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Photometry, radiometry and “the candela”: evolution in the classical and quantum world

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Photometry, radiometry and "the candela": evolution in the classical and quantum world

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Abstract

The metrological fields of photometry and radiometry and their associated units are closely linked through the current definition of the base unit of luminous intensity - the candela. These fields are important to a wide range of applications requiring precise and accurate measurements of electromagnetic radiation and, in particular, the amount of radiant energy (light) that is perceived by the human eye. The candela has been one of the base units since the inception of the International System of Units (SI) and is the only base unit that quantifies a fundamental biological process – human vision. This photo-biological process spans an enormous dynamic range of light levels from a few photon interaction involved in triggering the vision mechanism to more than 10^{15} photons per second level that is accommodated by the visual response under bright daylighting conditions. This position paper, prepared by members of the Task Group on the SI of the Consultative Committee of Photometry and Radiometry Strategic Planning Working Group (CCPR WG-SP), reviews the evolution of these fields of optical radiation measurements and their consequent impact on definitions and realization of the candela. Over the past several decades, there have been significant developments in sources, detectors, measuring instruments, and techniques, that have improved the measurement of photometric and radiometric quantities for classical applications in lighting design, manufacturing and quality control processes involving optical sources, detectors and materials. These improved realizations largely underpin the present (1979) definition of the candela. There is no consensus on whether this radiant-based definition fully satisfies the current and projected needs of the optical radiation community. There is also no consensus on whether a reformulation of the definition of the candela in terms of photon flux will be applicable to the lighting community. However, there have been significant recent advances in radiometry in the development of single photon sources and single photon detectors and the growth of associated technologies, such as quantum computing and quantum

cryptography. The international acceptance of these new quantum-based technologies requires improved traceability and reliability of measurements at the few photons level. This review of the evolution of the candela and the impact of its possible reformulation might lead, in the future, to a reformulation in terms of quantum units (photons). This discussion is timely since redefinitions of four of the other SI base units are being considered now in terms of fundamental constants to provide a more universally realizable quantum-based SI system. This paper also introduces for the first time a fundamental constant for photometry.

1. Introduction

The International System of Units (Systeme international d'unitées, SI), since its adoption in 1960, has become the basis of traceable standardized measurements world-wide [1]. This system has evolved over the past 50 years to reflect current best measurement practices and to meet emerging and pressing needs. These changes have largely been driven by advances in science and technology while, at the same time, being responsive to the practical needs of industry, science and society for a highly stable and uniformly realizable system of measurement. Thus, these changes in definition have been made only when this would represent a significant step forward for the user community. The current SI system has seven base units and the dates of adoption of the present definitions range from 1889 for the definition of the kilogram to 1983 for the definition of the metre [2]. There are significant efforts now being directed to redefining four of these base units (kg, mol, K, A) in terms of fundamental constants [3-5]. This proposed change would represent a significant advantage in providing more universally realizable definitions of these SI units, particularly for the measurement of electrical quantities, and would also eliminate the last definition in terms of a material artefact – the kilogram. Similar discussions are being carried out with regard to the other base units. This paper reviews the evolution of optical radiation measurements and deals with discussions within the Consultative Committee of Photometry and Radiometry (CCPR) on whether the evolution of the SI base unit for luminous intensity, the candela, can take advantage of recent improvements in classical radiometry and photometry and development of novel quantum devices and techniques to better serve the needs of its expanding user community.

The present definition of the candela links any photometric quantity to the corresponding radiometric quantity expressed in terms of the watt at one frequency only (corresponding to a wavelength of about 555 nm in air) [6]. Radiometry describes the optical radiation and response in purely physical terms whereas photometry takes into account both the purely physical characteristics of the radiant power stimulating the visual system and the spectral responsivity of the latter. The net effect is intrinsically subjective and sets photometric quantities apart from purely physical quantities [6].

The traditional applications requiring high accuracy photometric and radiometric measurements are lighting design, manufacturing and use of optical sources, detectors, optical components, coloured

materials and optical radiation measuring equipment. In this classical world, the primary optical radiation scales are generally based on cryogenic radiometry with traceability linked to the SI units of electricity. For work in the UV, deep-UV and in the infrared region, primary source scales are also based on calculable sources such as synchrotron and Planckian radiators with traceability to the SI units of thermometry, electricity and length. The standard uncertainties in the primary detector scale are currently around the 0.005 % level, and are based purely on characterisation and calculation. The primary source scale, particularly in the visible range, is derived from the primary detector scale through the use of filter radiometry and uncertainties are currently around the 0.2 % level. The detector and source scales are established at discrete wavelengths and then made spectrally continuous through the characterisation of intermediate standards, such as trap detectors and blackbody sources.

In scaling down to the photon counting regime there is an unavoidable loss in accuracy. For high-accuracy absolute radiometry at the quantum level, predictable or quasi-single photon sources and photon detectors are needed. Quantum optics techniques offer improved uncertainties in this regime, as they are directly applicable to measurements at photon counting levels and can provide a direct, and therefore more effective, way of delivering measurements in the photon counting regime.

The recent advances being made in managing and counting individual photons and producing single-photon sources show tremendous promise of producing within a few years a radiant flux with a well-established number of photons per second with an unprecedented precision and accuracy beyond the standard quantum limit [7,8]. Moreover, the ability to reliably manipulate individual photons will foster the development of new types of instruments that will require, in turn, advances in metrology to create new quantum-based calibration methods and standards. For these reasons, a reformulation of the candela has been proposed in terms of photon units. This reformulation is considered to be a small, but useful step in the future direction of photometry, radiometry and the "candela" in the quantum world. For instance, the emerging fields of nanotechnology and quantum communication are promising new technologies. While their immediate challenges are for new metrological approaches for reliable characterization of properties at the nanoscale, it is foreseen that to advance the progress of these technologies in building verifiable large-scale systems, they will need accurate measurements traceable to the SI using quantum-based radiometric units.

Responding to these challenging needs for traceable, accurate measurements at the single or few photons level is having an impact on the focus of metrology programmes of the National Metrology Institutes (NMIs). This technological revolution may lead to new quantum-based realisations of the SI units with improved accuracy. The inclusion of photon aspects in the explanations of the definition of the candela might be a critical enabler for these emerging technologies. However, there is no unanimity

within the CCPR on this point. In any event, the CCPR has been pro-active by discussing here a possible reformulation of the candela to meet the metrological needs of these new quantum-based technologies.

II. Photometry: The vision mechanism

Most information to human beings about their immediate environment depends on the surrounding light. This light can be natural or artificial but it must be of adequate quality and quantity for the intended application. The interaction with light can be treated as a wave or a particle, depending on the application. The idea that light consists of small packets of highly localized energy called photons, was first introduced by Max Planck to explain the spectral behaviour of a perfect emitter, the so-called blackbody source. This concept of photons is also used in describing the physical stimulus for vision, the result of optical radiation acting on biological receptors as basically one photon interacting with one molecule. The minimum number of photons that are needed to produce a threshold visual response depends upon the observer and stimulus variability but it is of the order of only 6 to 9 photons [9].

Human vision - the interaction of photons with the absorbing photoreceptor molecules in the eye - is one of the most important means that humans use to rapidly obtain information on their surroundings and to make key decisions ranging from the safety of a situation to the quality of goods. However, not all photons are "created equal" and only photons with wavelengths in the range of 360 nm to 830 nm (approximately) are effective at stimulating the "sensation" of vision. The amount of energy associated with a photon of wavelength, λ, is given by

$$E(\lambda) = \frac{hc}{\lambda} \tag{1}$$

where $h = 6.6256\text{x}10^{-34}$ J s is Planck's constant and $c = 2.997\text{x}10^{8}$ ms^{-1} is speed of light in vacuum.

The energy of the photon of a specific frequency, ν, can also be expressed as

$$E(\nu) = h\nu \tag{2}$$

These equations give the correspondence between the wave and the particle nature of the photon [10].

II.1 Interaction: photon-to-molecule

When a beam of light (photons) travelling in a medium encounters a different medium,, a variety of outcomes are possible depending upon the nature of the surface interaction: it can be transmitted, reflected, absorbed, refracted, scattered or diffracted [11]. This interaction with atoms or molecules affects the amplitude and/or direction of the photon flux. Because a photon is a discrete "indivisible" amount of radiant energy, it will transfer all of its energy to a single atom or molecule in this medium [11]. All photons that contribute to a particular output event are indistinguishable to the human eye. The response of the bulk material to this discrete photon flux is a measure of its quantum efficiency, for a given optical interaction process. For example, for a perfect reflecting diffusing material, the number of reflected photons (output event) is equal to the number of incident photons for all wavelengths, and the quantum

efficiency of this ideal reflection process is unity. A perfect reflecting diffuser is also a perfect white with a maximum value of luminous reflectance. In reality, most materials preferentially absorb, reflect or transmit photons of different frequencies and this selective spectral modulation of the incident light by the viewed object is responsible for its appearance. This visual response can only occur if the eye is looking at the light leaving the object. To understand this phenomenon, it is necessary to consider the interaction of the light with the structure of the eye (see Figure 1).

