Methods of total spectral radiant flux realization at VNIIOFI

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Abstract. VNIIOFI carries out works on realization of independent methods for realization of
the total spectral radiant flux (TSRF) of incoherent optical radiation sources - reference high-
temperature blackbodies (BB), halogen lamps, and LED with quasi-Lambert spatial
distribution of radiance. The paper describes three schemes for measuring facilities using
photometers, spectroradiometers and computer-controlled high class goniometer. The paper
describes different approaches for TSRF realization at the VNIIOFI National radiometric
standard on the basis of high-temperature BB and LED sources, and gonio-spectroradiometer.
Further, they are planned to be compared, and the use of fixed-point cells (in particular, based
on the high-temperature δ(MoC)-C metal-carbon eutectic with a phase transition temperature
of 2583 °C corresponding to the metrological optical "source-A") as an option instead of the
BB is considered in order to enhance calibration accuracy.

1. Introduction

Accuracy of light measurements in all industries, in scientific research significantly influences the
level of development of new technology, and quality of manufactured lighting products. One of the
main quantities in practice is the luminous flux.

At present, in the rapidly developing technologies for the production of a new generation of light-
emitting diodes (LEDs) characterized by a wide variety of shapes of emission spectra and the
widespread use of modern compact high-speed spectroradiometers on CCD matrices, which allow
measuring such spectral characteristics of radiation sources as color coordinates, color rendering index
and correlated color temperature, in addition to measuring the integral characteristics - luminous flux
and illumination value, it is extremely important and relevant to reproduce the total spectral radiant
flux (TSRF) to ensure, at the present level, the unity of measurements in the field of
spectroradiometry.

Nowadays VNIIOFI is proceeding with works aimed on creating spectroradiometric facilities based
on a goniometer and spectroradiometer for realization and dissemination a unit of spectral radiant flux
in the mode of total or partial flux from standard radiation sources in order to improve metrological
support of energy-saving lighting products based on LEDs. The article discusses various methods for
reproducing and transfer of TSRF on reference sources - the blackbody (BB) or calibrated LED, which
are currently being studied at VNIIOFI, with the introduction of a goniometer and spectroradiometer
into the standard facility, which expands its functionality as a result of the reproduction of the standard
spatial distributions of radiance and irradiance of monochromatic radiation.
The TSRF quantity is being realized for the first time in the Russian Federation in the wavelength range from 0.3 µm to 1.1 µm based on a goniometer and spectroradiometer with envisaged standard uncertainty \( u_c \) from 0.19 % (at 0.65 µm) to 0.94 % (at 0.3 µm).

2. Luminous flux realization at national standards

Realization of luminous flux and TSRF of non-coherent optical radiation was carried out at VNIIOFI’s national standards [1] by several methods, starting from 2003. The realization methods are based on a high-temperature wide-aperture blackbody (HTWABB) of BB3500M model as an external source of reference radiation with Planckian spectral distribution (see Fig. 1) [2]. An alternative technique of luminous flux realization is based on a LED as a reference optical source, whose characteristics are measured by goniophotometer with \( V(\lambda) \) – corrected photometer.

The basis for the reproduction of the unit of luminous flux performed at the initial stage of work at VNIIOFI was the comparison of the total flux of the photometric lamp and the luminous flux of the HTWABB in a certain solid angle using an integrating sphere (IS), when the signal is recorded by means of photometer. The value of luminous flux

\[
\Phi_l = \int_{\Omega} I(\theta, \varphi) d\Omega = \frac{l^2}{k_0} \int_{\Omega_0} i(\theta, \varphi) d\Omega
\]

is determined from the measured signal \( i(\theta, \varphi) \) of the photometer defined by the angles \( \theta, \varphi \). Here we introduce the notations: \( k_0 = I_0/E_0 \) is the illuminance responsivity factor, \( l \) is the distance from the radiation source to the input aperture of the IS on which the photometer is placed. The quantity of illuminance when calibrating a photometer against BB is defined as

\[
E_0 = 683 \cdot \int_{380}^{780} V(\lambda) E_0(\lambda, T) d\lambda
\]

in the visible wavelength range.

