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PHOTOMETRY OF LIGHTING DEVICES: CURRENT STATE AND PROSPECTS FOR DEVELOPMENT

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ABSTRACT

The article is a dedicated review of recommendations, methods, and tools for establishing and communicating the standard measurements of photometric, energy, and photon value units. The article considers how photometric values units are reproduced and traced through to the basic units of the International System of Units (SI), as well as how methods and tools of transposing standard measures from primary standards to measuring devices in test centres and laboratories. Modern day measurement requirements for test methods and facilities for illumination devices used in different illumination systems are also considered.

Keywords: optical radiometry, photometry, colorimetry, spectroradiometric approach, detector based approach, photon quantity, goniophotometry, image photometer

1. INTRODUCTION

Recent decades have seen a significant leap forward in the development of light sources [1,2], radiation receivers [3,4], measurement methods and precision instrument design as a whole [5–7].

This process develops alongside the introduction of quantum technology into metrology [8], which arises from the understanding of the wave nature of light, and stems from the definition of the candela as a base unit of luminous intensity in 1979.

International choice in favour of quantum technology or photonics requires improving measurement tracing and reliability for both single photon and multiphoton processes. The latter requirement remains in the research and development stage, but the evolution in the candela reproduction method is in the direction of the quantum approach (for example, candela is the luminous intensity of a monochrome radiation source in a certain direction with 540x1012 Hz frequency, radiant intensity of 1/683 W/sr and photon radiant intensity equal to $(683 \text{ x } 540 \text{ x}10^{12} \times 6.626068\,96 \times 10^{-34})^{-1}$ photon/s·sr.). The shift is timely, considering that four units of the SI system (kg, mol, Kelvin and Ampere) have been redefined in physical constant terms in order to create a universal quantum SI system based on fundamental constants [9,10,11].

Document [12] prepared and officially approved by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM) is a memorandum for the practical use of the candela definition, which updates and expands the preceding version of this document that was limited by it approach to the candela based on the 1979 definition, which is still applied. Photometry and measurement units used in optical radiometry are closely connected by the candela definition as the base unit of the SI. The memorandum covers the implementation of the candela, as well as other units of measuring radiometric and photometric standard values. Recent progress in the generation and application of separate photons provide many possibilities in evaluating radiation fluxes by the number of photon. Therefore, the approved document also includes information on the practical realisation of a transition away from measuring radiometric and photometric values to measuring photon quantity.

1.1. Photometry and radiometry

Candela is the base unit of luminous intensity as a photometric value in the SI. The definition of a candela in the SI establishes the link between radiometric and photometric units. In 1979 at the 16th General Conference on Measures and Weights, the following definition of candela [*cd*] as the unit of luminous intensity was accepted [13]:

"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 Watt per steradian."

It follows from this that, in SI units, the spectral luminous efficiency K_{cd} of monochromatic radiation with a frequency of $540\cdot10^{12}$ Hz is equal to 683 cd·sr/W or lm/W exactly.

This definition is formulated using only physical terms and only for one frequency of electromagnetic radiation. The purpose of photometry is to measure radiation parameters in the visible spectrum in a way that the results correspond with the observer's visual perception of this radiation. Most light sources have a wide frequency spectrum. For this reason the International Commission on Illumination (CIE) established several weighting functions, called relative spectral luminous efficiency functions. They describe relative spectral sensitivity, or a reaction spectrum of an average human eye under certain observation conditions. These functions are expressed as dependencies on wavelength in standard air (dry air at 15 ˚C and 101325 Pa containing 0.03 % volume carbon dioxide) normalised relative to their maxima. The candela definition is intended to connect up these functions, setting their values at a specified frequency. The K_{cd} constant, together with the relative spectral luminous efficiency function brings together radiometric and photometric values in a unified metrological system.

In 2007, the *Bureau International des Poids et des Mesures* (BIPM) and CIPM (as it part) formed an agreement with the CIE, according to which it was confirmed that:

- CIPM (BIPM) is responsible for the definition of photometric units in the SI;
- CIE is responsible for standardisation of relative spectral luminous efficiency functions of the human eye.

Overall, the equation linking a preset radiometric value spectral distribution $X_{e,\lambda}(\lambda)$ with its corresponding photometric value X_{vx} is expressed as follows:

$$X_{v,x} = \frac{K_{cd}}{V_x(\lambda_a)} \int_\lambda X_{e,\lambda}(\lambda) V_x(\lambda) \cdot d\lambda, \tag{1}$$

where λ_a = 555.017 nm is wavelength in standard air [3], which corresponds to the frequency specified in the candela definition, and lower index x indicates a CIE relative spectral luminous efficiency function. The most important of these visual perception functions, is relative spectral luminous efficiency for an observer's eye as it adapts to daylight vision condition $V(\lambda)$, tabulated by the CIE with an interval of 1 nm for the wavelength range (350–830) nm. Recently the CIE standardised the relative spectral luminous efficiency function for twilight sight (mesopic function). This function is intended to be used at luminance levels between those corresponding to day time sight conditions and those corresponding to night time vision conditions (eye's adaptation during twilight). This concluded the standardisation process for functions [14,15] connected with conditions of vision.

1.2. Photometry and photon quantity

Photon quantity are characteristics of optical radiation expressed through known numbers of photons or photon fluxes. Because of the dual nature of electromagnetic radiation, photometric and/or spectral energy values can be expressed using photon quantity.

For wavelengths in air, relations between the spectral energy value $X_{e,\lambda}(\lambda)$ at the corresponding wavelength, and coincident photon value $X_{p,\lambda}(\lambda)$ is expressed as follows:

$$X_{e,\lambda}(\lambda) = \frac{hc}{\lambda} \cdot n(\lambda) \cdot X_{p,\lambda}(\lambda), \tag{2}$$

where h is Planck's constant, c is the speed of light in a vacuum, $n(\lambda)$ is the refraction spectral index of standard air.

Having combined equations (1) and (2), we obtain a general equation connecting photometric value $X_{v,x}$ and its corresponding photon value $X_{p,\lambda}(\lambda)$:

$$X_{v,x} = K_{p,x} \int_{\lambda} X_{p,\lambda}(\lambda) \frac{n(\lambda) V_x(\lambda)}{\lambda} d\lambda, \tag{3}$$

where

$$K_{p,x} = \frac{K_{cd} hc}{V_x(\lambda_a)}, \tag{4}$$

and $K_{p,x}$ is the transformation coefficient of photon quantity into photometric for the relative spectral luminous efficiency function $V_x(\lambda)$.

Photon quantity are especially important for the evaluation of illumination devices (ID) of the photosynthetic active radiation (PAR) [16.17]. In order to evaluate this, the photon number is correlated with the molecule number of the substance which absorbs them.