When optical radiation enters the human eye, it is first refracted by the cornea - the transparent layer on the front of the eyeball - then passes through the pupil in the centre of the coloured iris, and is further refracted by the crystalline lens to form an inverted and reversed image at a nodal point behind the lens. The pupil regulates to a certain extent the amount of radiation entering the eye by contracting or dilating. Only those photons that eventually form an image on the photosensitive area at the back of the eyeball, known as the retina, and are above a threshold value dependent upon the state of adaptation, contribute to vision.

In the retinal area, there are hundreds of millions of photosensitive cells but they comprise only two different types of photoreceptors – the rods and cones. The rods and cone receptors contain visual pigment molecules that are activated by the incident photons and produce a visual response (sensation). The amount of light that is absorbed by these two types of photoreceptors depends upon the wavelength and intensity of the photon, the direction of light striking the retina, and the portion of the retina where the light is absorbed. The rods and cones also have different temporal responses when adapting to changes in illumination level. With appropriate periods of light-and dark-adaptation, the human eye is sensitive to optical radiation with luminance values varying over an enormous range of about 11 orders of magnitude from seeing objects under bright direct sunlight (10^{5}cdm^{-2}) to a few photons in a flash of light (10^{-6}cdm^{-2})

At very low luminance levels, the cones do not respond and only the rods are stimulated and contribute to the visual response. The rods contain only one type of photopigment molecule – rhodopsin, which is sensitive over the entire visible spectrum with an absorption maximum at 507 nm in the blue-green portion of the spectrum. The rods are concentrated in the peripheral portion of the retina and are completely absent in the small central area called the fovea. Under normal daylighting levels, the absorbing molecules in the rods are bleached and only the cones are sensitive and contribute to vision. There are three different classes of photopigment molecules or receptors in the cones, each with a different broad and overlapping absorbance spectrum that peak in different portions of the visible spectrum. These three classes of cones are concentrated in the central 2° field of view of the fovea and are referred to as the L-(long-wave-sensitive), M-(medium-wave-sensitive) and S-(short-wave-sensitive) wavelength cones, respectively. The cones in this foveal area give the highest level of visual acuity (spatial resolution) and colour discrimination. Under illumination conditions intermediate between normal and dim (twilight) levels (~10^{-2}cdm^{-2}), e.g. at dusk, both the rods and cones are operative and contribute to vision.

The photons that are absorbed by the photopigments in the rods and/or cones are the physical stimulus for vision. This photon absorption is then converted to electrical signals which are transmitted by the optic nerve to the visual cortex at the back of the brain where it produces a visual sensation. Since photons (quanta) are discrete events, a single quantum is absorbed by a single photopigment molecule. The resultant sensation does not depend upon what quanta are "caught" but rather on the "quantum catching" ability of these receptors [12]. This is known as the Principle of Univariance which assumes that the effectiveness of an absorbed quantum in producing a visual effect is independent of its wavelength [13]. The corollary is that equal numbers of absorbed photons lead to indistinguishable sensations. The response of the human visual system to this total number of photons per unit time (photon flux) or total number of photons presented is then a measure of its quantum efficiency, for a given vision regime.

The overall quantum efficiency depends upon the transmission through the optic media, the absorption in the photoreceptors, their subsequent activation and detectivity by the nervous system [14]. Studies have shown that human observers require exposure to an average of about 100 photons in a brief flash of light for threshold visibility and much of the literature reports an overall quantum efficiency of about 0.06 at these low light levels so that an observer is able to "detect" only a few photons [15]. The quantum efficiency of the visual process at high light levels is much smaller and is estimated to be about 0.005 [16]. The sensitivity performance of the human eye over this wide dynamic range of vision is shown in Fig. 2 on a logarithmic scale which is divided approximately equal between scotopic (rod) and photopic (cone) vision.

Since the dark-adapted (scotopic) eye has only one type of photoreceptor - the rods, the resulting visual sensation from interaction with incident light (photon stimulus) is monochromatic and only sensitive to changes in lightness levels. In the daylight-adapted (photopic) eye, there are three different photopigments in the cones with different "quantum catching" abilities [17]. The simultaneous stimulation of these three different types of cones by incident light in different proportions is sufficient to discriminate millions of different colours (trichromatic model of human colour vision).

II.2 Action spectra and CIE Observers

To measure light so that the result of the measurement correlates as closely as possible with the visual sensation by a human observer exposed to the same radiation, the International Commission on Illumination (CIE) introduced two spectral luminous efficiency functions, $V(\lambda)$ and $V'(\lambda)$ describing, respectively, the relative spectral responsivity of the average human eye for photopic (light adapted) and scotopic (dark adapted) vision [18,19]. The CIPM has approved the use of these functions with the effect that the corresponding photometric quantities are defined purely in physical terms as quantities proportional to the integral of a spectral power distribution, weighted according to a specified function of wavelength [6].

According to [6], any photometric quantity X_v such as luminous flux, luminous intensity, luminance or illuminance, is defined by the following equation:

$$X_v = K_m \int_\lambda X_{e,\lambda}(\lambda) V(\lambda) d\lambda \tag{3}$$

where $X_{e,\lambda}$ is the corresponding radiometric spectral quantity (which is a spectral concentration of radiant flux, radiant intensity, radiance or irradiance, respectively), and the multiplicative constant K_m is the *maximum* luminous efficacy (of radiation) for photopic vision. For scotopic vision, the photometric quantities are defined by a similar integral equation. The present definition of the candela defines the luminous efficacy of radiation as exactly equal to 683 lm/W at a frequency of 540 terahertz and this defines the intersection point of the spectral luminous efficiency functions that applies to photopic, scotopic and mesopic vision [6,20], thereby allowing the full range of visual response functions to be accommodated. This precisely defined frequency corresponds to a wavelength of 555.016 nm in standard air whereas the maximum spectral luminous efficiency of $V(\lambda)$ for photopic vision, K_m is defined at a wavelength of 555 nm exactly and that of $V'(\lambda)$ for scotopic vision, K'_m is defined at a wavelength of 507 nm exactly. To avoid confusion in the use of these various quantities, it is proposed to give a special notation to the luminous efficacy constant given in the candela definition (see Section VI). Thus, according to the SI definition of the candela, the value of K_m is 683.002 lm/W but it is normally rounded to 683 lm/W without affecting accuracy. The corresponding multiplicative constant for scotopic vision K'_m is 1700.06 lm/W but is normally rounded to 1700 lm/W. At present, only the CIE photopic and scotopic spectral luminous efficiency functions have been ratified by the CIPM. However, the CIE has recently recommended a standardized mesopic function for adoption by the CIPM. This will provide, in the near future, a unified system of photometry that allows specification of visual stimuli at all light levels.

Equation (3) summarises three conventions of the current system of photometry [18]:

1. The use of spectral weighing functions with radiometric quantities
2. The law of arithmetic additivity for photometric quantities
3. The choice and definition of the photometric base unit, including the setting of its magnitude.

It should be noted that the law of additivity is a simplifying assumption and obeyed imperfectly in many visual responses[18]. This is not surprising since the strict additivity of light is to be expected when only a single photopigment molecule is involved, as is the case under scotopic conditions, but it can break down under high radiance levels when there are contributions from three different photopigment molecules under photopic conditions. The fact that these simple principles of photometry have been successfully applied for more than 75 years, demonstrates their general usefulness.

Optical radiation is not only important to human vision but also to a range of other photobiological and photochemical effects. These photo-induced changes in living and non-living organisms are referred

to as “actinism” or actinic phenomena and an action spectrum is defined as the relative spectral effectiveness of optical radiation for a specified actinic phenomenon, in a specified system [21]. For example, the erythema action spectrum measures the spectral dependence of UV radiation to produce erythema (reddening) of the human skin. The determination of action spectra is generally carried out using monochromatic sources of radiation and the spectral response is normalized to unity at the wavelength of “maximum action” where the smallest dose suffices to induce the required effect. Photon quantities are commonly used in these experimental determinations of molecular level photon interactions. While metrology techniques are well-advanced in the fields of classical photometry and radiometry, this is not the case for these photon-based optical radiation measurement applications. In recent years, there has been increasing demands for metrological approaches towards standardizing these measurements to obtain reliable quantitative information. In response to this pressing need, the BIPM organized a Workshop in 2009 on the subject of Physiological Quantities and SI Units to identify the challenges to standardization and to consider necessary next steps to improving the quality and traceability of these optical radiation measurements that produce various actinic effects in the human body [22]. However the scope of this paper is limited to the discussion of the biological response of the human eye to visible radiation (photometry) which is the first biological quantity to be measured in the SI system.

The action spectrum of the human visual system is the reciprocal of the relative energy at each wavelength needed to produce a constant visual effect. As already stated, the responsivity of the human eye to incident photons depends upon their wavelength. This relative spectral responsivity function, also known as the relative luminous efficiency function of the human eye, was determined experimentally [23]. Gibson of the National Bureau of Standards analyzed at least six different sets of these data and proposed a standard visibility curve for adoption by the CIE at their meeting in 1924.

The science of photometry made a significant advance as a metrological method when the CIE adopted this 1924 visibility curve [24]. This function was standardized as the CIE Standard Photometric Observer for photopic vision, the so-called $V(\lambda)$ function, as the average action spectrum of many human observers for a 2° field of view, under relatively high luminance levels (cone vision). This provided a precise scientific basis for specifying the visual effect of optical radiation in such a way that the results correlated as closely as possible with the visual sensation that a normal human observer would experience when exposed to this radiation.

