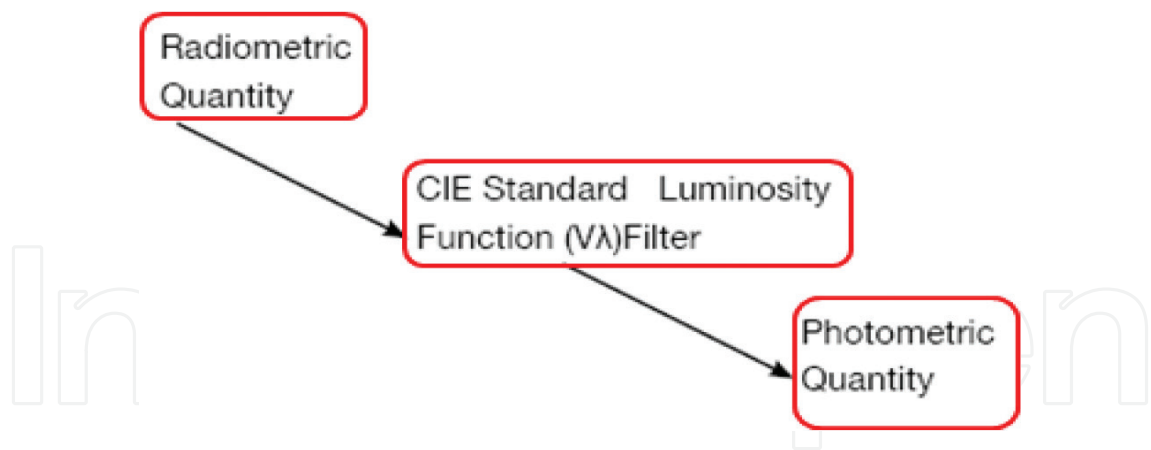


Figure 11. Relationship between radiometric units and photometric units.

2.3.3. Luminous intensity (I_v)

Quotient of the luminous flux (Φ_v) leaving the source and propagated in the element of solid angle $d\omega$ containing the given direction divided by the element of solid angle, as shown in **Figure 12** [4]. The unit is candela (cd).

$$I_v = \frac{d\Phi_v}{d\omega} \tag{4}$$

2.3.4. Illuminance (E_v)

Quotient of the luminous flux Φ_v incident on a surface divided by the area dA of that element, as shown in **Figure 12** [4]. The unit is lux (lx) and is equal to lumen per square meter (lm/m²).

$$E_v = \frac{d\Phi_v}{dA} \tag{5}$$

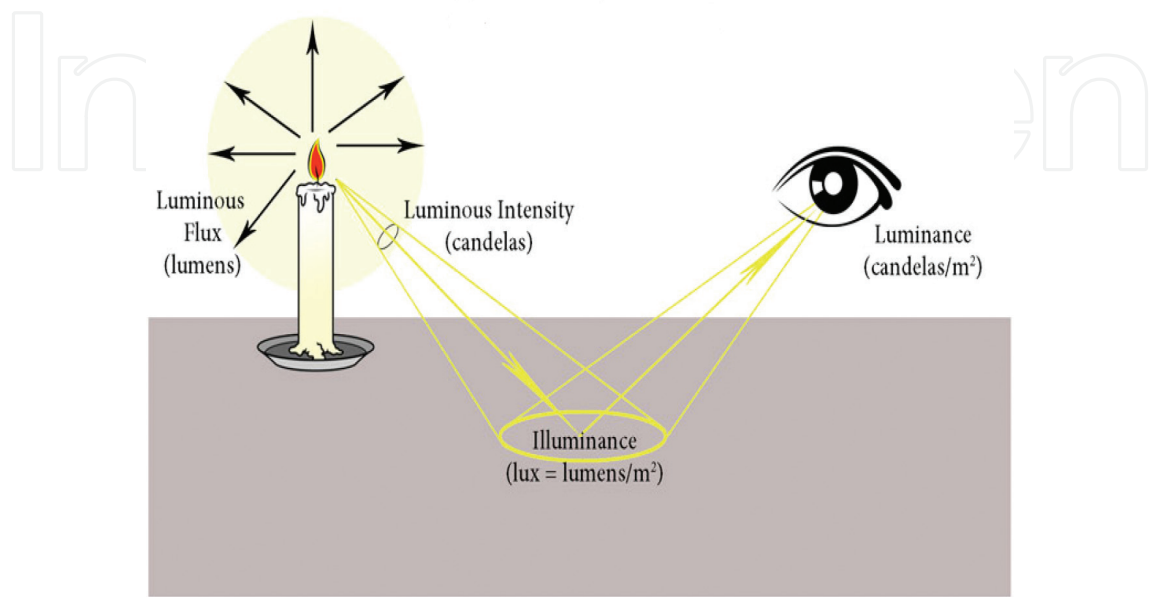


Figure 12. Luminous flux, luminous intensity, illuminance, and luminance [15].