Avogadro's number (($N_A = 6.026 \cdot 10^{23}$ mol $^{-1}$) represents the unit of photon flux [18] in the PAR interval. Thus photon flux Φ_{ph} at the wavelength λ in the PAR spectral range will be equal to:

$$\Phi_{ph}(\lambda) = \frac{N_{ph}}{N_A} = \frac{\Phi_e(\lambda)\lambda}{N_A hc}, \text{ [µmol/s]}, \tag{5}$$

where photon number $N_{ph} = \Phi_e(\lambda)/E_{ph}(\lambda)$, i.e. it is equal to the relation of spectral radiation flux $\Phi_e(\lambda)$ to quantum energy of the corresponding wavelength $E_{ph}(\lambda) = hc/\lambda$.

2. REALISATION OF CANDELA AND DERIVATIVE UNITS OF RADIOMETRIC, PHOTOMETRIC AND PHOTON QUANTITY MEASUREMENTS

The existing methods of realising radiometric and photometric measurements units are described in more detail in [8]. As the definition of the candela connects photometric measurements units with radiometric ones, the practical implementation of photometric units is almost always based on the practical implementation of radiometric units.

Two main methods are usually used to implement radiometric units. They are the detector-based and the source-based methods, depending on what they are based on: a primary standard receiver, or a primary standard radiation source. The realisation of measurement units size of photon quantity, such as photon flux (photon number per second), or photon irradiance (photon number per second per unit area) for low levels of radiation fluxes can be achieved with radiometric methods based on a receiver or a source of radiation and describing transition from radiometric values to photon ones. However, single-photon sources can also be used and photon quantity can be obtained via a photon count. This third approach is referred to as the photon-based method.

The method of measuring using an absolute radiometer involves the principle of electric replacement (Electrical Substitution Radiometer – ESR), i.e. heating using optical radiation is compared with heating by electric power, which replaces the optical radiation. This well-known method is often applied with radiometers cooled to ultralow temperatures (<~ 20 K), where the influence of many sources of error significantly decreases. These devices are called cryogenic radiometers.

Predictable Quantum Efficiency Detectors (PQED) present a method based on a high-efficiency semiconductor material with small losses in a certain spectral interval of wavelengths. As a rule, this is based on a silicon photodiode which uses an exact method of transforming photons to electrons and registers the quantity of the incident optical radiation proceeding from measurement results of the generated photocurrent. This approach is initially based on the separate photodiode "self-calibration" principle, and it increased its importance after emergence of trap detectors with quantum efficiency close to one due to creation of radiation traps forming reflections from several photodiodes with electrically combined outputs, [3, 4, 18, 19].

An absolute source is a source, the optical radiation characteristic of which can be calculated based on the measurement results of other physical parameters, for example, thermodynamic temperature. Optical radiation generated by any other source can be measured by direct comparison with such an absolute source. There are two types of sources, which can be considered absolute under certain conditions:

- Model of Planck's radiator (black body model, Fig.1): For a cavity with a high thermal emissivity (very close to one), the radiated spectral radiance can be predicted using Planck's radiation law, com-

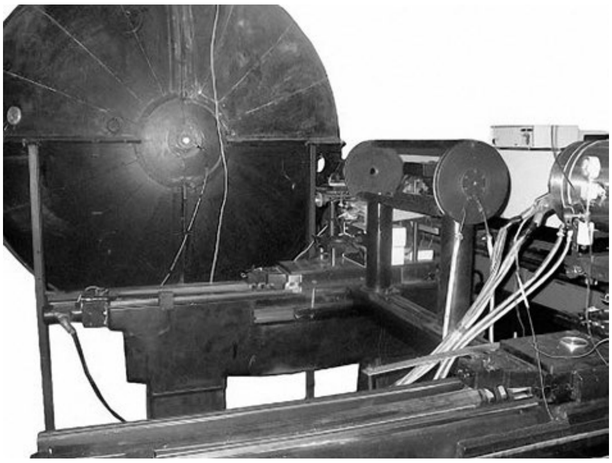

Fig.1. State Primary Standard of luminous intensity and luminous flux unit, VNIIOFI, Moscow [21]

ing from the thermodynamic (absolute) temperature of the cavity. In this case it can be traced back to the SI base temperature unit – Kelvin. For many fields of application requiring a high precision, cavity absolute temperature is determined using a calibrated radiometer with a colour filter (which is called a filtered radiometer). And in this it can be traced back to electric SI units. If the radiance of the source is constant in all directions, then having used a precise aperture placed in front of the Planck's radiator in a certain direction at a significant distance, the computed value of its spectral radiance can be transformed to a predicted spectral radiant intensity, spectral irradiance at a preset distance or to spectral flux distribution within a certain solid angle [20, 21].

- <u>Electron accumulator ring generating synchrotron radiation, Fig.2:</u> Electrons moving with relativistic velocities along circular trajectories generate synchrotron radiation. Under certain conditions, this source can be considered as absolute. In this case, the power of the synchrotron radiation beam generated by one electron moving along a circular trajectory with frequency v [W·rad^{-1}], can be predicted using Schwinger's equation based on the known and measured values of electrical and geometrical parameters. Any number of electrons, even one, can be accumulated without any changes in the configuration of the radiation spectrum. In this case, tracing can be to electric units and to SI units of length.
- Synchrotron radiation covers a big photon fluxes interval, up to 12 orders of magnitude, which allows bringing the photon flux in line with the sensitivity of the studied detector [22, 23].

Traceability in measurements based on the reproduction of photon quantity relies on the definition of candela being connected with photon quantity by means of photometric and radiometric values [8, 24]. Separate photons can be generated for by nonlinear materials, for example, as well as optical and electric sources of single photons, and can be counted by photo multipliers, one-photon impact avalanche and transit-time diodes, superconducting detectors nanowire based and phase transition detectors.

The most widespread method of photometric value measurement is based on the use of a standard photometric detector, the spectral sensitivity of which precisely corresponds to the necessary function of relative spectral luminous efficiency. The receiver (photometer and photometric head) has a precise aperture calibrated over the area (traceability to the SI length units) and a measured spectral sensitivity (traceability to the absolute radiometer [25]). Using the comparison method or direct measurements, the photometric unit is transferred to other light sources or to photometric heads with standard status, which become secondary standard photometric sources (or photometers) for transmission of the correspondent photometric value. In this case, traceability to the SI units is "detector-based", and hence to the electric SI units. This method usually requires additional measurements of the photometer's spectral sensitivity in order to determine

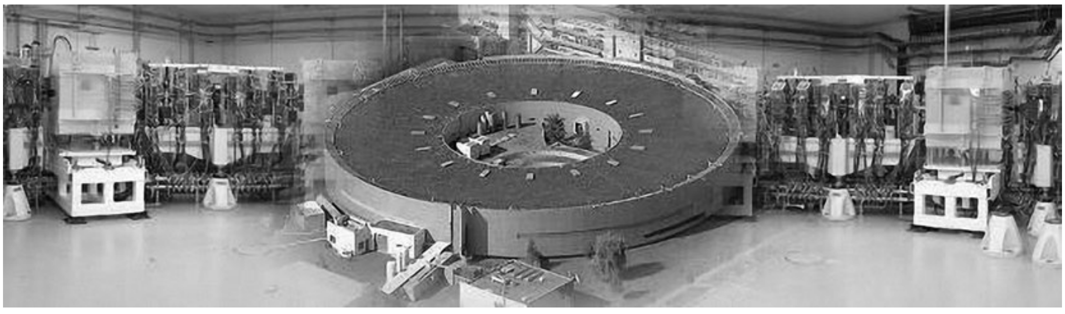

Fig. 2. Source of synchrotron radiation BESSY II, PTB, Berlin [22]

the quality of spectral correction of the receiver relative to the CIE relative spectral luminous efficiency function. To determine a photometer correction quality, one should know relative spectral characteristic of the measured light source [26, 32].