The adoption of the $V(\lambda)$ function was also critical in the CIE standardization of the colour-matching functions of the Standard Colorimetric Observer in 1931 [25]. The colour-matching experiments that underpinned this standardization were specially designed so that the physical stimulus was incident on the same region of the retina that was used for measuring the 1924 $V(\lambda)$ curve. This meant that the spectral sensitivity of the eye that was measured in these two cases was comparable and the physical stimulus and resultant visual perceptions could be analyzed and compared quantitatively on a metrological basis.

The CIE 1931 Standard Colorimetric Observer is only recommended for use for small, 1° to 4° size stimuli. For larger stimuli, where the stimulus falls on a larger area of the retina beyond the foveal region, a different action spectrum applies. For this reason, the CIE also standardized a large field colorimetric system based on the visual observations conducted in a 10° visual field [26]. However, to-date, this CIE 1964 (10°) Standard Colorimetric Observer has not been adopted by the CIPM as a standard photometric observer for use in these larger fields of view and the V(λ) function remains the cornerstone of practical physical photometry.

The action spectrum that was experimentally determined for rod-only (scotopic) conditions, the so-called $V'(\lambda)$ function, was found to have a similar shape to the cone-only $V(\lambda)$ function, but with its peak at a shorter wavelength than the photopic curve. This difference between the photopic and scotopic curves is called the Purkinje effect [27] and it has been found that the wavelength of maximum luminous efficiency changes sigmoidally between the scotopic and the photopic states in the so-called mesopic or Purkinje illumination range where both the rods and cones are stimulated.

It is important to remember that the visual perceptions predicted by this human vision model and the CIE Observer functions apply only to hypothetical Standard Observers and are only strictly valid for restricted conditions of viewing, particularly illumination levels and fields of view. However, the real benefit of the CIE Standard Observers is that they provide unambiguous and consistent photometric and colorimetric scales. This CIE system of colour and photometric specification was first applied to coloured signal lights and is now the basis of almost all colour industrial technologies. Although this CIE system has worked well to the present day, the CIE continues to work on further improvements and refinements of these CIE Standard Observer functions and work is ongoing to define visual performance action spectra based on the cone absorption fundamentals [28,29] and for the mesopic range [30].

An important assumption of our present standard photometric system and CIE colorimetry system is the additivity law. This states that the luminous intensity of a mixture of lights is the sum of the luminous intensities of the individual lights, where it is necessary to spectrally weight the radiant (photon) intensities by the action spectrum. In the case of photon intensities, it must also be weighted by 1/λ [11,31]. It has been found that this empirical relationship is reasonably obeyed provided that the observation conditions remain invariant (i.e. the same size of physical stimuli, presentation on the retina, and light exposure).

The number of photons of all wavelengths emitted or contained in a given beam of light is the photon number, N_p and is determined from the spectral concentration of the radiant energy of the light. These radiometric quantities which are differential with respect to wavelength or frequency are denoted by having a subscript λ or ν in their symbol designation, i.e. E_λ, or E_ν, where ν is the photon frequency and λ is the wavelength in vacuum, as follows:

$$dN_P = \frac{E_\nu}{h\nu} d\nu = \frac{\lambda E_\lambda}{hc} d\lambda \qquad (4)$$

Integrating,

$$N_P = \int dN_P = \int \frac{E_\nu}{h\nu} d\nu = \int \frac{\lambda E_\lambda}{hc} d\lambda \tag{5}$$

This integrated number of measured photons, when spectrally weighted by the action spectrum for photons, determines the threshold visibility of a scene and is important in characterizing the dose from pulsed sources, such as pulsed lasers and flash lamps. However, if the scene is illuminated continuously, the relevant measurement quantity is not the number of photons in the exposure, but the number of photons per unit time, i.e. the photon flux. This photon flux, ϕ_P (in s^{-1}) is given by:

$$\phi_P = \frac{dN_P}{dt} \tag{6}$$

This quantity is also important whenever a radiation detector produces a signal that is proportional to the photon flux incident on its photosensitive surface (e.g. a photon counter). Thus, depending upon the radiometric application, it is more important to measure photon flux or radiant quantities.

III. Radiometry: Source-based primary methods

The most commonly used sources for conventional absolute radiometry are blackbody radiators and electron storage rings (synchrotron radiation sources). These photon sources produce radiant power over a wide spectral range and their output can be calculated from fundamental principles based upon the knowledge of some physical parameters. The details of the theory of these sources can be found in the existing literature [32]. For several years, high-temperature blackbodies were the only available primary sources for the realization of radiometric units in the infrared, visible, and ultraviolet spectral regions, until the electron storage ring BESSY was shown to be another primary radiation source (see Section III.2).

III.1 Planckian radiator

In 1860, Kirchhoff found that an ideal blackbody, in thermodynamic equilibrium, emitted radiant energy whose spectrum was a function only of wavelength and temperature, independent of the nature of the body. The theoretical interpretation of this blackbody emission was the most prominent problem in physics for more than 30 years, as the exact mathematical expression describing the spectrum could not be derived using thermodynamics or classical statistical mechanics. On the basis of data on the blackbody radiation spectrum collected by Lummer and Pringsheim in 1899, Planck formulated the blackbody radiation law in 1900, known as Planck's law, by introducing the quantum hypothesis [33,34]. This milestone event was not only the beginning of quantum physics, but also the beginning of radiometry as a new field of metrology, where the solution to the blackbody problem had also provided the solution to the search for a reference source for optical radiation measurements [35-37].

The measurement quantity evaluated by Planck and given in his original radiation law was the spectral density of radiant energy. However, the more appropriate quantity for radiometry is the spectral radiance, $L(\lambda,T)$. Since the two quantities are closely related, Planck's blackbody spectral distribution law today refers usually to spectral radiance. According to this equation, the spectral radiance, of a blackbody in vacuum at any temperature, T, is given by:

$$L(\lambda,T) = \frac{2hc^2}{\lambda^5}\left(\frac{1}{e^{hc/\lambda kT} - 1}\right) \tag{7}$$

where k is Boltzmann's constant (1.3807×10^{-23} J/K) and the temperature T is taken on the absolute scale in kelvin.

This blackbody source or Planckian radiator is then a predictable primary level photon source and blackbody spectra can be calculated from an accurate measurement of the temperature and application of Planck's radiation law. Blackbody radiators emit unpolarized radiation and their wideband spectra usually peak in the infrared region, but high-temperature blackbodies operating at temperatures near 3500 K peak in the visible range and emit significant radiation over a wide wavelength range from 200 nm to 3000 nm. In practice, most blackbody sources are not perfect absorbers having unit emissivity and this wavelength-dependent emissivity factor needs to be accounted for when using these sources in realizing spectral irradiance and spectral radiance scales.

A blackbody source can be used as a radiance standard by measuring its temperature, T, with traceability to the International Temperature Scale, which is currently the ITS-90. The uncertainty of this blackbody radiance reference source is then limited by the accuracy in measuring thermodynamic temperature T (in Planck's law) from T_{90}. The uncertainty associated with an ITS-90 temperature determination does not usually include the uncertainty in the thermodynamic temperature of the ITS-90 fixed-points. For intermediate temperature blackbodies (up to 1300 K), the temperature is measured using contact thermometry; usually by a platinum resistance thermometer so the traceability and uncertainty of the blackbody primary source is to the ITS-90 temperature scale. However, for realizing spectral radiance scales in the UV-visible-NIR region, a high temperature blackbody source is needed. In this case, radiometrically-calibrated narrow band filter radiometers are used for determining the thermodynamic temperature directly and traceability and uncertainties are directly linked to absolute radiation measurements and to radiometric SI units (and thus to electrical SI units, because the cryogenic radiometer is based on the equivalence of optical and electrical heating power; see Section IV.1).

With detector-based radiometric standards achieving very small uncertainties in the 0.01% range or below (see section IV), several NMIs now measure thermodynamic temperature by radiometric means, traceable to those detector-based standards, rather than using an ITS-90 derived source-based scale [38-46]. This practice also anticipates changes in thermometry, where the new mise-en-pratique for the

definition of the kelvin (currently being prepared by the Consultative Committee for Thermometry (CCT)) will support direct radiometric measurement of thermodynamic temperatures.

III.2 Synchrotron radiation

The use of synchrotron radiation (SR) for basic and applied radiometry in the UV, vacuum UV and X-ray range is now well established after more than 25 years of research and development [32,49,50]. For this method of source-based radiometry, i.e. the use of a storage ring as a primary source standard, the spectral photon flux Φ emitted from bending magnets into an aperture placed at a distance d from the radiation source point is calculated from classical electrodynamics theory. This requires the measurement of all storage ring parameters entering into the calculation, i.e. electron energy, magnetic induction at the source point, and stored beam current I and the geometry parameters. Storage rings cover a considerably broader spectral range than blackbody radiators and are the radiometric basis in the UV, vacuum UV and X-ray range. Because of the special efforts needed and the limited access to storage rings, only few such facilities are being used around the world for basic radiometry; a complete listing of these storage rings and their details of operation are given in Reference [32]. Notably, the Physikalisch-Technische Bundesanstalt (PTB) is using the Metrology Light Source (MLS) [51,52] in the NIR, VIS and extreme UV range and BESSY II [53] in the X-ray range, SURF III serves the National Institute of Standards and Technology (NIST) as primary standard [54].