**Figure 1.** Scheme of realization of luminous flux, spectral radiance (SR), spectral irradiance (SI) and spectral radiant intensity (SRI) at VNIIOFI National standard based on a high-temperature wide-aperture blackbody of BB3500M model as an external source.
To realize the luminous flux quantity by means of BB and photometer, the VNIIOFI measurement facility [2] was used consisting of: BB3500M blackbody with precision diaphragms and a system for measuring its thermodynamic temperature based on absolutely calibrated filter radiometer or (alternatively) on the TSP2 pyrometer calibrated against the high temperature fixed points with assigned thermodynamic temperatures [3]; a group photometer with amplifiers and a system for measuring its spectral characteristics; IS with 2-m diameter; systems for power supply, registration and automated mechanical movement and alignment.

3. TSRF realization with spectroradiometer and photometer

Modern requirements to optical sources assume knowledge of not only the spatial, but also the spectral distribution of their radiation. The work on modernization of the National standard allowed adding into the TSRF measurement scheme a spectroradiometer (see Fig.2) and a goniometer scanning the radiation source in 2π-geometry (Fig.3). Reproduction of TSRF from an external source (either BB or LED) using a spectroradiometer as an independent measurement tool provides spectral information, in addition to a photometer:

\[ \Phi_t = 683 \cdot l^2 \int_{380}^{780} V(\lambda) \int_{0}^{2\pi} \int_{0}^{\pi} \frac{i(\lambda,\theta,\phi)}{k_0(\lambda)} \sin \theta d\theta d\phi d\lambda \]  

where \( i(\lambda,\theta,\phi) \) – is the signal measured by a spectroradiometer using a goniometer, \( k_0(\lambda) \) - is the spectral illuminance responsivity factor.

The same reference source with spectral radiant intensity \( I(\theta,\phi) \) is measured with a photometer and \( I(\lambda,\theta,\phi) \) with a spectroradiometer, and their luminous fluxes can be equated:

\[ 683 \cdot \int_{380}^{780} V(\lambda) I(\lambda) d\Omega d\lambda \equiv \int_{\Omega_0} I d\Omega = \Phi_t. \]  

Relative measurements of the signal \( i(\lambda) \) are carried out by a non-calibrated spectroradiometer, and we find as follows:

\[ I_{rel}(\lambda) = \frac{i(\lambda)}{i(\lambda_0)} = \frac{I(\lambda)}{k_{scale}(\lambda)}. \]  

As a result, we find the required TSRF

\[ \Phi(\lambda) = \int_{380}^{780} k_{scale}(\lambda) \cdot I_{rel}(\lambda) d\lambda. \]  

The upgraded scheme of realization of the TSRF from optical source (in comparison of the radiation fluxes from an external source, BB or LED, and from the DUT under calibration, for example a lamp located in the center of the IS) using the spectroradiometer is shown in Fig.2.

The measuring facility includes a 2-m integrating sphere (with BaSO₄ coating and 50-mm entrance aperture), a spectroradiometer of the Konica Minolta CS-2000 type (with diffraction grating and Hamamatsu back thinned CCD working in a range of 380-780 nm, physical resolution approx. 0.5 nm, optical resolution FWHM approx. 3.5 nm, integration time 10-10000 ms); fast photometer (Hamamatsu photodiode with V(\lambda)-correction in class A < 1.5 % and < 0.1 % linearity, equipped with low-noise electronics of a dynamic range of 6 orders of magnitude and speed of 50 measurements per second), and mounting unit.

LEDs with the following characteristics are used as a quasi-Lambert source for the spatial distribution of the source brightness: power 30 W, luminous flux 1500 lm, color temperature 3500 K. The spectral flux of the LED source will be measured by a goni-spectroradiometer in 2π-geometry.
Figure 2. Scheme of TSRF realization applying BB or LED as an external source.

4. TSRF realization on the basis of gonio-spectroradiometer

From the analysis of the results of patent studies of practically used goniometers and spectroradiometers for measuring the optical flux of optical sources, it has been established that the most suitable and popular for the study of the characteristics of photometric lamps and light-emitting diodes are structures that ensure the angular rotation of the source in the horizontal plane while simultaneously scanning the goniometer's movable lever at other angles with a detector node fixed on it. Measuring devices that provide such a scheme for realization and dissemination of the TSRF unit that corresponds to the R&D chosen at this stage for constructing the VNIIOFI standard facility use the designs developed in NIST (USA) [4], PTB (Germany) [5], NMIJ (Japan) [6] and LMT Lichtmesstechnik GmbH Berlin (Germany) [7].