If photon quantity are measured in the process, then they can be transformed into the correspondent photometric values using equation (3).

Practically, all methods of determining photometric, energy and photon parameters result in traceability to the base units of the SI, Fig. 3.

3. EQUIPMENT OF TEST LABORATORIES FOR OPTICAL RADIOMETRIC MEASUREMENTS

Equipping and metrological support of accredited test laboratories and centres in the field of optical radiometry is integral to enabling modern energy efficient, ecologically sound illumination which provides a high quality environment.

The international lighting community pays a lot of attention to the uniformity of measurement, which can enable a reliable evaluation of lighting product parameters.

From October 2012 until August 2013, international laboratory comparisons *IC2013* of the measurements of illumination devices with light emitting diodes were prepared and undertaken by a group of international experts within the IEA 4E SSL Annex special programme of the International Energy Agency. These comparisons revealed some differences in the results of participant laboratories which were caused by measurement techniques, the equipment used and by choice of criteria for evaluation of measurement uncertainty [27, 28].

IEA 4E SSL Annex 2017 has declared a new initiative of international comparisons of test laboratories and centres covering measurements by goniophotometers, which is based on protocols of the CIE new standard [30]; there are a number of associated prototype documents including: European standard EN13032–4, IESNA LM79 standard, Korean standards KS C7653 and KS C7651, as well as other international and national materials.

The new CIE standard [29] proposes the following systems protocols to test characteristics of illumination devices (ID):

– Systems with integrating spheres: integrating sphere with a photometer, integrating sphere with a spectrometer;

– Goniophotometric systems: goniometer with a photometer (including near-field region goniophotometers with image photometers (luminance meters), goniometer with spectral radiometer, goniometer with three-channel colorimeter;

– Luminance meters (photo-electric and digital);

– Spectroradiometric installations with standard radiation sources to measure spectral characteristics of the tested ID in a preset observation geometry.

Measurements of small size devices, for which no luminous intensity distribution measurements are needed (for example, of LED lamps), are carried out using systems with integrating spheres. Measurements of luminaires, for which luminous intensity distribution data is needed, are carried out using goniophotometric systems. To analyse spectral and colour characteristics, sphere – spectrometer, goniometer – spectral radiometer (spectrometer) or goniometer – colorimeter systems are used.

The goniometer – colorimeter system is only recommended for the measurement of relative colour characteristics.

Spectroradiometric stands are used to determine absolute spectral characteristics of light sources (LS) and of illumination devices, as well as to calculate characteristics measured within certain geometries (observation angles), for example, to determine a blue light hazard radiance parameter L_b [30, 31].

All instruments making up the measurement system, as well as integrated system optical stands, should be verified (calibrated) with traceability to the SI units.

3.1. Requirements for integrated photometers

The spectral characteristics of photometers, luxmeters, photometric heads and luminance meters used within photometric installations should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for $V(\lambda)$ curve, [36].

Total coefficient f_1' correction factor (sphere – photometer, goniophotometer, luxmeter) should not exceed 3 % [26, 32, 33].

If this requirement is met, spectral discrepancy only needs to be corrected for tested devices with colour light emitting diodes. This requirement can also be sidestepped if a correction for spectral discrepancy is assumed for each tested device. In this case, current f_1' values are added into the

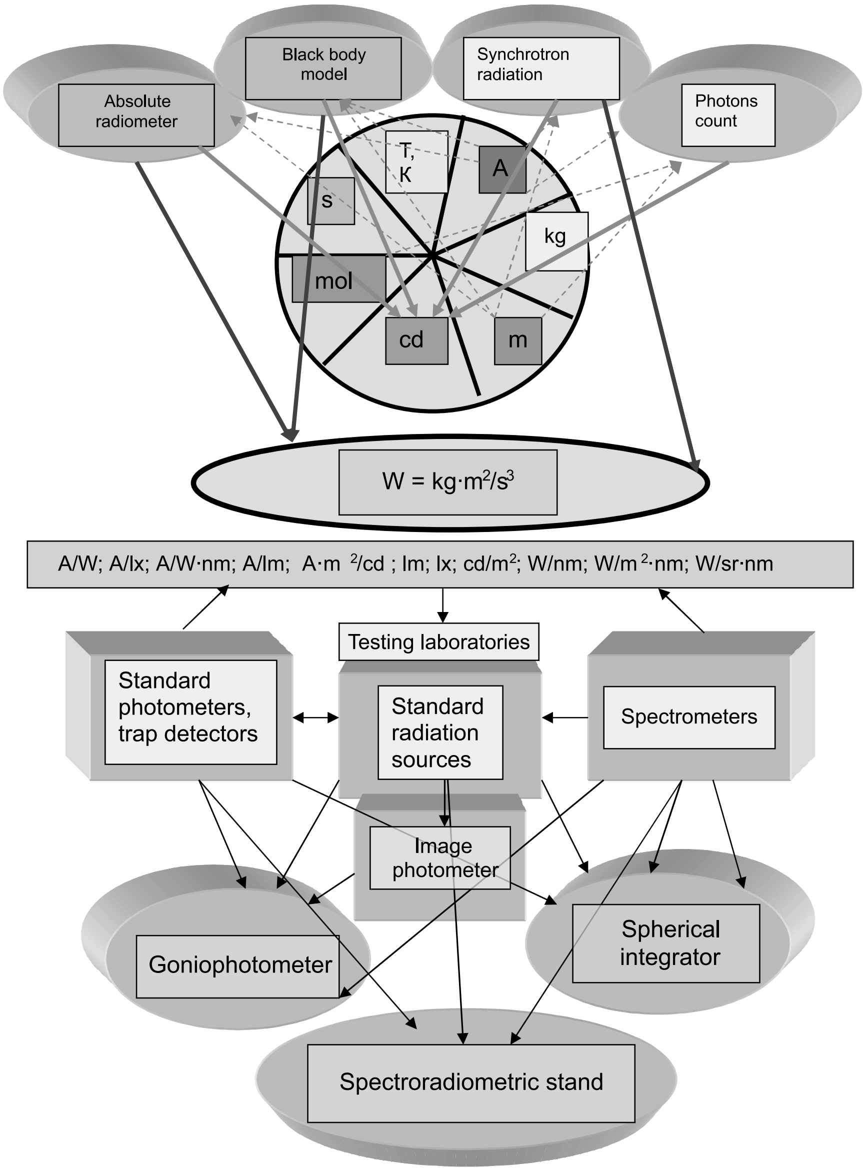

Fig.3. Traceability to the base units of the SI and transmission of unit size from primary and special standards of optical radiometry of incoherent radiation to measuring systems of testing laboratories

measurement protocol. If no correction is made for spectral discrepancy, its effect should be accounted for in the uncertainty calculations. Even if corrections are made, the impact should still be considered in the uncertainty calculations connected with correction quality under $V(\lambda)$ [34, 35].