A special feature of SR and storage rings is their ability to cover a large dynamic range in photon flux Φ of up to 12 decades. For wavelengths shorter than the length of the stored electron bunches which are typically in the mm range, Φ is directly proportional to the number N of stored electrons, i. e. the electron beam current I.

$$\Phi(\lambda, N) = N\, \Phi_{\text{Schwinger}}(\lambda, 1 \text{ electron})\,(1 + \varepsilon(\lambda)). \tag{8}$$

$\Phi_{\text{Schwinger}}$ is the photon flux calculated according to Schwinger [55] for one stored electron and the known set of storage ring and geometry parameters. The influence of the vertical size of the source is given by the term, $\varepsilon(\lambda)$. This term is dependent on wavelength and vertical acceptance angle and is small for typical calibration geometries. At the MLS, ε is about 10^{-4} for photon energies below 10 eV [52]. Thus, there is no need for high-accuracy measurement of ε and any possible change of ε with the value of the stored beam current can be corrected numerically.

The direct proportionality of Φ and N enables a straightforward investigation of the linearity of detection systems and the adjustment of the photon flux to the sensitivity of the detection system under study. For example, at the MLS operated with only a countable number of stored electrons (below about 1000 electrons), SR in the VIS is used by a device at a fixed distance from the source point, the relative stability of the normalized spectral photon flux is well below 10^{-4} [52]. Since the MLS is a primary standard, a reproducibility of the absolute flux is expected at this level.

During normal operation of a storage ring, I is typically more than 100 mA. This corresponds to about 10^{11} or more stored electrons depending on the revolution frequency ν of the electrons which is in the MHz range. $I = N$ e ν, where e is the elementary charge. At the MLS, e.g., one stored electron corresponds to 1 pA of beam current.

Any number of electrons down to a single electron can be stored without change in the shape of the emitted spectrum. Taking advantage of this feature requires both special operation of a storage ring and methods for the measurement of I over more than 11 orders of magnitude. This has been realized by PTB already at BESSY I [56,57] and is at present routinely performed at BESSY II [53] and the MLS [51]. For very low beam currents, i.e. less than about 1000 stored electrons, N is determined unambiguously by counting the number of stored electrons via observation of the emitted SR flux which shows a step per electron provided that the SR detection system is sufficiently sensitive. This electron counting technique for providing very low photon fluxes is routinely applied by PTB at the MLS [52], at BESSY II [53] and by NIST at SURF III [58].

Most of the storage rings worldwide are built and operated to provide brilliant radiation in the X-ray range. The direct use of the photon beam of such a facility for measurements in the VIS would in many cases cause degradation of optical components like windows or filters or of detectors due to the hard radiation. For measurements in the VIS, low-energy storage rings like the MLS and SURF III are ideal sources which even enable adjustment of the spectrum by tuning the electron energy. Due to the flexibility of operation at these small facilities, extremely low spectral photon fluxes of about 1 s^{-1} nm^{-1} can be realized, depending on wavelength and angular acceptance. At the MLS, e. g., the integrated photon flux from a single stored electron in the bandpass defined by the spectral luminous efficiency for photopic vision $V(\lambda)$, amounts to 23 s^{-1} for a typical angular acceptance [59]. A controlled increase of this flux within 11 orders of magnitude is possible. By use of an undulator, more than 2 orders of magnitude higher fluxes could be obtained.

In addition to the source-based radiometry described above, detector-based radiometry over a wide dynamic range can also be performed at storage rings. This means utilising monochromatized SR in combination with a primary detector standard. PTB and NIST operate dedicated beamlines for detector calibration at their storage rings providing radiation of high spectral purity. Cryogenic electrical substitution radiometers serve as primary detector standards (see Section IV.) [60-62]. Equation (8) still holds in principle but on the right hand side it has to be multiplied by the transmittance $T(\lambda)$ of the beamline which should be constant, i.e. not dependent on the thermal load of the photon beam which can change with the beam current by 11 orders of magnitude. In principle, the monochromatized photon flux of the beamline at a certain wavelength is determined by an absolute radiometer at high numbers N of stored electrons. Based on the linearity of the emitted photon flux with N and the constant transmittance and stability of the beamline, extremely low absolute photon fluxes of monochromatic radiation can be

realized. In practice in most cases highly linear semiconductor photodiodes are used as secondary standards in the monochromatized beam to check the linearity and stability of the set-up.

The principles described above for the calibration of photon counting devices, mainly in the (soft) X-ray range, have been used by PTB since 1985. Energy-dispersive X-ray detectors like Si(Li)s are routinely calibrated in the direct SR beam when operating BESSY II at very low beam currents [63,64]. A combination of source and detector based radiometry has been used to calibrate flow proportional counters [65], HPGe [66] and CCD detectors [67,68]. The quantum efficiency of photon counting devices for Lyman-α radiation has been determined detector-based by use of monochromatized SR [69]. Recently, first investigations of low photon fluxes of the MLS in the VIS have been performed which proved the stability of the flux of better than 10^{-4} over many hours [59], as expected.

IV. Radiometry: Detector-based primary methods

The origins of modern radiometry can be considered to date back to the late 19th century when the first absolute thermal radiometers were independently developed by Angstrom [70] and Kurlbaum [71]. Kurlbaum's was the first to be designed as an absolute primary standard for light measurement.

An absolute radiometer is an instrument which can detect and quantify the level of incident optical radiation, where the means of quantification is by direct reference to another measurable physical phenomena (with a route of traceability to SI electrical units which are of lower uncertainty than given by the radiometer alone) and that is self-calibrating, i.e. the radiometer does not require external calibration against another optical power measuring instrument or reference source.

The operating principle of an absolute radiometer is the comparison of the heating effect of optical radiation with that of a substituted amount of electrical joule heating and is now commonly called Electrical Substitution (ES) and the radiometers Electrical Substitution Radiometers (ESRs).

A typical radiometer, operating in ambient conditions, consists of an optical absorbing element, linked via a poorly conducting heat link, to a reference heat sink maintained at a constant temperature. When optical energy is incident on the optical absorbing element, it is partially absorbed (dependent largely on the absorption properties of the surface material) and this creates a temperature gradient between the absorber and the reference heat sink, proportional to the amount of incident optical energy. This temperature gradient can be detected and quantified by some form of heat sensing element. To quantify the optical energy in terms of radiant power and SI units of watt, requires substitution of the absorbing element and direct reference to another measurable physical phenomena – the equivalent amount of heat energy generated by electrical joule heating, with the temperature sensing device being used in a relative sense as a "null detector".

The underpinning concept of ES is that the heating effect of the measured electrical power is directly equivalent to that of the incident optical power, i.e. the heat flow paths generated by each source

of energy are directly equivalent. Unfortunately, in the general situation, and at ambient temperatures, this is not the case and a number of subsequent experiments need to be carried out to correct for these effects and to determine their contribution to the measurement uncertainty. In particular, the important sources of error are:

- Loss of optical radiation due to imperfect absorbance.
- Non-equivalence due to thermal resistance (difference) between optical and electrically generated heat.
- Incorrect measure of electrical power due to joule heating in leads.
- Differences in heat flow paths – optical and electrical
- Background radiation changes

Over the last century a wide range of techniques and methods have been devised to characterise such absolute radiometers and a good review of these can be found in [72] and references therein. However, in the late 1970s, it was realised that many of these sources of error can be significantly reduced by cooling the radiometer to cryogenic temperatures, in particular the temperature of liquid helium ~ 4 K [73].

IV.1 Absolute cryogenic radiometers

The operating principle of a cryogenic radiometer is the same as that of any ESR but with the advantage that operation at low temperatures reduces all of the parameters limiting the accuracy of room temperature ESRs to a very low level. A recent review of the subject and its applications can be found in [74] but for a fuller treatise [75].

The first successful cryogenic radiometer was that of Quinn and Martin [75] which was not designed for work on optical radiometric scales but for the determination of the Stefan-Boltzman constant (σ) and thermodynamic temperature by total radiation thermometry in the range from -40 to +100 °C. The instrument measured the total radiation emitted from the blackbody through a precisely known solid angle defined by two apertures and the σ constant could then be determined.

Quinn and Martin calculated the uncertainty attributable to their experimental determination and compared their value for σ with the theoretical calculation given by fundamental constants in Codata [76]. The experimental value measured for σ was (5.66959+0.00076) x10^{-8} W m^{-2} K^{-4}, compared with that from Codata of (5.67051+0.00019) x10^{-8} W m^{-2} K^{-4}. The agreement of these results within their combined uncertainties confirms that the systematic and experimental uncertainties determined for the QM radiometer are reasonable and that the instrument is truly an absolute radiometer to at least 2 parts in 10^4. This was more than an order of magnitude smaller than the similar experiment carried out earlier by Blevin using an ambient temperature ESR [77].

The application of cryogenic radiometry to optical radiometry was first suggested by Geist in combination with Blevin and Quinn [78], and led to an experiment performed by Zalewski and Martin to

compare the silicon photodiode self-calibration technique (see Sec. IV.2) with the QM radiometer. The experiment required the modification of the QM radiometer to allow the measurement of laser radiation, rather than blackbody radiation. The results of the experiment were not published but demonstrated the feasibility of using a cryogenic radiometer as the basis for optical radiometric scales [79].

