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Metrological and Methodical Aspects of Spectral-Energetic Calibrations of Optoelectronic ERS Equipment

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Abstract. The paper presents the results of modernization and the metrological characteristics of the Kameliya measuring complex of JSC "Russian Space Systems", as well as the methodological aspects of spectral-energetic calibrations of optoelectronic ERS equipment and the results of a brightness distribution study of the ribbon filament body of the TRU 1100-2350 lamp in operating mode. Optical circuits for measuring the spectral characteristics of optoelectronic ERS equipment, optical elements and blocks based on the Kameliya measuring complex are presented. The carried out work provided the possibility of obtaining the relative spectral characteristics of not only multi-zone scanning devices, but also measurements of transmission and reflection spectra of optical elements (spectral filters, mirrors, lenses) and optical units of remote sensing equipment in the wavelength range $\lambda = 0.4$-14 μm. In addition, a method has been developed for measuring the spectral characteristics of optical radiation sources ($\lambda = 0.4$-14 μm) and the results of the study of the brightness distribution of the filament of the TRU 1100-2350 lamp are presented.

Keywords: metrological characteristics, calibration, multispectral scanning device, measuring complex, spectral characteristic, optical layout, spectral radiance (SR)

Introduction

Radiometric measurements obtained with the help of Earth remote sensing (ERS) equipment are most relevant in such applications as:

- weather analysis and weather forecasting on a regional and global scale
- analysis and forecasting of the state of the seas and oceans
- analysis and forecasting of conditions for aviation flights
- detection and control of natural and man-made disasters and emergencies
- ecological control of the environment
- ensuring global monitoring in the interests of meteorology, climatology, and bioresource assessment.

The expansion of the nomenclature of multi-zone scanning devices (MSD) for hydrometeorological purposes (MSU-GS [1], MSU-MR [2], MSU-SR-M, MSU-MR-MP, MSU-O, RIVR) under development at JSC "Russian Space Systems", the increase in the number of flight models and in the pace of improvement of ERS-equipment design features dictate the corresponding development rates of the reference, experimental and stand, as well as, regulatory and methodological bases.

The demand for improvement of the hardware-methodical complex of metrological support and MSD radiometric parameter monitoring is conditioned by the following reasons:

- increase in radiometric accuracy, resolution and field-of-view of advanced ERS optical electronic equipment
- improvement of existing measuring tools and the creation of fundamentally new ones for assessing MSD characteristics
- the need to develop uniform, certified in accordance with metrological rules and standards, means and methods for calibrating and controlling MSD parameters
- the need to develop a system for ensuring unity and the accuracy required for the reproduction and transmission of differential quantities of multispectral and integrated optical radiation in the context of national standards and conditions of MSD standard operating in space.

The MSDs being developed at JSC "Russian Space Systems" produce high quality multizone video images in the wavelength range λ = 0.4-13.5 μm and undergo a ground-based radiometric calibration procedure. The procedure is necessary for the measurement of absolute values of effective radiance (ER) of objects L_{eff} (1) in the visible and near-infrared (IR) spectral range (λ = 0.4-2.5 μm) and of ER and radiation temperature in the thermal IR range (λ = 2.5-14 μm) for each spectral channel of the equipment.

$$L^n{}_{eff} = \int_0^\infty L(\lambda) S_n(\lambda) d\lambda \text{, [W/(sr·m}^2\text{)]} \qquad (1)$$

where $L^n{}_{eff}$ is the ER of the object, measured in channel n; $L(\lambda)$ is the spectral radiance (SR) of the object; $S_n(\lambda)$ – the relative spectral sensitivity of the MSD channel *n*.

MSD radiometric calibration is understood to be the procedure of forming a conversion characteristic for every spectral channel as the dependence of the output signal on the ER or the equivalent radiation temperature of the reference emitter (with account for the specified accuracy).

In accordance with the requirements of international documents [3] for advanced ERS radiometric equipment, it is required to ensure an ER measurement error of no more than 5% in the λ = 0.4-2.5 μm range and an absolute radiation temperature measurement error of 0.1-0.5 K in the range λ = 2.5-14 μm.