Spectral light functions different from $V(\lambda)$ should be used when measuring photometric characteristics under night or twilight observation conditions [14, 15].

3.2. Integrating sphere

An integrating spheres should be equipped with auxiliary lamps for measuring self-absorption.

Self-absorption depends on the ratio of the tested device (TD) to the size of the sphere, on the TD and standard lamp configuration and size, as well as on TD reflection characteristics and on the sphere coating.

When the TD is installed in the centre of the sphere (4π-geometry), its surface area should be no more than 2 % of the area of the sphere's inner surface. When the TD is installed at the opening of the sphere (2π-geometry), the opening diameter should not exceed 1/3 of the sphere diameter. When the TD is installed at the centre of the sphere (4π-geometry), its long axis should align with the line drawn between the photometric head detector and the sphere's centre so that the screen size is minimised.

The inner coating of the sphere should be diffusing, not spectrally selective and not fluorescent. For the measurements, it is recommended to use spheres with a coating reflection factor of no less than 90 %. The light source holder and ancillary equipment inside the sphere should be as small as possible and have coating of the maximum possible diffuse reflection. To enable cosine correction, a diffuse nozzle or an auxiliary sphere is installed on the input opening of the photometric head or spectral radiometer. Measurement reproducibility when closing and opening the sphere should be within ± 0.5 %. Change in sphere sensitivity between calibrations is permissible at no more than 0.5 %.

Calibration of the integrating sphere is performed using a luminous flux standard lamp. Its luminous intensity spatial distribution should be similar to that of the test device. Any difference between the luminous intensity distributions should be accounted for in the uncertainty budget.

3.2.1. Sphere – spectral radiometer system

Sphere – spectral radiometer system should be calibrated using a full radiation flux spectral distribution standard with traceability to the SI units. In the event that no such calibration standard is available, the calibration can be done using a standard lamp of irradiance spectral concentration and of a standard lamp of full luminous flux, with traceability to SI units. In this case the used method and related parameters (for example, angular uniformity of spectral distribution, or correlated colour temperature of the standard lamp) should be noted in the measurement protocol. It is imperative to perform a joint calibration of the sphere system together with the spectral radiometer. The spectral radiometer used in the sphere – spectral radiometer system should meet the following requirements:

– Interval of wavelengths between 380 and 780 nm;

– Uncertainty of wavelength set using a spectral radiometer should be no more than 0.5 nm with $k = 2$;

– Spectral width of the slit and scanning pitch should be no more than 5 nm.

The spectral radiometer should have a linear response relative to incoming radiation at each wavelength of the visible interval. The impact of a nonlinear response and inner light scattering should be accounted for as an uncertainty.

The auxiliary lamp to measure self-absorption should have a radiation spectrum in the visible wavelength range.

3.2.2. Sphere – photometer system

A sphere – photometer system should be calibrated using the full luminous flux standard with traceability to SI units [36]. The standard lamp and tested device should have similar radiation spectral distributions.

A sphere – photometer system should have a relative spectral distribution corresponding to the function of the relative spectral luminous efficiency of monochromatic radiation for daylight $V(\lambda)$ curve (see also requirements listed in 3.1.). If spectral correction is necessary, the correction factor is calculated. Relative actinic coefficient is performed based on the data on TD relative spectral distribution and relative spectral sensitivity of the system, i.e. accounting for relative spectral characteristic of the photometric head and contribution of relative spectral distribution of the sphere function $\rho(\lambda)/(1-\rho(\lambda))$, where $\rho(\lambda)$ is spectral reflection factor of the sphere's inner surface material [37].

It is recommended that the auxiliary lamp to measure self-absorption would have a radiation spectrum similar to the TD spectrum, especially when measuring one-colour modules.

3.3. Goniophotometers

A goniophotometer should have scanning angular interval corresponding to the full solid angle, in which the TD radiates light. It is especially important to measure full luminous flux.

Angular TD adjustment should accurate within ± 0.5° of the preset direction. The angular display should have a resolution no less than 0.1°.

When measuring the spatial distribution of luminous intensity, the radiation source is considered to be a point light source. Luminous intensity is obtained from the measured illuminance according to the inverse-square law.

For far-field goniophotometers, measurements are taken at the following distances:

– For a TD with a distribution close to cosine (Lambert distribution with radiation angle ≥ 90°), in all *C-planes*: $\geq 5d$;

– For a TD with a wide angular distribution, different from cosine (radiation angle ≥ 60º), in some *C-planes*: ≥ *10d*;

– For a TD with a narrow angular distribution, a high gradient luminous intensity distribution, when the photometer (spectral radiometer) signal must be protected from reflected light glares: ≥ *15d*;

– For a TD with large unlit areas between the lighting surfaces: ≥ *15 (d+s)*, where *d* is the maximum size of the radiating RD surface, and *s* is the biggest distance between two neighbour lighting surfaces.

For near-field goniophotometers, the distance is not normalised.

Full luminous flux is calculated by integrating the illuminance distribution. Therefore, measurement does not require the use of far-field region goniophotometers.

Goniophotometers with a dead zone of more than 0.1 *sr* of the solid angle can be used to measure full luminous flux as long as corrections are made in the calculations.

3.3.1. Goniophotometer – photometric head system

Relative spectral distribution of a photometric head should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for the daylight $V(\lambda)$ curve. If necessary, a spectral correction factor is applied, based on known values of the TD radiation relative spectral distribution and of the photometric head relative spectral sensitivity. The correction coefficient for spectral discrepancy corresponds to the CIE standard [34].

The goniophotometer should be calibrated using a luminous intensity standard or illuminance standard with traceability to the SI units [37]. If the full luminous flux is measured, then calibration requires a standard of full luminous flux with traceability to the SI units.

The dead angular area of the goniophotometer should not influence the measurement results of the full luminous flux standard lamp.

3.3.2. Goniophotometer – spectral radiometer system

A goniophotometer – spectral radiometer system should be calibrated against a radiant intensity spectral distribution standard or irradiance spectral standard with traceability to the SI units [38].