This experiment led NPL to design a new cryogenic radiometer optimised for laser radiation, the so-called primary standard (PS) radiometer [80]. Similar instruments are now in wide use within NMIs as the basis of their radiometric and photometric scales. In general, such radiometers utilise polarised laser radiation as a convenient monochromatic source of radiation and require the measurement of transmittance of a window, inclined at Brewster's angle, to provide a calibration link to more conventional transfer standard detectors, e.g. photodiodes. However, there are notable exceptions to this; for example, at NRC the radiometer has been optimised for operation with a monochromator and the transfer standard photodiodes are contained within the vacuum chamber, removing the need for measurements of window transmittance [81]. In all cases the key principles are the same:

- the cryogenic radiometer measures the radiant power contained within a nominally monochromatic beam of radiation
- the beam then illuminates a detector under test
- the response of the detector under test is consequently determined.

Through appropriate choice of "test detector" and wavelength a full spectral responsivity can be determined for any wavelength by interpolation [82]. By measuring the wavelength of the monochromatic beam, the photon flux can be obtained in a straightforward manner.

The overall uncertainty budget presented in Table 1 is for the NPL-designed radiometer utilizing a mechanical cooling engine to cool the radiometer to cryogenic temperatures [83] but can be considered typical of what can be achieved in the measurement of spectral radiant power at any wavelength in the visible range. Although there are additional contributions to the resultant uncertainty budget related to the properties of any transfer standard detector, its calibration and any geometric defining element, this table can be considered the baseline uncertainty for the realisation of the candela.

Uncertainties of <0.01% are now routinely reported for many radiometric quantities traced to a cryogenic radiometer. Direct comparisons of different absolute radiometers provide a means of investigating changes in responsivity or other kinds of deterioration and calibration practices. However, it should be remembered that a cryogenic radiometer is simply a well-characterised instrument and, unless linked to a more fundamental concept, it has the potential for unknown systematic errors or drifts that can then propagate into all other radiometric quantities. The development of alternate traceability routes with comparable uncertainty levels and ideally linked to fundamental constants, will enable more robust independent comparisons and ensure the long-term integrity of the radiometric SI scales and disseminated units. Several comparisons of this nature have already been carried out, at least to uncertainty levels

around 0.02%, confirming the underlying principle of cryogenic radiometry [48,84-90]. The PS radiometer of NPL was compared with the QM radiometer, which effectively linked optical radiometric quantities and, in particular the candela, to the Stefan-Boltzman constant [48]. Efforts have also been made to link the Boltzmann constant by measuring the total radiance (or exitance) of a blackbody cavity radiator at the triple-point temperature of water (which is exactly known by the definition of the kelvin) [47,48]. Unfortunately, the latter of these two projects [47] was not completed although successful in its aims and the instrument used for the first comparison [48] is no longer in existence. The efforts to establish alternate routes based on the predictable quantum efficiency of photodiodes or a predictable photon flux, are described elsewhere in this paper; these have merit not only in this context, but in providing a direct traceability route in the low photon flux regime.

The last 25 years has seen the development and adaptation of cryogenic radiometry towards a number of new and diverse applications. Although any individual cryogenic radiometer can only operate over a relatively small dynamic range, they can, in principle, be tailored to meet any power level governed only by the choice of temperature sensing element, heat link, and available cooling power. In addition to their use with lasers and monochromators for establishing primary spectral responsivity scales in the visible and near visible spectral regions they have been designed to measure far UV, soft X-ray in conjunction with synchrotron radiation [60-62] and also tera-hertz radiation [91]. Cryogenic radiometers have also been used to determine the thermodynamic temperature of blackbodies [92], and designed for the measurement of total solar irradiance [93] and for establishing traceability for Earth viewing radiometers in space [94].

IV.2 Silicon photodiode as photon-to-electron converter

Silicon photodiodes of high quality are convenient detectors of visible light. They are sensitive, their spatial responsivity is uniform and the response is linear with respect to intensity of light. Silicon photodiodes are also fast detectors and their responsivity changes very little over extended periods of time. The spectral responsivity of a silicon photodiode can be modeled by

$$s(\lambda) = n\frac{e\lambda}{hc}\left[1-\rho(\lambda)\right]\left[1-\delta(\lambda)\right] \qquad (9)$$

where n is the refractive index of air for wavelengths, λ in air. The correction factors are related to reflectance $\rho(\lambda)$ of the detector and to relative losses/gains $\delta(\lambda)$ of the charge carriers in the photodiode. The latter correction factor determines the internal quantum efficiency of the photodiode whereas the external quantum efficiency also includes photon losses due to reflection.

The responsivity, $n\,e\lambda/hc$ in Eq. (9) corresponds to an ideal detector, where each of the incoming photons produces one electron-hole pair to be measured in an external electrical circuit. This type of detector would operate as an ideal photon-to-electron converter with unity conversion efficiency. If an ideal photon-to-electron converter would be available, the problem of measuring the flux of

(monochromatic) photons could be converted to a potentially simpler problem of measuring electric current. Furthermore, counting of single photons would then be equivalent to counting of single electrons.

In a practical photodiode, recombination of the electron-hole pairs reduces the responsivity as compared with an ideal device. In 1980, a series of papers was published to determine the recombination losses in the Si-SiO_2 interface by self-calibration techniques [95-97]. When combined with reflectance data, these measurements allowed the spectral responsivity $s(\lambda)$ of the silicon photodiode to be determined within 0.1 % uncertainty at the longer visible wavelengths [96].

A convenient way to eliminate the specular reflection losses is to arrange several photodiodes in a trap configuration and to measure the combined photocurrent of all diodes [98,82]. In such a trap detector, the specularly reflected light at oblique incidence is successively directed from one photodiode to another. In Figure 3, the third photodiode is aligned at normal incidence so that the light beam exits the detector after five reflections. In the visible, the residual reflectance of the overall detector is typically 0.3 %, a value that is sufficiently small to allow interpolation between a few reflectance measurement wavelengths with less than 0.01 % uncertainty in responsivity [99].

The remaining factors influencing the responsivity of the trap detector are those due to diffuse reflectance, photon absorption without charge carrier generation, and charge carrier losses/gains, where the third effect is typically most significant. Their combined effect can be determined at selected laser wavelengths by comparing the responsivity of a trap detector and of an absolute cryogenic radiometer [80,100,101] operated at near liquid helium temperatures. These cryogenic radiometers provide a reference for trap detector calibrations at the expanded uncertainty level as low as 0.008 % [89]. Internal quantum efficiency models have been developed for the purpose of interpolating the calibration results between the laser wavelengths [102-104]. As a result, trap detector responsivities, and thus the photon-to-electron conversion efficiencies, can be determined with expanded uncertainties of around 0.02 % in optimal conditions [103].

In striving to reduce this uncertainty further and/or to remove its dependency on calibration from an independent primary standard e.g. cryogenic radiometer, we have to look at how to create the ideal unity quantum efficient detector or at least independently predict its quantum efficiency. Quantum efficiency losses due to specular reflectance can be eliminated in a straightforward manner through use of the trap detector configuration and variants of it; however reducing the recombination losses of charge carriers is not so easy. A typical value of $\delta(\lambda)$ of the trap detector is 0.2 % in the middle of the visible range. Most of the volume recombination takes place close to impurity atoms in the doped silicon [97]. The challenge of designing a photodiode with almost ideal internal quantum efficiency is then to produce the p-n junction in a highly pure silicon substrate without any intentional impurity doping. The solution to this problem is a thick silicon oxide layer grown on a high purity p-type silicon wafer. The oxide layer has

a trapped surface charge at the Si-SiO_2 interface producing an induced p-n junction in the p type substrate material [105-107].

It has been suggested that the induced junction photodiode would have predictable internal quantum efficiency at liquid nitrogen temperatures so that the value of $\delta(\lambda)$ of Eq. (9) would be less than 1 ppm [107]. Such a predictable quantum efficient detector (PQED) might allow replacement of the present absolute optical power standard—the cryogenic radiometer—with a more convenient solid-state detector. To achieve a low level of uncertainty, the associated reflectance of the PQED must be of the same order of magnitude. It can be shown that a simple two-photodiode design of Fig. 4 is suitable for the PQED if diffuse reflectance from the surface of the photodiode is less than 1 ppm [108]. For higher scattering up to 100 ppm, a more advanced detector structure may allow control of this uncertainty component at the level of 1 ppm [109]. Experimental tests are underway to determine how close to an ideal photon-to-electron converter can be achieved with the induced junction photodiodes [110]. The device design is optimised for p-polarized incoming light beam. For the predictable quantum efficient detector this is not a limitation, since the detector is operated close to liquid nitrogen temperatures behind a Brewster angle window.

V. Radiometry: Measurement challenges in the quantum world

The major problem of modern radiometry is how to cover the wide dynamic range of radiometric measurements with reliable and traceable methods. As we have seen, for photometry, this dynamic range extends over more than 15 decades. The problem of dynamic range in photometry is "solved" by the eye itself which has different types of receptors operating at different luminance levels. Thus, for photometric measurement and for photometric units, the links to the SI are realizable by the present CIPM definition of the candela and the CIE photometric system. The situation is different for radiometry because different types of instrumentation based on different physical principles are used to measure radiometric quantities at different levels of flux. Thus, for radiometric measurement and for radiometric units, the links to the SI are more difficult to establish over the full dynamic range.