2.3.5. Luminance (L_v)

Quantity defined by the formula [4]:

$$L_v = \frac{d\Phi_v}{dA \cdot \cos\theta \cdot d\omega} \quad (6)$$

where $d\Phi_v$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\omega$ containing the given direction, dA is the area of a section of that beam containing the given point, θ is the angle between the normal to that section and the direction of the beam. The unit is candelas per square meter (cd/m^2).

3. Traceability and the accreditation of the laboratories

The traceability to the SI unit through a National Metrology Institute (NMI) is defined as the property of the result of measurement or the value of a standard whereby, it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties [16], as shown in **Figure 13**. Traceability only exists when metrological evidence is collected to document the traceability chain and quantify its associated measurement uncertainties. In most cases, the ultimate reference for a measurement result is the SI definition of the appropriate unit and the stated reference is usually a national laboratory that maintains a realization of the unit. This is a practical way of stating traceability and reflects the usual chain of measurement comparisons.

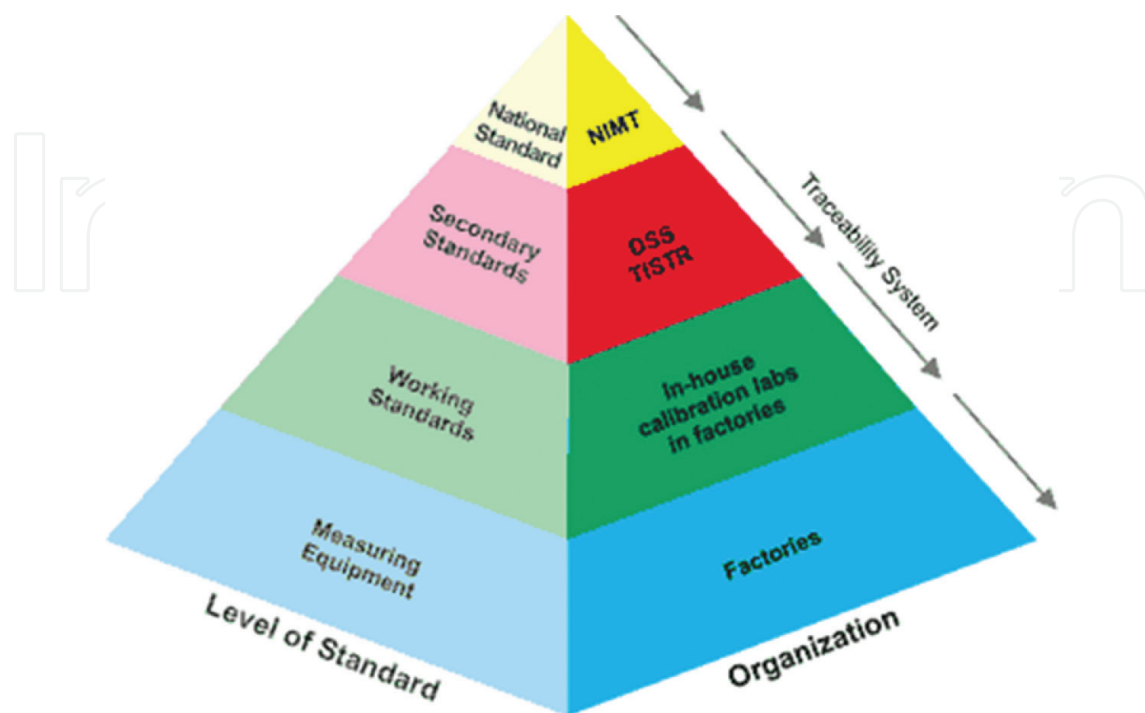


Figure 13. The traceability chain [17].