Metrological characteristics of the modernized complex *Kameliya*

The radiometric complex of JSC "Russian Space Systems" consists of:

1) the *Kameliya* measurement complex (Figure 1) engineered for the calibration of the monochromatic illuminant, diffuse illuminant and MSD, as well as for spectral characteristic measurement in the wavelength range λ = 0.4–2.5 (included in the State Register of Measuring Instruments and is checked annually by VNIIOFI as a reference measurement instrument);

2) IR measurement complex intended for radiometric calibration of MSD and measurement of spectral characteristics in a λ = 2.5–14 μm range.

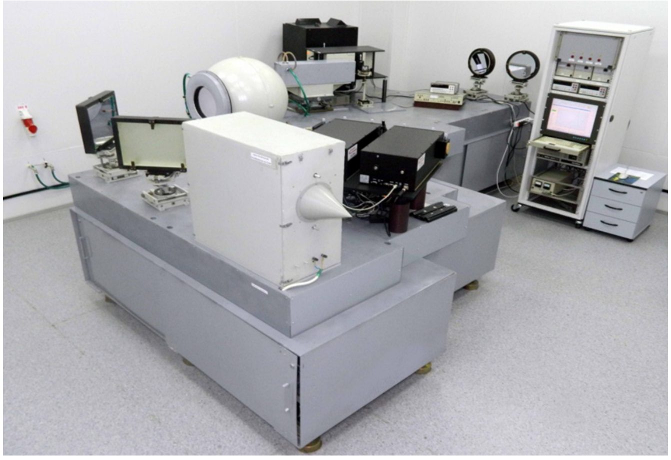


Fig. 1. The *Kameliya* measurement complex.

Currently, the metrological base of JSC “Russian Space Systems” for MSD development has been modernized.

The main areas of modernization, aimed at increasing radiometric calibration accuracy, are:

1) a class ISO8 clean room with antistatic protection of workplaces and automatic maintenance of the preset temperature (22 ± 2^{0}C, adjustable from 18 to 25^{0}C) and humidity (50 ± 10%) was certified and put in service in the assembly, adjustment, calibration and testing of optoelectronic equipment sections;

2) two digitally controlled modern monochromators in a subtractive configuration DM55S (λ = 0.4–2.5 µm) and MS257 (λ = 0.4–14 µm) were put into operation as part of the modernized *Kameliya* complex;

3) a universal program for controlling monochromators and data accumulation, which allows to automate the process of measuring spectral characteristics, has been developed. This considerably increases the capability for receiving and processing results along with reducing the random component of measurement errors;

4) the upgraded *Kameliya* complex has been certified and a pattern approval certificate for measuring instruments RU.E.377.A No. 55245, registration No. 57492-14 has been received (the metrological characteristics are set forth in Table 1);

5) an optical circuit with a maximum clear aperture of 230 mm for taking spectral characteristics of MSD in the range λ = 2.5–14 µm, where a model of an absolutely black body (ABB) type 67033 with a temperature range from +50^{0}C to +1050^{0}C (stability of ±0.02% in 24-hours) has been implemented;

Table 1. Metrological characteristics of the *Kameliya* complex, according to the results of the last calibration