When using a system to measure the full luminous flux or full spectral luminous flux, calibration requires the full spectral luminous flux standard with traceability to the SI units. The dead angular area of the system should not influence the measurement results of the full spectral luminous flux standard lamp.

The spectral radiometer used in the goniophotometer – spectral radiometric system should meet the following requirements: wavelength interval between 380 and 780 nm; wavelength determination uncertainty should be no more than 0.5 nm with k = 2; spectral width of the slit and scan pitch should be no more than 5 nm. The spectral radiometer should have a linear response to incoming radiation for each wavelength of the visible interval. Nonlinearity and inner light scattering should be accounted for as contributing to the uncertainty of the measurement.

3.3.3. Goniophotometer – colorimeter system

A goniophotometer – colorimeter based system should include three-channel colorimetric heads to measure colour co-ordinates *X*, *Y*, *Z*, which should have spectral sensitivity correspondant to the CIE standard colour functions. The *Y* channel should also meet the requirements for goniophotometer – photometric head system (see section 3.3.1).

If these conditions are not met, then the system can be only used to measure colour differences.

3.4. Luminance meters

The measurements need photo-electric luminance meters, which measure point luminance, and digital luminance meters, which capture surface luminance image distribution. The luminance meters are calibrated using a luminance standard with traceability to the SI units [37].

The relative spectral distribution of a luminance meter should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for the daylight $V(\lambda)$ curve [36].

If necessary, a spectral correction factor applied based on known values of relative spectral distribution of TD radiation and the photometer relative spectral sensitivity. The correction factor of spectral discrepancy from *V (λ)* function is determined according to the formulas given in [33, 39].

When measuring with a digital luminance meter, measurement uncertainty can be estimated by comparing results to the luminance distribution of a typical LED device using a traditional photoelectric luminance meter.

3.4.1. Image luminance meters [40, 41, 42]

The main purpose of digital luminance meters (imaging luminance measurement device) (ILMD) is to measure a projection of spatial luminance distribution of extended sources and of illuminated surfaces.

A luminance meter forming an image, i.e. image luminance measurement device or ILMD, is a device consisting of an image detector (for example, charge coupled device CCD), a photometric correcting filter, a lens, electronic components (analogue-digital converter, a sample-hold circuit, built-in software for information processing and a display). The devices differ by calibration types.

Type I ILMD: Only luminance calibration. Each pixel (i, j) of luminance image L (i, j) only contains information on the luminance observed within the scene.

Geometric information for the image evaluation is not required.

Type II ILMD: Each pixel (i, j) of luminance image L (i, j) contains both the scene luminance value, and accompanying information on direction ϑc $(i, j)/\varphi c$ (i, j) and location of $x_s(i, j)/y_s(i, j)$, as well as on visible solid angles $\Delta\Omega_{Pixel}$ (i, j). For ILMDs of this type, both photometric and geometric calibrations are necessary.

The properties of "classical" luminance meters are described in [33]. For ILMDs some additional features need to be considered:

- Measurements and evaluations are usually performed by computer programs. Conversion of the physical signal (collected images) into luminance values can be complex, and sometimes processing and compressing images algorithms are used (for example, to reduce the size of the data).
- ILMDs have a large number of more or less independent receivers, called pixels. If the system is seen as a totality of separate receivers, then each receiver has its own characteristics. However in practice these pixels are combined (mechanically or mathematically) to form several measurement areas (evaluation areas).
- Some available ILMDs enable easy substitution of optical system parameters (changes in focal length, focus, aperture, lenses and neutral colour filters).
- Generally, the parameters serving to describe the ILMD, refer to a specific configuration (a stable focal length, a constant focus, invariable apertures), which should be displayed together with the quality indicators.
- A luminance image is a totality of luminance values Y (i, j) measured by the image detector which is a part of the ILMD with $(N{\cdot}M)$ sensitive elements (pixels).
- ILMDs should be calibrated by means of luminance standards using a uniform lighting Lambert surface, the size of which significantly exceeds the object field being a part of the evaluation area. The luminance standard used for the calibration is itself calibrated as an intermediate standard, by means of a calibrated luminance meter by the replacement method (a receiver calibrates a receiver) or using a photometric head in the illuminance mode with an additional precise aperture on a lighting surface of the luminance standard.
- An ILMD can be also calibrated using a source with a known spectral distribution of radiation, essentially different from radiation of a black body (for example, for colour LEDs).
- In this case, the spectral sensitivity of the measuring device should differ significantly from zero in the whole spectral interval, which will allow determining the mismatch correction factor.
- Correction coefficients can also be calculated based on the spectroradiometric measurement results. Spectral standards of radiance are required for this. Using the calibration data of these standards, (integral) photometric values should be computed according to their definitions. The correlation between he standards' spectral characteristics need to be considered here, as this will impact the uncertainty of the measurement.
- When calculating measurement uncertainty, the distribution of the luminance standard luminous intensity needs ot be accounted for, especially in the event of large angles of the photometer measurement fields, or if the replacement method is implemented using various angles of measurement fields of the intermediate standard and of the calibrated luminance meter.

• Photometers should be calibrated regularly within the manufacturer recommended time frame, or if there are suspicions that the device's characteristics changed.

3.5. Goniophotometer of near field region [42]

The concept of the fundamental phenomenological photometry is based on the values ***of luminous flux Φ, luminous intensity I = dΦ/dw, illuminance E = dΦ/dA,*** considered with implementing conditions (within a preset approximation) of the law of inverse-squares, i.e. the conditions at which the receiver and the radiation source can be considered as point. In practice, we deal with extended light sources and with light devices, for which photometric characteristic measurement requires long distances. At the same time, fundamental photometry deals with the concept of ***luminance L = dΦ/dwdAcosθ.*** Luminance is a characteristic of the luminant physical surface and does not depend on distance. The light field theory proposed by A.A. Gershun in the early 1930s, and his telecentric method of luminous intensity measurement, allowed interpreting the luminance concept having attributed it an infinitely small solid angle equivalent to a geometrical ray.

So, an elementary cone ***dw*** can be considered as an infinitely thin ray with a differential section ***dAcosθ.*** Luminance ***L*** has the following ratio to luminous intensity: ***L=dI/dAcosθ***, where the differentiation area surrounds the point light source. Similarly, luminance can be expressed via illuminance: ***L=dE/dwcosθ.*** Then illuminance expression ***E*** will be: $E = \int_w L\cos\theta dw$. The integration is implemented over the entire image of the hemisphere crossed by a solid angle ***dw*** (an elementary cone). The latter illuminance expression is useful, because it allows computing illuminance at a point on a surface created by an extended source of luminance distribution for a differential source surface is known (an elementary cone being a beam of rays).