Generally, goods and services are produced by a process that operates under a quality system. Nowadays, people are more conscious about quality more than before. In modern economy, calibration and testing activities play important roles in assuring the quality of goods, services and purchasing decisions. Currently, quality system registration seems to be a popular method of providing assurance of product quality, but it has become quite clear that, for testing and calibration activities, this is not good enough. The internationally recognized standard for the accreditation of laboratories is ISO 17025: General Requirements for the Competence of Testing and Calibration Laboratories [18]. Accreditation is verification that a laboratory has executed a featured system appropriate for its operations. It is verification of measurement uncertainty claims and of traceability to the International System of Units (SI). Accreditation facilitates trade and commerce by eradicating technical barriers to trade. The accreditation of calibration laboratories is particularly important through its impact on international commerce. A final benefit is that an accredited laboratory has been found to perform better in interlaboratory comparisons than unaccredited laboratories, providing additional assurance to users of accredited services [19].

4. Evaluating and expressing uncertainty

Accurate measurements and associated uncertainty propagation are the backbone of science and industry [20]. Measurements have been the cornerstone of the quantitative sciences since antiquity. However, concepts, terms, units and methods for expressing measurement results [21] and their uncertainties are still contested despite extensive and successful attempts at international consensus resulting in the International Vocabulary of Metrology (VIM) and Guide to the Expression of Uncertainty in Measurement (GUM) more than a decade ago [22–26]. The philosophy of measurement also continues to be a dynamic field of enquiry [27–30] rekindled since the early 2000s [31–34] when the Bureau International des Poids et Mesures (BIPM) began to engage in chemical measurements in addition to physical measurements.

The concept of uncertainty as a quantifiable attribute is relatively new in the history of measurement, although error and error analysis have long been a part of the practice of measurement science or metrology. It is now widely recognized that, when all of the known or suspected components of error have been evaluated and the appropriate corrections have been applied, there still remains an uncertainty about the correctness of the stated result, that is, a doubt about how well the result of the measurement represents the value of the quantity being measured. The uncertainty of the result of the measurement reflects the lack of exact knowledge of the value of the measurand. The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects.

The ideal method for evaluating and expressing the uncertainty of the result of a measurement should be applicable to all kinds of measurements and to all types of input data used in measurements. Also, the actual quantity used to express uncertainty should be directly derivable from the components that contribute to it. A measurement is a set of operations having the object of governing values of a particular quantity called the measurand. In general, the result

of a measurement is only an estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate [35]. In general, a measurement has imperfections that give rise to an error in the measurement result. Traditionally, an error is viewed as having a random component and a systematic component. Random error presumably arises from unpredictable variations of influence quantities. It is not possible to compensate for the random error of a measurement, but increasing the number of observations can usually reduce it. A systematic error arises from a recognized effect of an influence quantity on a measurement; it can be quantified and a correction can be applied to compensate for the effect. According to GUM [35], it is assumed that the result of a measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effect. Uncertainty components are grouped into two categories based on their method of evaluation "A" and "B." Both types are based on probability distributions, and the uncertainty resulting from either type is quantified by variances or standard deviations. Type A standard uncertainty is calculated from series of repeated observations and is the square root of the statistically estimated variance (i.e., the estimated standard deviation). Type B standard uncertainty is also the square root of an estimated variance, but rather than being evaluated by repeated measurement, it is obtained from an assumed probability density function based on the degree of belief that an event will occur. This degree of belief is usually based on a pool of comparatively reliable information such as previous measurement data, experience, manufacturer's specifications, calibration certificates, and so on. Once all the uncertainty components, either Type A or Type B, have been estimated, they are used to calculate the combined standard uncertainty, which equals the square root of the combined variance obtained from all variance and covariance components using what is termed as the law of propagation of uncertainty. When reporting expanded uncertainty instead of combined standard uncertainty, the multiplying factor k should be stated as well as the approximate level of confidence associated with the interval covered by the expanded uncertainty.

The Joint Committee for Guides in Metrology (JCGM) provides authoritative guidance documents to address measurement needs and is currently developing an expanded Guide to the Expression of Uncertainty in Measurement (GUM) that will provide measurement uncertainty propagation methods for a range of applications. Therefore, a comprehensive set of new worked examples to support modern industrial and research practices and to promote the consistent evaluation of measurement uncertainties are needed for this document [36].