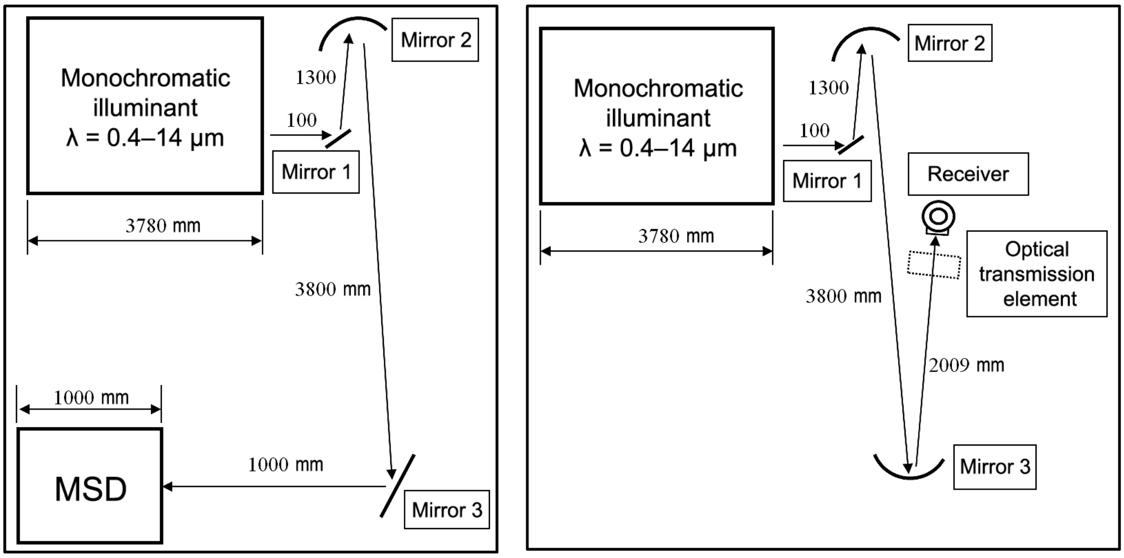
Characteristic	Characteristic value
Wavelength range, µm	0.4–2.5
Absolute value of spectral radiance of the diffuse illuminant at the wavelength of 0.98 µm, W/(sr·m^3)	$5.3{\cdot}10^8$
Maximum clear aperture of radiant flux, mm	230
Relative error in the results of measuring the absolute value of the spectral radiance of the diffuse illuminant at the wavelength of 0.98 µm, %	±6.4
Relative error in the results of measuring the relevant distribution of spectral radiance of the diffuse illuminant in the wavelength range from 0.4 to 2.5 µm, %	±5.1
Relative error in the results of measuring relative spectral distribution of radiation from a monochromatic illuminant in the wavelength range from 0.4 to 2.5 µm, %	±4.7

6) optical circuits and methods for measuring relative spectral characteristics of transmission and reflection of optical elements and blocks, as well as of optical emission sources in a spectral range of λ = 0.4–14 µm, have been developed;

7) a large-size temperature simulation chamber with a nitric environment (with an operating volume of 16 m^3 and an operating temperature range inside the chamber from +5^{0}C to +35^{0}C) for MSD radiometric calibration and for testing the impact of environment temperature changes on equipment has been commissioned and certified.

Methodological aspects of spectral-energetic calibrations of optoelectronic ERS equipment. Measurement of relative spectral characteristics in the wavelength range of λ = 0.4 – 14 µm

Figure 2 presents the typical optical schemes for measuring MSD spectral parameters based on the *Kameliya* measurement complex (Figure 2a: 1,3 – planar



a) b)

Fig. 2. Optical schemes of relative spectral characteristic measurements obtained by the *Kameliya* measurement complex.

mirrors, 2 – spherical mirror) (f = 1300 mm) and on the measurements of spectral characteristics of transmittance of optical elements and units (Figure 2b: 1 – planar mirror, 2 – spherical mirror (f = 1300 mm), 3 – spherical mirror (f = 2009 mm)).

Calibration of the monochromatic illuminant (MI) and MSD is carried out according to the measurement scheme given in Figure 2a.

According to the measurement scheme given in Figure 2b, two types of measurements are performed: illuminant calibration against a reference receiver and measurement of the transmission coefficient of optical elements (units).

Currently, the techniques for measuring the spectral characteristics of reflection of optical elements (for various angles) and sources of optical radiation in the λ = 0.4–14 μm spectral range have been implemented.

The monochromatic illuminant (MI) consists of the following elements: a TRU 1100- 2350 lamp (used for the λ = 0.4–2.5 μm range) or a type 67033 ABB model (used for λ = 2.5–14 μm range) as sources of radiation. They are connected with the help of a deflecting mirror, a condenser and a double monochromator of a subtractive configuration with digital control MS257 (spectral range: 0.4–14 μm).

In order to properly exclude the MI spectral characteristics together with the layer of air and to minimize measurement errors, it is necessary to provide the same optical path length for both stages: (MI + MSD measurement, Figure 2a) and (MI + reference receiver measurement, Figure 2b). Concurrently, the stability of measurement conditions (temperature, humidity and atmospheric composition (especially for the IR range)) is to be ensured.