There are physical light sources the nature, which do not have a certain luminant surface since they have volume, for example, plasma. Another example is light from the atmospheric scattering of solar radiation.

When considering radiation sources of volume, an important feature is real luminance or image luminance. In other words, luminance at a point in space and in a preset direction can be defined as luminous flux in relation to the unit of area of this direction within a single-unit solid angle. So instead of considering the luminant surface, we look at the light field around an observer (objective or visual), and the fundamental luminance concept is used as a geometric beam of rays for a comprehensive description of spatial luminance distribution from an extended light source.

Gershun's light field theory is broadly applied today: 3D computer graphics and specialised software enable calculating and building illuminance at any point of any surface in 3D space, if the luminance of all rays crossing this point is known [43].

A practical application of the Gershun's theory is the technique for determining luminance of an imaginary plane around an extended light source using a near field goniophotometer, which includes a goniometer and a photometer as a luminance meter, sequentially measuring luminance up to 250,000 geometric rays (spatial cones) at any point in space. The luminance meter is installed on a moving arm, which rotates around the illumination device in the vertical plane. The luminaire can rotate in the horizontal plane (Fig. 4). The luminance measurement device is a CCD video camera, adjusted according to relative spectral luminous efficiency and equipped with a set of lenses. Selecting the corresponding lens, the camera is focused on the luminaire light body. Each sensitive matrix element

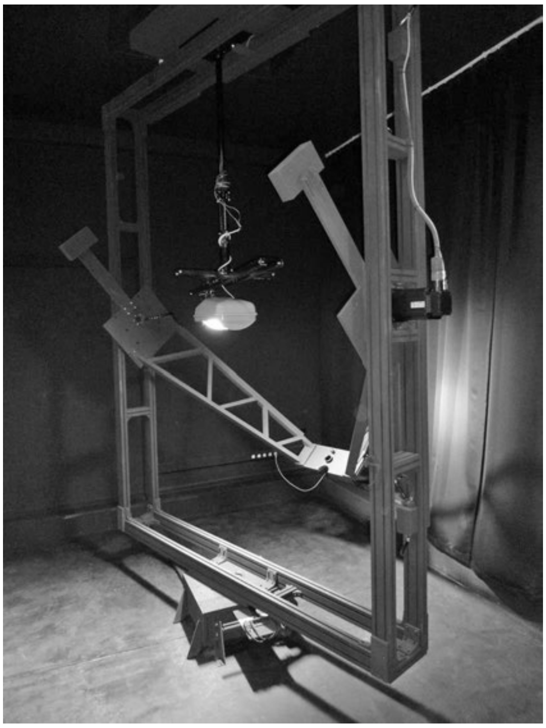

Fig 4. Near field goniophotometer RIGO 801 (VNISI named after S.I. Vavilov)

measures luminance of a pyramidal volume in the preset direction. Thus a digital iluminance meter forming the image is a part of the near field region goniophotometer (Fig. 4.).

3.6. Spectroradiometric measuring system

A spectroradiometric measuring system can be based upon an optical stand, for example an optical bench like OCK 2. The spectral radiometer used as part of the measuring system can be based on a CCD matrix at the output of a dispersive circuit; it can be scanning with a double monochromator. In any case, the spectral radiometer is the comparator in the circuit of spectral distribution of the radiation standard source and of the tested device. Using mini spectrometer allows for rapid measuring techniques, but measurement accuracy decreases. The scanning spectrometer is used for precise absolute measurements of irradiance, radiance, radiant intensity or radiation flux spectral distribution. To compare each of these values with a standard value, additional equipment is required: a special optical system for image projection, or input slit illumination mode is needed, or an input into fibre-optical path of the mini spectrometer with a CCD matrix at the output is necessary (Fig. 5). Measurement units are traced to Planck's radiator, i.e. to thermodynamic temperature T, K.

4. MEASUREMENTS OF PHOTOMETRIC CHARACTERISTICS OF MODERN TDS (LED LAMPS, LED MODULES, LED LUMINAIRES)

When testing modern illumination devices, the following luminous and colour parameters are reported: full luminous flux, light efficacy, partial luminous flux, luminous intensity distribution, luminance and illuminance distribution, colour co-ordinates, correlated colour temperature (CCT) and colour rendition index.

For each, measurement error and uncertainty is analysed, and the total error is calculated taking into account tolerance and acceptance intervals for uncertainty limits with a confidence probability of 95 %. The tolerance interval includes errors connected with the standard test conditions (for example, temperature in the laboratory, circuit power supply voltage, etc.).

Particular attention must be given to tolerance levels when the manufacturer establishes the data reported in the specification ID of each specific type [29, 44].

4.1. Full luminous flux

A method for luminous flux measurement is selected depending on the geometric parameters of the tested device and on the characteristics which need to be measured. Measurement methods using an integrating sphere with a photometric head or a spectral radiometer can be applied.

Determination of luminous flux can be performed by the measured distribution of luminous intensity or illuminance distribution and by photometric measurement distance.

In the integrating sphere the following provisions apply to TD installation:

– 4π-geometry is applied for all light source types, including LED devices. The TD is installed at the centre of the sphere in the working position. If possible, the TD is oriented so that minimum direct light is directed to the screen. Linear sources should

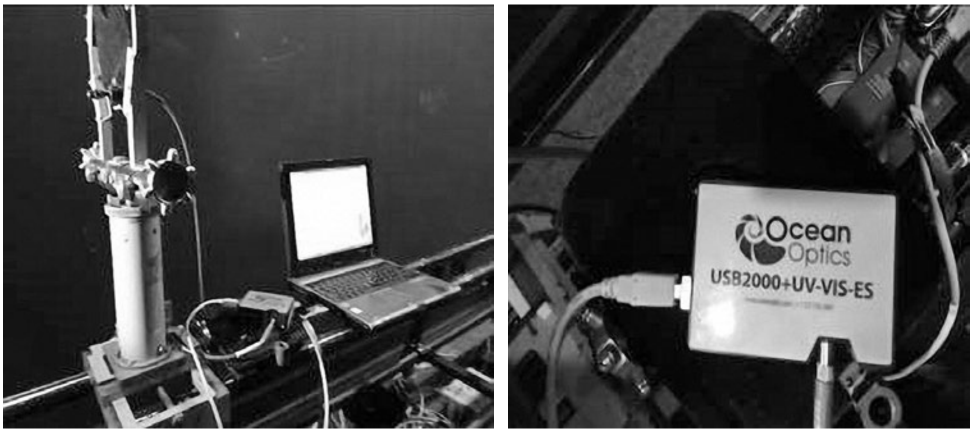

Fig. 5. Elements of a spectroradiometric stand with a mini spectrometer (VNISI named after S.I. Vavilov)

be installed so that their axis aligns with the line drawn between the centres of the photometric head and the sphere. The sphere is calibrated by means of a luminous flux standard lamp, which is installed at the same position as the TD.