The realization of the TSRF based on a reference source – the blackbody radiator or the calibrated LED source, when the goniometer and the spectroradiometer are included in the standard, extends its functionality as a result of the realization of the reference spatial distributions of the irradiance and radiance for monochromatic radiation. In addition, the novelty of the works performed on the standard is the realization of an additional, radiometric value, the spectral density of the total radiant flux, which is extremely important to unify measurements in the field of spectroradiometry at the present level by transferring units to organizations utilizing secondary standards, centers of standardization and metrology, laboratories, carrying out measurements of spectroradiometric and photometric characteristics of products of energy-saving LEDs, and multielement IR radiation detectors.

The third scheme for the realization of the TSRF from optical source in the form of a halogen lamp is based on a goniometer (made by GL Optic, Poland) (Fig. 3), which includes a 127-mm integrating sphere with a spectroradiometer (1) and a high-speed photometer class A (Fig. 4) - all elements are temperature stabilized.
Figure 3. Computer-controlled high-class goniometer designed and manufactured by GL-Optics.
1) Integrating sphere with temperature-stabilized spectroradiometer and high-speed photometer;
2) Main rotation axis - uniform rotation with a constant angular speed;
3) DUT slow uniform rotation with a constant angular speed.

Figure 4. Scheme of calibration of the spectroradiometer and photometer located in the detector block (1), according to spectral characteristics, according to the reference BB with the radiation flux generator in the form of a block of precision apertures (A), similar to the scheme in Fig. 1.

Characteristics of computer-controlled high-class goniometer designed on the basis of blackened aluminum profiles are as follows: radius of measuring arm 500 mm, both axis driven be a stepping motor with a smooth acceleration and speed control, set of baffles reducing stray light, handle for precise fix of light sources (170-mm max. size of the light source), possibility of changing a position of light source within 180 degrees, laser system for geometry control. Rotation axis (2) and (3) of uniform rotation with a constant angular speed are shown in the figure. Mounting unit enables precise fixation of a measuring unit to a goniometer arm, or to a calibration system based on BB source.

The calibration scheme of the spectroradiometer and photometer according to the spectral characteristics of the reference blackbody radiator with a block of precision apertures (A), similar to the diagram in Fig. 1, is shown in Fig. 4. In this case, the radiation from the BB falls on the input of the integrating sphere, at the output of which a spectroradiometer and a photometer are located.

5. VNIIOFI project on developing high power LED light sources
VNIIOFI has started a project on developing and investigating high power LED light sources, which are to be used as standard sources for luminous intensity, luminous intensity distribution, luminous flux and colour measurements. Design of LED source (presented in Fig.5) features a light head and a parametric current source (PCS). Three heads were built: two white with power of 30 W and 68 W and
a blue one of 30 W. Each LED was selected as the most stable from a batch after seasoning (with photometric stability of 0.02 % for approximately 10 h) [8].

![LED source](image)

**Figure 5.** Scheme and external view of a standard LED source designed at VNIIOFI.  
1) Chip-on-board type LED, 2) Opal glass, 3) PTFE tube, 4) Aperture, 5) Peltier element, 6) Heatsink, 7) Fan, 8) Pt1000 temperature sensor.

6. Conclusions
The paper describes different approaches for TSRF realization at the VNIIOFI National radiometric standard on the basis of high-temperature BB and LED sources, and gonio-spectroradiometer. The TSRF quantity is realized for the first time in the Russian Federation in the wavelength range from 0.3 µm to 1.1 µm based on a goniometer and spectroradiometer with envisaged standard uncertainty \( u_c \) from 0.19 \% (at 0.65 µm) to 0.94 \% (at 0.3 µm).

Further, the use of fixed-point cells [9] (in particular, based on the high-temperature \( \delta(\text{MoC}) \)-C metal-carbon eutectic with a phase transition temperature of 2583 °C corresponding to the metrological optical "source-A") as an option instead of the BB is considered in order to exclude temperature measurements with filter radiometer or TSP-2 for enhancing calibration accuracy.

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