4.1. Type A evaluation

In the simplest case (and fortunately the most usual one) of Type A evaluation, the input quantity X_i is treated as a random variable and is reasonably well approximated by the normal distribution [10]. The best estimate of the expected value of the random variable is denoted by x_i and is obtained from the arithmetic mean of a series of n independent observations obtained under the same conditions of measurement:

$$x_i = \frac{1}{n} \sum_{k=1}^n x_{i,k} \quad (7)$$

The individual observations $x_{i,k}$ differ in values because of random variations in the influence quantities or random effects. The experimental variance of the observations, which estimates the variance of the probability distribution of X_i , is given by:

$$s^2(x_{i,k}) = \frac{1}{n-1} \sum_{k=1}^n (x_{i,k} - x_i)^2 \quad (8)$$

This estimate of variance and its positive square root, $S(x_{i,k})$ termed as the experimental standard deviation, characterize the variability of the observed values $x_{i,k}$.

According to statistical theory, the best estimate for the variance of the mean x_i is given by:

$$s^2(x_i) = \frac{s^2(x_{i,k})}{n} = \frac{1}{n(n-1)} \sum_{k=1}^n (x_{i,k} - x_i)^2 \quad (9)$$

The Type A standard uncertainty for that component is then defined as the positive square root of this last quantity:

$$u(x_i) = \sqrt{\frac{1}{n(n-1)} \sum_{k=1}^n (x_{i,k} - x_i)^2} \quad (10)$$

The number of observations n should be large enough to ensure that x_i provides a reliable estimate of the expectation for X_i and that $u^2(x_i)$ provides a reliable estimate of the variance of the expectation for X_i . The number of degrees of freedom, defined as $v_i = n - 1$ should always be given when Type A evaluations of uncertainty components are documented.

4.2. Type B evaluation

With Type B evaluation, an estimate x_i of an input quantity X_i has not been obtained from repeated observations and the associated standard uncertainty is evaluated by scientific judgment based on all of the available information on the possible variability of X_i [10]. This information may include previous measurement data, experience, manufacturer's specifications, calibration certificates, and so on. Type B evaluation calls for insight based on experience and general knowledge; it is, however, as reliable as Type A evaluation.

4.3. The typical uncertainty budget for measurements

4.3.1. The components of a typical uncertainty budget for luminous intensity calibrations (detector-based method) [9]

The following are the descriptions of the abovementioned uncertainty budget items [9] (**Table 1**):

- **Calibration of reference photometers:** The uncertainty of reference photometer is stated in the calibration report issued by the national laboratory or the calibration laboratory that conducted the calibration.

- **Long-term drift of the reference photometers between recalibrations:** Estimated maximum drift of the reference photometer between calibrations.
- **Photometer temperature variation:** If the photometer has no temperature controller or temperature sensor, and the laboratory temperature is kept within
- **Distance scale of the bench (0.5 mm in 3 m)**
- **Alignment of the lamp distance (1 mm in 3 m)**
- **Spectral mismatch correction**
- **Lamp-current regulation (0.01%)**
- **Lamp-current measurement uncertainty (0.01%)**
- **Stray light**
- **Random noise (lamp drift, etc.)**
- **Repeatability of the test lamp (including alignment)**

4.3.2. The typical uncertainty budget for total luminous flux measurements

The components of a typical uncertainty budget for total luminous flux measurements are shown in **Table 2** [9].

Uncertainty factor	Type	Relative standard uncertainty (%)
Calibration of reference photometers	B	
Long-term drift of the reference photometers between recalibrations	B	
Photometer temperature variation	A	
Distance scale of the bench (0.5 mm in 3 m)	B	
Alignment of the lamp distance (1 mm in 3 m)	A	
Spectral mismatch correction	B	
Lamp-current regulation (0.01%)	A	
Lamp-current measurement uncertainty (0.01%)	B	
Stray light	B	
Random noise (lamp drift, etc.)	A	
Repeatability of the test lamp (including alignment)	A	
Relative combined standard uncertainty		
Relative expanded uncertainty (k = 2)		

Table 1. Typical uncertainty budget for luminous intensity calibrations (detector-based method).