– TDs are installed to operate on the wall of the sphere. 2π-geometry is applied for light sources, including LED devices with hemispherical and directed distribution without inverse radiation. A screen is used to prevent direct illumination of the photodetector by the light source. The sphere is calibrated using a luminous flux standard lamp with hemispherical distribution, which is installed in the same position as the TD.

If the TD and the luminous flux standard lamp have different size and reflecting characteristics, then a self-absorption correction coefficient should be applied using an auxiliary lamp.

For the sphere – spectral radiometer system, measurement of the auxiliary lamp and correction of self-absorption are performed based on spectral measurements.

Differences in the angular intensity distribution of the TD and luminous flux standard lamp should be estimated and corrected.

4.2. Partial luminous flux

The relationship between full and partial luminous flux can be measured with a goniophotometer. To determine cone angle α, partial luminous flux is obtained from the sum of intensity distributions $I(\theta_i, \varphi_j)$ measured with scanning pitch $\Delta\theta$ and $\Delta\varphi$.

Full luminous flux is measured using an integrating sphere, and partial luminous flux is determined as the product of the fluxes relation by the full luminous flux value.

When determining partial luminous flux in cone angles of 90º or more, the measurements should be made from a scanning pitch no more than 5º for angles θ (angle γ in co-ordinates system C, γ) and no more than 45º for angles φ (angle C in co-ordinates system C, γ). A lesser angular pitch of scanning can be applied for TDs of a special application (for example, for street luminaires).

4.3. Luminous efficacy

Luminous efficacy η_v is the relation of luminous flux Φ radiated by an LED device, to the consumed electric power P_{tot}.

$$\eta_v = \Phi / P_{tot} \tag{5}$$

Luminous flux measurement techniques are described above, and a number of special requirements to characteristics of the power supplies and of the electric parameters of illumination devices apply when testing and measuring [29]:

– AC/DC voltage, current and power should be measured with precise equipment;

– The calibration error of an AC voltmeter should be no more than 0.2 %, and te calibration error of a DC voltmeter should be no more than 0.1 %;

– The calibration error of the power measurement instrument (power analyser) for alternating current should be no more than 0.5 % with a frequency of about 100 kHz; lower frequencies (5 kHz or 30 kHz) are acceptable if there are no components with frequency higher than 30 kHz;

– Total coefficient of harmonious distortions for voltage measured at the tested device should not exceed 1.5 %. If the power factor exceeds 0.9, this coefficient should be no more than 3 %.

4.4. Luminous intensity distribution

When measuring luminous intensity spatial distribution, except especially stipulated cases, the C, γ co-ordinates system is used [45].

The angular interval between indications of vertical plane luminous intensity and the angular interval between neighbour vertical planes should be such that the obtained luminous intensity distribution allows for an interpolation of the measurement results with satisfactory accuracy. The plane number is determined by the nature of the distribution (symmetric or non-uniform) and by ultimate goal of the measurement. Luminous intensity distribution measurements are made using a goniophotometer.

4.5. Axial luminous intensity and radiation angle

When determining luminous intensity distribution using a goniophotometer, direction (0.0) usually aligns with the optical axis of the radiation source. The axis passes through the photometric centre and is perpendicular to the light emitting plane (except for special requirements of the manufacturer).

Axial luminous intensity is determined towards the observed radiation angle (i.e. the axis, around which luminous the intensity distribution is almost symmetric), and the radiation angle is estimated around the observed optical axis of the ray.

4.6. Luminance measurement

When luminous surfaces are sufficiently uniform, the following measurement approaches can be used:

– Measuring average luminance of the whole luminaire in one or several directions by measuring luminous intensity (its distribution) with a goniophotometer, and then calculating average luminance by dividing luminous intensity by the illuminated surface area;

– The luminance spot measurement method, which is used to evaluate the spatial irregularity of luminance by large street luminaires [45].

The average luminance of small sites (luminance spots) on the luminous surface of a luminaire is measured in one or several directions. Maximum and minimum luminance values are usually set. The number and position of these points should be specified in the regulating documents. The measurements are carried out by means of a goniophotometer in a preset direction or using a luminance meter measuring average luminance at each spot. This method is applied for LED luminaires, which do not have a scattering coating that is a sum of point light sources.

5. MEASUREMENT OF COLORIMETRIC CHARACTERISTICS OF MODERN TDS (LED LAMPS, LED MODULES AND LED LUMINAIRES)

Spectral radiometers are used to measure colorimetric characteristics. Three-channel colorimeters cannot measure absolute colorimetric values with sufficient accuracy. Therefore they can be only used to determine colour differences in different directions.

Values of colorimetric characteristics of LED lamps, modules and luminaires may have a range of angles.

Colorimetric or spectral measurements are taken in the following geometries: along a preset direction, determination of a directed distribution using goniometer – colorimeter, or goniometer – spectral radiometer system. Spatially averaged measurement results can be obtained using the following methods:

– Measurement of full luminous flux using a sphere – spectral radiometer system with a subsequent recalculation into spatially averaged colorimetric characteristics;

– Measurement of radiation flux spectral distribution using goniometer – spectral radiometer system with a recalculation of these measurements into full luminous flux and spatially averaged colorimetric characteristics;

– Measurement of colour co-ordinates $X(\theta, \varphi)$, $Y(\theta, \varphi)$, $Z(\theta, \varphi)$ by means of goniometer – colorimeter system. Spatially integrated colour co-ordinates are calculated using the formulae:

$$X = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} X(\theta,\phi)\sin\theta d\theta d\phi \qquad (6)$$

$$Y = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} Y(\theta,\phi)\sin\theta d\theta d\phi \qquad (7)$$

$$Z = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} Z(\theta,\phi)\sin\theta d\theta d\phi \qquad (8)$$

Colour co-ordinates, correlated colour temperature and other colorimetric characteristics are calculated using colour co-ordinates.

Colour rendition index can be only obtained using spectroradiometric methods [46].

5.1. Correlated colour temperature (for white LED radiation sources)

Chromaticity can be characterised by correlated colour temperature and by a colour difference parameter D_{uv}, which corresponds to a certain distance from the Planck's radiator curve in the CIE co-ordinates system (u', 2/3v'). This distance is positive for points over the curve and negative for points under the curve. Calculations of correlated colour temperature are made according to the CIE recommendations [47, 48].

5.2. Angular colour uniformity

Angular colour uniformity is determined as the greatest deviation of colour co-ordinates (u',v') of a LED radiation source in different directions from spatially averaged colour co-ordinates (u'_a, v'_a) and calculated using the formula:

$$\Delta_{u',v'} = \sqrt{(u' - u'_a)^2 + (v' - v'_a)^2} \quad (9)$$

Colour co-ordinates (u', v') are measured with a goniometer – colorimeter system or goniometer – spectral radiometer system with a vertical angle interval of no more than 10º (2.5º is recommended) and with a horizontal angle interval of no more than 90º (22.5º is recommended). For reflecting lamps, angular pitch should be no more than 1/10 of the radiation angle (diameter of the cone radiating more than 1/2 of the intensity maximum) but no more than 10º. Measurement data at points where the luminous intensity is less than 10 % of the maximum, can be ignored for the calculations.