In the classical world of radiometry at high flux levels, the primary optical radiation scales for sources and detectors are generally based on cryogenic radiometry with traceability linked to the SI units of electricity. In the visible range, the detector and source scales are established at discrete wavelengths in the 0.1 mW to 1 mW regime with state-of-the-art uncertainties around the 0.005 % level. In scaling down to the quantum world of radiometry at very low flux levels, photon counting techniques are used, with an unavoidable degradation in accuracy. For high-accuracy absolute radiometry at the quantum level, predictable or quasi-single photon sources and photon detectors are needed. Quantum optics techniques offer improved uncertainties in this photon counting regime, as they are directly applicable to

measurements at photon counting levels and can provide a direct, and therefore more effective, way of delivering traceable measurements in this challenging regime.

V.1 "Photons on demand"

A key requirement for the progress of *quantum information* technology is the development of sources that deterministically produce single photons upon request (on-demand source). Recently, single-photon sources and entangled-photon sources have become available, where the key issue is the non-Poisson generation of single photons.

A laser beam can be described by a single-mode coherent state with Poissonian photon-number distribution, $p(n) = \frac{\mu^n}{n!} e^{-\mu}$, where μ is a mean photon number in the beam. Thus, a highly attenuated laser pulse with very small μ approximates quite well a single-photon Fock state with the probability ratio of multiple photons to a single-photon going to 0 as $\mu \rightarrow 0$. Unfortunately, the fraction of vacuum states then increases dramatically. Moreover, the mean photon number cannot be made arbitrarily low because of detector dark counts.

Quasi-single-photon states can be prepared more efficiently by using signal and idler photon pairs generated by spontaneous parametric down conversion (SPDC) [111]. SPDC is a deterministic single photon source (see also Sec. V.2), where the number of photons in one mode is thermally distributed and the total number in all modes is Poissonian distributed. The key feature is a strong time correlation between photons in the pair. Ideally, if a photon counter detects one photon in the idler path then, for an extremely short time interval, of the order of hundreds of femtoseconds, the other photon in the pair is in the signal path. However, losses in the signal beam and dark counts of the trigger detector can result in no photon in the signal beam even if the trigger detector has clicked. SPDC photons can be satisfactorily used as a heralded single photon source, albeit random, and provide a useful approximation capable of demonstrating single photon-ness. In general, the probability of having multi-photon states is rather low, mainly because the efficiency of the overall SPDC conversion is very poor. Eventually, these states can be effectively eliminated by using techniques available in the literature [112,113]. In conclusion, a SPDC quasi-single-photon source is characterized by a substantial reduction in the portion of vacuum contributions, i.e., empty signals, compared with an attenuated laser.

Colour centers in synthetic diamond with a substitutional nitrogen atom and a vacancy at any adjacent lattice position, represent an interesting single-photon source with strong anti-bunching and a spectral width about 1 nm at room temperature [114].

In quantum dots, i.e. semiconductor nanostructures characterized by a two- or more-level electronic system, the photon is emitted by recombination of an electron-hole pair that can be created by optical pumping or by an electric current [115]. The chosen material determines the wavelength of the

emitted beam while the spectral width is a function of the number of excited energy levels and the average number of created electron-hole pairs.

Single-photon-like states can also be generated by radiative transitions between electronic levels of a single atom (ion) or molecule caught in a trap and placed inside (or sent into) an optical cavity, interacting both with the excitation laser beam and the vacuum field of the cavity [116]. These single-photon sources have desirable properties such as a narrow spectrum and high collection efficiency due to the presence of the cavity. However, the practical feasibility of such sources is still low because of their technological complexity (among others, high vacuum is needed). Furthermore, semiconductor quantum dots and colour centers face the problems of spectral dephasing and inhomogeneity, which make it difficult to find independent emitters that generate indistinguishable photons for applications, such as quantum computing.

Organic molecules in a crystalline host matrix offer another candidate as a practical scalable single-photon source [117]. At low temperatures, some molecular transitions become lifetime limited and offer almost unity quantum yield. Recently, two independent Fourier-limited solid-state single-photon sources have been demonstrated [118]. The solid-state arrangement of this approach enables very long measurement times using the same emitter, practical frequency tunability of individual molecules, and a straightforward method for scaling and miniaturization.

As a consequence of the number of technologies being pursued to develop single photon emitters with different source properties, a number of new metrics are needed to assess these sources. Suitable metrics include the methods and measurement facilities that have been developed for: quantitative characterization of statistical properties of light and *non-classical* signature of single photon sources, such as their anti-bunching behaviour, purity, degree of indistinguishability, and ability to be used for entanglement [113,119]. Capabilities for quantifying the classical and quantum characteristics of photons have also been demonstrated in the measurement of single photon/correlated photons with Hanbury-Brown Twiss, two-photon and Michelson interferometers [120,121].

The present challenge is to improve the accuracy of these measurements and enable them to characterise sources under varying conditions of pumping, temperature, geometry and wavelength. As an example, a good measure of the quality of single-photon sources is its second-order autocorrelation function, i.e., the correlation measured in a Hanbury-Brown-Twiss-type experiment. The signature of true (ideal) single-photon emission is an absence of any coincidences at zero time difference between the two detectors.

V.2 Single-photon detectors and photon number resolving detectors

Conventional single-photon counting detectors cannot distinguish between one or more photons arriving at the same time, so they are not suitable for the measurement of photon-number distribution of single-photon emitters. Nevertheless, they are widely used in the quantum information community.

The most common photon counters are avalanche photodiodes (APD). When APD single-photon detectors are operated in a so-called Geiger mode, i.e. when a reverse voltage is applied on the junction that exceeds the breakdown voltage, collision ionization multiplies the single photoelectrons generated by an impinging photon thereby triggering an avalanche of thousands of carriers. To reset the detector, the avalanche must be quenched - either in a passive or active way. In passive quenching, the voltage on the APD is decreased by a large resistor placed in the detector circuit. In the case of active quenching, the bias voltage is lowered by an active control circuit, allowing higher repetition rates to be reached (up to 10MHz). Photons at specific wavelengths can be detected by a proper choice of chip material. For the visible and near infrared region (up to 1.1 μm), silicon can be used. Commercially-available counting modules offer low dark count rates (below 50 per second), high quantum efficiencies (up to about 70%), and maximum count rates reaching 10 MHz. Dark counts due to thermal noise are kept at a reasonable level by cooling to temperatures of about −20 °C. Note that the dark counts represent an important limiting factor.

For single-photon detectors, classical calibration techniques are based on the use of a strongly attenuated laser source whose (unattenuated) intensity has been measured by means of a power-meter. The uncertainty of this kind of measurement is principally limited by the uncertainty in the calibration of the very low transmittance required for reaching the single-photon level.

This limitation has prompted the study of an alternative scheme, based on the use of photons produced by means of spontaneous parametric down-conversion (SPDC), where photons are emitted in pairs strongly correlated in direction, wavelength, and polarization. Moreover, the two photons of the same pair are emitted within a coherence time τ_{coh} tens of femtoseconds from each other. Since the observation of a photon of a pair in a certain direction (signal) implies the presence of the other one in the conjugated direction (idler), when this last count is not observed, this is due to non-ideal quantum efficiency of the idler detector which can be determined via this method. This absolute technique and variants are becoming attractive for national metrology institutes to realize absolute radiometric standards because they rely simply on the counting of events, involving a remarkably small number of measured quantities, and do not require any reference standards. The scheme for calibrating single-photon detectors by using SPDC has been detailed in the literature [122-141] and is based on the specific properties of this process, where a photon of the pump beam (usually a laser beam) "decays" inside a non-linear crystal into two lower-frequency photons, 1 and 2 (conventionally dubbed "idler" and "signal"), such that energy and momentum are conserved:

$$\omega_{pump} = \omega_1 + \omega_2,$$

$$\vec{k}_{pump} = \vec{k}_1 + \vec{k}_2 .$$

These relations are usually called perfect phase matching conditions. The process can be spontaneous (SPDC) when no modes of radiation, except the pump modes, are injected through the input face of the crystal. If a seed mode is injected, its presence stimulates the process and many more photons of the pump are converted. The scheme is schematically depicted in Fig. 5.

In essence, the calibration procedure consists of placing a couple of photon-counting detectors, D_1 and D_2 down-stream from the nonlinear crystal, along the direction of propagation of correlated photon pairs for a selected pair of frequencies: the detection of an event by one of the two detectors guarantees with certainty, due to the SPDC properties, the presence of a photon with a fixed wavelength in the conjugated direction. If N is the total number of photon pairs emitted from the crystal in a given time interval T_{gate} and $\langle N_1 \rangle$, $\langle N_2 \rangle$, and $\langle N_c \rangle$ are respectively the mean numbers of events recorded during the same time interval T_{gate} by the signal detector, the idler detector, and in coincidence, we have the following obvious relationships:

$$\langle N_1 \rangle = \eta_1 N ;$$

$$\langle N_2 \rangle = \eta_2 N ;$$

where η_1 and η_2 are the detection efficiencies in the signal and idler arms. The number of coincidences is

$$\langle N_c \rangle = \eta_1 \eta_2 N ;$$

due to the statistical independence of the two detectors. Then the detection efficiency can be found as

$$\eta_1 = \langle N_c \rangle / \langle N_2 \rangle ;$$

This simple relation, slightly modified by subtracting the background counts and correcting for acquisition dead-time, is the basis for the absolute calibration of single-photon detectors by means of SPDC. This method has now realized measurement uncertainties comparable to those of traditional methods [141]. A detailed uncertainty budget for the SPDC technique has been recently reported by Polyakov and Migdall [141] where they show that that the current state-of-the-art uncertainty of this method (0.18%) compares well with traditional methods (0.17%) and that the two methods are in agreement within 0.14%..