The following are the descriptions of the abovementioned uncertainty budget items:

- **Calibration of luminous-flux standard lamps:** The uncertainty of the luminous-flux standard lamps is stated in the calibration report issued by the national laboratory or the calibration laboratory that performed the calibration. This uncertainty normally includes the repeatability of the lamp.
- **Aging of standard lamps:** This uncertainty is calculated from the aging rate of the standard lamps and their calibration intervals. For example, if the aging rate is 0.02% per hour and the lamp is recalibrated every 50 h of its burning time, the uncertainty due to aging of the lamp is estimated to be 1.0%.
- **Self-absorption correction:** Uncertainty of the determination of the correction factor.
- **Spectral mismatch correction:** Uncertainty of the determination of the spectral mismatch correction factor $u(\text{SCF})$ which can be determined regarding Eq. (11) and according to reference [29] by the following Equation [10, 37]:

$$SCF = \frac{\int_{360}^{830nm} P_e^T(\lambda) \times V(\lambda) d\lambda \int_{all-wavelengths} P_e^S(\lambda) \times R(\lambda) d\lambda}{\int_{all-wavelengths} P_e^T(\lambda) \times R(\lambda) d\lambda \int_{360}^{830nm} P_e^S(\lambda) \times V(\lambda) d\lambda}$$

(11)

where

is the relative spectral output of the test source;

is the relative spectral output of the standard source;

is the relative spectral responsivity of the photometer; and.

is the spectral luminous efficiency function that defines a photometric measurement.

$$u^2 = \sum_{variable} \left(\frac{\partial SCF}{\partial variable} \right) \times u^2(variable)$$

(12)

Uncertainty factor	Type	Relative standard uncertainty (%)
Calibration of primary standard lamps	B	
Aging of standard lamps	B	
Self-absorption correction	A	
Spectral mismatch correction	B	
Repeatability of test lamps	A	
Spatial nonuniformity of the sphere response	B	
Lamp electrical control	A	
Relative combined standard uncertainty		
Relative expanded uncertainty (k = 2)		

Table 2. Typical uncertainty budget for luminous intensity calibration (source-based method) [9].

- **Repeatability of test lamps:** Calculated as the standard deviation of the all measurements for each lamp.
- **Spatial nonuniformity of the sphere response:** This uncertainty is associated with differences of the angular intensity distribution of the test lamps and the standard lamp.
- **Lamp electrical control [10]:** The uncertainty of less than 0.01% in the calibration of voltmeter and standard resistor used for measuring and setting the electrical operating conditions of the lamps may result in 0.08% uncertainty in the lamp output.

5. Conclusion

In this chapter, we concentrate on the measurement of absolute amounts of optical radiation, which requires careful definition for the photometric and radiometric quantities such as total flux, intensity, illuminance, luminance, radiance, exitance and irradiance. Also, it was necessary to distinguish between the difference of the exitance and irradiance quantities in the physical meaning. The metrological traceability chain is the sequence of measurement standards and calibrations that were used to relate the measurement result to the reference. To produce accurate, reproducible and international acceptable results, the measurement of absolute amounts of optical radiation needs careful and detailed consideration of a broad range of physical concepts. A measurement has imperfections that give rise to an error in the measurement result. Therefore, measurement results should be expressed in terms of estimated value and an associated uncertainty. Actually, an error is viewed as having a random component and a systematic component. Random error presumably arises from unpredictable variations of influence quantities and is not possible to compensate for the random error of a measurement, but increasing the number of observations can usually reduce it. We provide an explanation to how to estimate and build the uncertainty budget of measurements for the most important quantities. The components of a typical uncertainty budgets for luminous intensity calibrations (detector-based method) and total luminous flux measurements are represented and explained in detail in this chapter.

Abbreviations

ω	solid angle
ω_0	Steradian unit of solid angle
EM	electromagnetic radiation
SI unit	International system of units
L_e	radiance
Φ_e	radiant flux
I_e	radiant Intensity

E_e	irradiance
ε	the angle between the normal <i>of</i> the surface element and the direction <i>of</i> propagation
E_e	irradiance
M	exitance
CIE	Commission Internationale de l'Eclairage
$V(\lambda)$	photopic vision (CIE Standard Luminosity Function)
$V'(\lambda)$	scotopic vision
Φ_v	luminous flux
I_v	luminous intensity
E_v	illuminance
L_v	luminance

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