Average values of colour co-ordinates (u'_a, v'_a) are obtained using a goniometer – colorimeter systems measurements and calculations according to formulae 6–8.

6. ERRORS (UNCERTAINTIES) OF THE MEASUREMENTS

For all measured characteristics an expanded uncertainty is calculated at 95 % confidence. Expanded uncertainty is determined to two significant figures.

Each test report should include information on uncertainty values of the measured parameters and test conditions [29].

Test laboratories should have a detailed uncertainty budget for similar product types. If such an uncertainty budget is calculated for several products, the parameters of which have a known interval (for example, colour temperature is between 2700K and 4000K), then the maximum uncertainty value is set within the interval.

Correction of the test results can be made using the characteristics of tested device, but not those of a similar product.

For luminous intensity distribution, measurement uncertainty should be estimated at least in one direction, in which luminous intensity is sufficiently uniform. Set angle uncertainty (including the TD position in the goniometer) should be shown separately.

For luminance distribution, measurement uncertainty should reported in at least one point, where luminance distribution is more or less uniform.

In the total uncertainty budget, the following factors should be accounted for:

– Accuracy of the set temperature and uncertainty of the temperature measurement;

– Accuracy of the set electric parameters and uncertainty of electric measurements (power supply, electric measurement devices);

– TD radiation ripple;

– Calibration standard (data from the calibration certificate);

– Performance data of the calibration standard (ageing, electric measurements, calibration process);

– Linearity of the measuring devices;

– Reproducibility and repeatability.

For all measurements, the contribution to the uncertainty budget of both the measuring system and technique, but also of the specific TD and its characteristics should be considered.

Besides these parameters, the factors given in Table 1 should be considered as part of the uncertainty budget when measuring light and colour characteristics.

Furthermore, the following factors must also be considered as part of the uncertainty budget:

– bandwidth of the alternating current power measuring instrument (influence, correction);

– input resistance of the alternating current power measuring instrument.

A correlation between luminous flux and electric power values should be applied to evaluate a decrease of the measurement uncertainty. For example, if the consumed current influences both the luminous flux of the tested device, and electric power in the same direction and with the same sensitivity, then this factor can be disregarded when evaluating the uncertainty of the light efficacy measurement.

A general description of how to determine uncertainty in photometry is given in [49].

7. CONCLUSION

1. At the turn of the century the International Committee for Weights and Measures together with the world scientific community undertook a major programme to redefine the main units of the SI system based on physical constants and their photon nature, which increases reproduction and trace-

Table 1. Factors determining total error of the method

Determined characteristics	Equipment used	Error components
Luminous flux, luminous intensity, luminance	Classical goniophotometer	– diffused light (spatial); – TD installation accuracy; – spectral discrepancy; – irregularity of the detector receiving site; – cosine error of the radiation receiver; – uncertainty of distance measurement, if using illuminance measurement mode; – irregularity (planeness) of mirrors and effects of polarisation; – spectral reflection from mirrors;
Luminous flux	Sphere – photometer	- self-absorption in the sphere; – thermal mode; – heterogeneity of the sphere surface reflection factor; – reflections within the sphere; – spectral discrepancy (detector + sphere, differences of spectral distribution of the standard source and TD); – measurement reproducibility when opening and closing the sphere; – stability of transformation factor of the sphere between calibrations; – cosine error of the photometric head; – fluorescence effect of the sphere coating;
Luminous flux, luminous intensity distribution, axial luminous intensity, radiation flux spectral distribution, luminance, luminance distribution	Sphere – spectral radiometer	– self-absorption in the sphere; – thermal mode; – heterogeneity of the sphere surface reflection factor; – reflections within the sphere; – spatial heterogeneity of sensitivity; – error in the set wavelength; – diffused light in the spectral radiometer; – spectral interval of the spectrometer; – measurement reproducibility when opening and closing the sphere; – stability of the transformation factor of the sphere between calibrations; – cosine error of the photometric head; – fluorescence effect of the sphere coating;
Luminous flux, luminous intensity distribution, axial luminous intensity, spectral distribution of radiation flux, luminance, luminance distribution	Goniophotometer – and spectral radiometer Near field goniophotometer	– uniformity of mirrors and the influence of polarisation; – spectral reflectiveness of the mirrors; – diffused light (spatial); – TD installation accuracy; – receiving site of the detector; – cosine error; – accuracy of the wave length set; – inner scattering of the spectral radiometer; – spectral width of the spectral radiometer slit; – uncertainty of the distance measurement, if the spectral radiometer is calibrated according to the irradiance spectral concentration standard; – uncertainty caused by mirror reflection, if the spectral radiometer is calibrated according to the standard of radiance spectral concentration

Determined characteristics	Equipment used	Error components
Colour characteristics	Sphere spectral radiometer, goniophotometer – spectral radiometer	– correlations connected with colour temperature measurement uncertainty of calibration source of radiation; – inner scattering of the spectral radiometer; – spectral width of the spectral radiometer slit; – accuracy of the set wavelength; – linearity in the dynamic interval of the whole spectral interval

ability accuracy and precision for correspondent values and measurement units as a whole.

2. The 1979 definition of the candela provides a practical value of luminous efficiency for a function of average daytime human vision at a wavelength of 555 nm. The candela, as a base unit of the SI system, remains the measurement unit of luminous intensity – an effective value.

3. Modern lighting equipment has made it necessary to consider the mechanisms of visual perception in more detail, for example when illuminating streets and roads using LED illumination devices, and to introduce mesopic photometry into the evaluation of illumination, primarily for roads.

4. The use of illumination devices with LEDs has led to a greater number of requirements for test equipment for accuracy, for absolute photometry methods only, for the prevailing spectroradiometric approach as compared to detector based photometry in the field of optical radiometry.

5. Implementing the spectroradiometric approach in photometry is difficult as there are no standard light sources of radiation flux spectral concentration available in world practice. These are necessary for test laboratories, because any spectral radiometer forming part of the goniometer, of a sphere or of a spectroradiometric stand, can only be a comparator of spectral characteristics of standard sources and tested devices.

6. Considering the realities of modern photometry from the point of view real practice in Russia, it is importnat to note that the test system as a whole is comprised foreign equipment, which needs to be imported, certified, added to the measuring instrument register of the Russian Federation and annually calibrated. This raises the price of the lighting product test procedure significantly.

7. Special attention must be paid to the domestic measurement instruments industry in photometry and colorimetry. Russian manufacturers and developers of modern information and measuring systems, as well as of precise instruments, require assistance of the Russian lighting industry in order to be equipped with their products.

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