A key challenge in the establishment of quantum photon-based detectors for optical radiation is the development of single-photon detectors able to reliably discriminate the number of photons emitted in a light pulse. These photon-number resolving (PNR) detectors are critical to the measurement of photon-number distribution of single-photon emitters and a key requirement for progress in quantum information technology. Furthermore, these detectors are needed for the characterization of sources that deterministically produce single photons upon request (on-demand sources). The application of multi-photon states strongly depends on the availability of PNR photon detectors with advanced low-noise and high-efficiency.

An important breakthrough in single-photon resolving detector technology has been the development of cryogenic devices based on superconductors operated close to the transition temperature (transition-edge sensors, TESs). These sensors consist of superconducting thin films electrically biased in the resistive transition. Their sensitivity is a result of the strong dependence of resistance on temperature in the transition and the low specific heat and thermal conductivity of materials at typical operating temperatures near 100 mK. The absorption of a single photon moves the device through the superconducting to normal transition with a large change in electrical resistance that allows one to detect the corresponding current change with a dc-SQUID amplifier. Due to their principle of operation, these detectors are rather slow with a dead time of about 15 μs. The device produces an electrical signal proportional to the heat produced by the absorption of a photon. By operating at temperatures lower than 0.4 K, TESs are able to resolve the number of absorbed photons [142,143]. Figure 6 shows the typical distribution of the pulse amplitudes of single-photon events as detected by TES. The histograms have been obtained by measuring the pulse heights using a digital oscilloscope, without any filtering of the signal apart from a low-pass filter. The bins of the measurements have been converted to photon numbers. Even if we can distinguish up to four photons, they are discriminated only in a statistical sense due to the broad overlap of the Gaussian distributions. To assign the correct number of photons to a pulse with an uncertainty lower than 1 %, two adjacent Gaussian distributions should overlap at 3σ from their mean values, i.e. with a signal-to-noise ratio higher than 2.5. The observed efficiency at temperature 125 mK is about 20 % with a dark-count rate about 0.001 s^{-1} [143]. More recent results show even better performance with a quantum efficiency over 80 % at 1550 nm [144]. As the quality of single-photon detectors and photon number resolving detectors continue to improve, it is expected that quantum radiometric techniques will achieve even lower measurement uncertainties and that, in the near future, they can be considered as an alternative metrological method to advance the accuracy of radiometry.

VI. Candela: Considerations for its possible reformulation

The candela was formally introduced in the SI in 1954 as the base unit for luminous intensity [1]. Before 1948, the unit of luminous intensity was based on flame or incandescent filament standards. It was then replaced by the "new candle" based on the luminance of a Planckian radiator (a blackbody) at the temperature of freezing platinum. This modification had been prepared by the International Commission on Illumination (CIE) and by the CIPM before 1937 and the decision was promulgated by the CIPM in 1946. It was then ratified in 1948 by the 9th CGPM (Resolution 7) which adopted a new international name for the unit, the candela (symbol cd) [145]; in 1967 the 13th CGPM (Resolution 5) gave an amended version of the 1946 definition [146]. It was decided to express the definition of the candela as follows:

The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newton per square metre.

However, there were experimental difficulties in fabricating a platinum blackbody or accurately measuring the temperature of non-platinum blackbody radiators. Also the temperature of these source-based realizations was far below that of modern light sources which introduce significant transfer uncertainties. At about this time, there were new possibilities offered by radiometry, i.e. the measurement of optical radiation power with greater precision and accuracy. These were the driving forces for the 16th CGPM (Resolution 3) to adopt a new definition of the candela in 1979 [147]:

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

The definition is given in terms of monochromatic radiation rather than the broadband radiation implied by the blackbody definition. Thus, there was a fundamental shift in the definition of the candela.. The value 1/683 watt per steradian which appears in the present definition was chosen so as to give the best continuity with the previous definition. Its theoretical value is 1/682 based on T(Pt)= 2042 K and the values for the radiation constants c_1 and c_2, whereas experimental values within the range 1/673 to 1/687 were obtained by relating photometric and radiometric units as realised by national metrology institutes at that time. Thus, the candela has evolved from a a very limited definition based on an artefact - a specified light source - to a more general definition that allows different methods of realisation - photometric or radiometric - with an exactly known numerical relationship of the lumen/watt ratio at a single defined frequency However, it is important to remember that photometric quantities are integrated over an extended wavelength range and to derive photometric quantities from radiometric spectral measurements, it is necessary to spectrally-weight the radiometric quantity by the appropriate standardized luminous efficiency function. In this way, radiometry and photometry have become strongly linked where photometric quantities can be obtained from radiometric measurements, thereby providing the foundation for more precise vision science.

To provide practical guidance in the implementation of this new definition, the Comité Consultatif de Photométrie et Radiométrie (CCPR) approved in 1983 the monograph “Principles governing photometry” [6], collecting the definitions and the tables of numerical values already adopted (or recommended) by the CGPM, the Comité International des Poids et Mesures (CIPM), and the Commission Internationale de l’Eclairage (CIE). For more than 75 years, these two international organizations, the CIPM and the CIE, have held a special complementary relationship in defining the basis for physical photometry. In April 2007, this special working relationship was formally recognized in a Memorandum of Understanding and Agreement of Cooperation, where it states that the CIPM is responsible for the definition and traceability

of the candela in the SI system and the CIE is responsible for the standardization of the action spectra of the human eye.

The current definition of the candela that was adopted in 1979 also offered the user more flexibility in the choice of method for realisation, whereas the 1948 definition was specific to the use of a particular source – a platinum blackbody at its freezing point. This evolution provided a great advantage - allowing the prospect of new techniques to realise the candela, without changing the definition of the base unit. Today, most national metrology institutes realise the candela by radiometric methods. This realisation can be performed by a direct method in which the standard lamp is directly calibrated for luminous intensity against an absolute radiometer. However, most realisations use an indirect method by calibrating a reference photometer, which is a filtered radiometer, by means of a cryogenic radiometer at a few discrete wavelengths for radiant flux responsivity and then interpolating these calibration data to other wavelengths. When using reference photometers comprising silicon photodiodes, standard lamps can be calibrated using this indirect radiometric method with expanded uncertainties of luminous intensity measurements as low as 0.2% [148-151]. Standard photometers can also be used to maintain the luminous intensity unit but there is no consensus on this approach and standard lamps are still widely used to maintain the photometric units by providing either a known luminous intensity in a given direction, or a known luminous flux. Thus, the ties between photometry and radiometry have increased over the past 30 years with photometry becoming largely an applied branch of radiometry. This evolution has made comparability between photometry and radiometry a growing concern for both scientific and commercial applications. It is noteworthy that the CIE spectral weighting function, $V(\lambda)$ is only indirectly included in the 1979 candela definition. It was thought at that time that the CIE recommendations for the Standard Photometric Observer would change in the near future as a better model for the visual system became available. History has shown that while modified and more accurate versions of $V(\lambda)$ became available, the use of the original $V(\lambda)$ function persists as it has continued to adequately serve the user community.

In 2005, the Consultative Committee of Units (CCU) recommended that steps be taken towards new definitions of the kilogram, ampere, kelvin and mole. Their current proposal is to redefine these four base units by fixing the values of the Planck constant h, elementary charge e, Boltzmann constant k, and the Avogadro constant N_A, respectively. At the latest meeting of the CCU in 2009, it was also discussed whether the formal definition of each unit should be given by specifying the value of the fundamental constant fixed by the definition (so-called "explicit constant" definitions), or by implicitly specifying an experiment to realise the definition (so-called "explicit unit" definitions) [152]. Although the CCU considered that explicit constant definitions were simpler and more fundamental, they recommended that the formal definition be immediately followed by a brief interpretation of the definition in the explicit unit form. The CCU also recommended adopting a standard format for all seven definitions. The words for the definition of the candela were also redrafted to match the standard format suggested for the definitions of

all seven base units, but without changing the meaning of the definitions, as new definitions were proposed only for the kilogram, ampere, kelvin and mole.

At the 2009 meeting of the CCPR, there was a lively debate on this subject. At the end of these discussions, there was basic agreement with the CCU proposal with some minor modifications, resulting in the following CCPR recommendation for the official explicit constant definition of the candela:

The candela, unit of luminous intensity in a given direction, is such that the luminous efficacy of monochromatic radiation of frequency 540×10^{12} hertz is equal to exactly 683 candela steradian per watt.

The CCPR confirmed that the concept of "luminous efficacy of radiation" is well established in the field of photometry. With regard to the explanatory text in the explicit unit form that follows the explicit constant definition, the CCPR introduced for the first time a fundamental constant for photometry, the constant K_{cd}, the subscript "cd" referring to the candela and made the following recommendation:

Thus we have the exact relation K_{cd} = 683 lm/W. The effect of this definition is that the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watts per steradian. This radiant intensity corresponds to a photon intensity of $(683 \times 540 \times 10^{12} \times 6.626\,068\,96 \times 10^{-34})^{-1}$ photons per second per steradian.

This new fundamental constant for photometry, K_{cd}, is similar to the other fundamental physical constants in that it is a constant of nature that has been measured experimentally. The latest "best value" of this photometric constant was officially adopted by the CIPM in 1979 and it is now recommended by the CCU and the CCPR that this new fundamental constant be one of the seven fundamental constants that are used to scale the entire SI system and are assigned a definite value without uncertainty. Thus, in the future, even if the CIE establishes an alternative luminous efficiency function, the value of K_{cd} will remain unchanged. Here the unit "photons per second per steradian" is used for photon intensity. This is in correspondence with the proposed redefinition of the ampere, in which the unit of "elementary charges per second" is used for electrical current. Note that both quantities, radiant intensity and photon intensity, are well established in the IEC/CIE lighting vocabulary [21].

The additional sentence in the explanatory text was a compromise between proponents within the CCPR for a radiant intensity formulation and those for a photon intensity formulation. The addition of this sentence did not alter in any way the current explicit unit definition, but made the proposed version acceptable to both sides in this ongoing debate within the CCPR. The one side is of the view that the current definition serves well the practical needs of the classical world, which are the predominant users of photometry and radiometry. The other side is of the view that pro-active steps need to be taken to consider the changing requirements in the quantum world of photometric and radiometric measurements and that the SI base unit for these measurements of light – the candela – needs to be clearly expressed in terms of

both radiant and photon quantities; this is not a substantial change in the current definition, but only an amending clarification. Recent advances in solid-state photonics, optical detectors and optoelectronics have yielded promising new techniques for the production, manipulation and detection of single photons and these will, in turn, create new photonic quantum technologies and application areas [153]. Thus, the proposed explanatory sentence in the definition of the candela to include quantum radiometric terms, e.g. photon intensity, might be beneficial in meeting these emerging needs for quantum-based metrology.

VII. Conclusions

The evolution of radiometry, photometry and the candela has been reviewed in terms of needs and developments in both the classical and the quantum world. The metrological basis of these physical quantities and associated SI base unit is linked to the important biological process of human vision which is generally described in terms of photon interactions. For several decades, the advances in this field of metrology have been spurred by research and development of new and improved source-based and detector-based primary methods. The current state-of-the-art uncertainties of these measurements largely meet the diverse community of users in the classical world of lighting, manufacturing, commerce and health and safety applications. However, there have been recent developments in producing novel single photon sources and single photon detectors. The measurement challenges in characterizing these new "photon on demand" sources and photon-number resolving detectors have been identified. The growth and potential of new quantum-based tools that exploit these new sources and detectors is largely limited by the lack of traceable quantum optical metrology tools and techniques. The definition and practical realization of the candela and the other photometric and radiometric units is regularly reviewed by the Consultative Committee of Photometry and Radiometry (CCPR) to ensure that it reflects current best measurement practices and meets the existing and emerging needs of its user community. The possibility of a reformulation of the candela has been discussed here in terms of expanding its scope of application from meeting existing and future needs in classical photometry and radiometry to including future needs in quantum radiometry. This would build on the existing official definition in terms of radiant intensity by providing an explanatory note in terms of fundamental photon units. This reformulation is considered by members of the photon counting community to be a small, but useful step in the future direction of photometry, radiometry and the "candela" in the quantum world. In addition to addressing the metrological needs of emerging quantum-based optical technologies and applications, this reformulation would also be in harmony with the proposed redefinitions of four of the seven SI base units – the kilogram, ampere, kelvin and mole - in terms of fundamental constants in a quantum-based SI system.

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Table 1. Corrections and uncertainties of the power of the laser beam expressed as parts in 10^4 of the measured power.

	Correction (parts in $10^{4)}$	**Uncertainty (parts in $10^{4)}$**
Window transmittance	3.0	0.3
Beam scatter	2.0	0.15
Absorptance of cavity	0.2	0.05
Electrical power measurement		0.05
Sensitivity of radiometer		0.1
Changes in thermal and scattered radiation		0.1
Sum in quadrature.		0.37

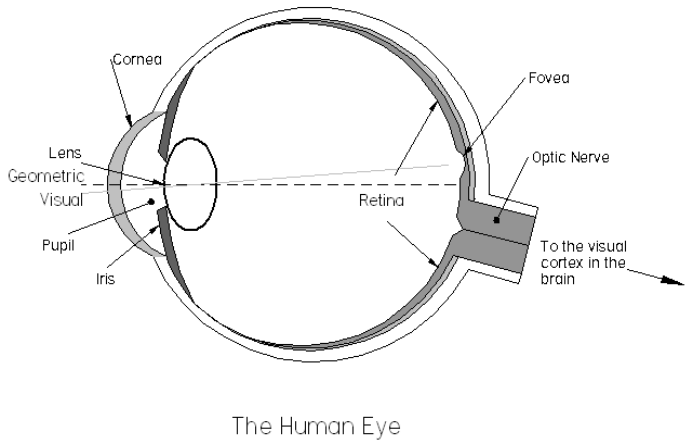


Figure 1. Schematic diagram of the cross-section through a human eye.

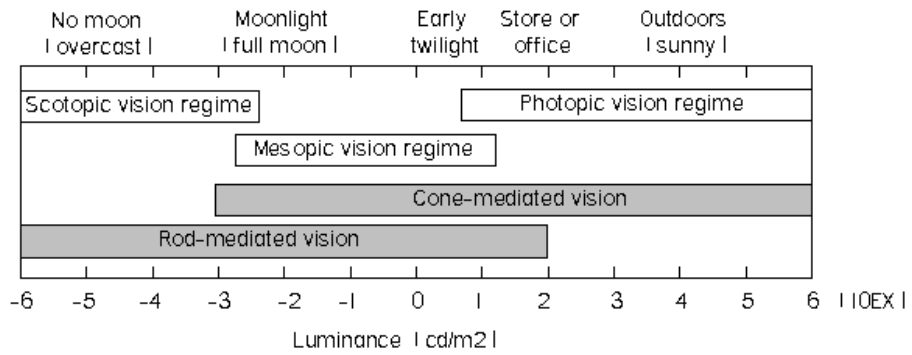


Figure 2. Approximate luminance ranges of human vision and corresponding photoreceptors.

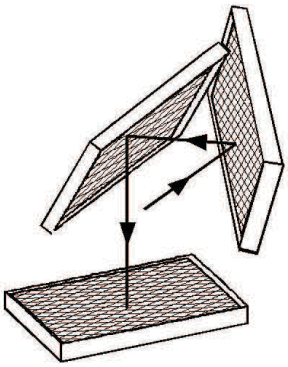


Figure 3. Schematic structure of a trap detector. The planes of incidence of the two upper photodiodes are perpendicular, making the reflectance out of the detector insensitive to the polarization state of the incoming light beam.

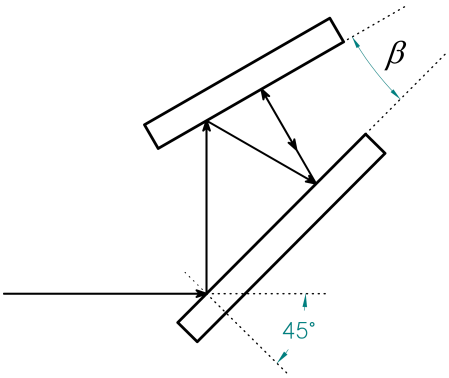
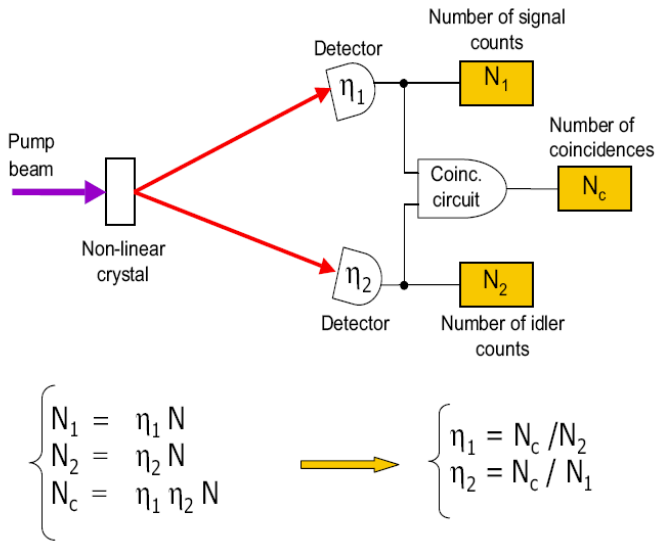


Figure 4. Schematic structure of a two-photodiode trap detector.



$$\begin{cases} N_1 = \eta_1 N \\ N_2 = \eta_2 N \\ N_c = \eta_1 \eta_2 N \end{cases} \Rightarrow \begin{cases} \eta_1 = N_c / N_2 \\ \eta_2 = N_c / N_1 \end{cases}$$

Figure 5. Scheme for absolute calibration of single photon detectors.

Figure 6. Typical distribution of the pulse amplitudes of single-photon events as detected by TES.