In Figure 3, the results of measuring the spectral characteristics of one of the cut filters in the IR range of the spectrum λ = 8.0–9.5 μm, carried out in accordance with the scheme in Figure 2b, are given as an example.

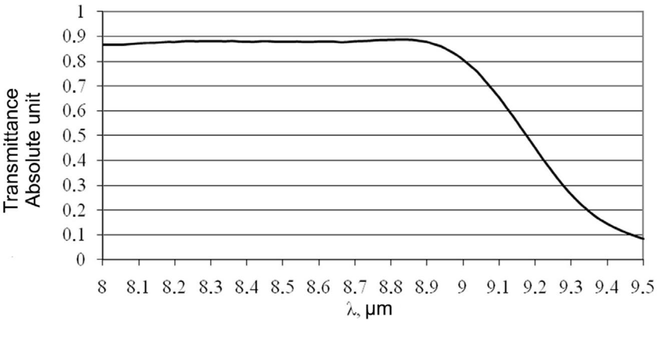


Fig. 3. Example of one of the cut filter's spectral characteristic in the IR range of the spectrum λ = 8.0–9.5 μm, obtained with the use of the *Kameliya* measurement complex in the IR range of the spectrum λ = 8.0–9.5 μm.

Such measurements (carried out in accordance with the scheme in Figure 2b) in the IR range of the spectrum (λ = 3.0–14 μm) have been made for each of the seven

IR channels of the fully manufactured MSU-GS beam splitting unit [1] (for the Electro-L No. 2 spacecraft). Also, the spectral characteristics (obtained in accordance with the scheme in Figure 2a) for all six channels (including IR channels) of the fully manufactured MSU-MR (for the Meteor-M No. 2 spacecraft [2]) have been received.

Figure 4 gives the relative spectral characteristics of one of the Al-based reflective coatings for various angles of reflection (10°, 45° and 60°) received with the use of the *Kameliya* measurement complex (with the implementation of an additionally designed instrument) in the IR range of the spectrum λ = 8.0–11.0 μm.

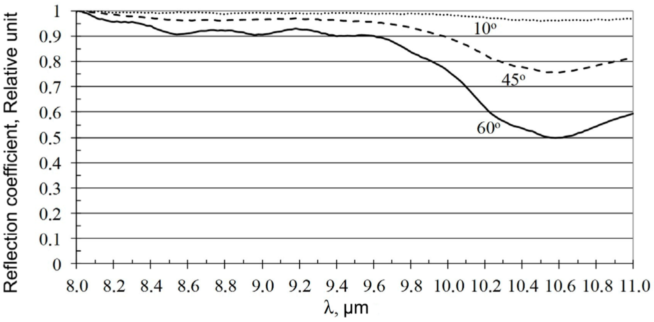


Fig. 4. Example of the spectral characteristics of one of the types of Al-based reflective coatings for different angles of reflection (10°, 45° and 60°) obtained with the help of the *Kameliya* measurement complex in the IR range of the spectrum (λ = 8.0–11.0 μm).

As the conducted studies show, the dependence of the spectral characteristic type of the reflective coating on the angle of reflection (Figure 4) in the IR range of the spectrum is explained by the absorption of the protective coating usually applied to Al mirrors. Despite the dielectric protective coating being amorphous, the IR vibrational spectra carry information about the short-range order of the atomic structure, which determines lattice absorption. In the case of normal incidence, only transverse optical phonons are recorded, whereas, in the case of oblique incidence, transverse and longitudinal phonons are recorded [4, 5]. The research results have demonstrated that, when choosing the reflective coating for mirrors designed to work at angles of more than 15° (deflecting and scanning mirrors for the IR range λ = 3–14 μm), the chemical composition, manufacturing technology, and thickness of the protective coating must be carefully considered to avoid dips in the value of the reflection coefficient in some wavelength ranges. Such dips substantially lower the quality of the optical path of infrared devices.

In Figure 5, measurements of the relative characteristics in the range λ = 400–2500 μm of a miniature halogen lamp with a rated power of 5 W (U_r = 12 V) for two different supply voltages (10 V and 6 V) is given.

Lamp filament brightness distribution of a TRU 1100-2350 lamp in operating mode

Absolute measurements of spectral radiance (SR) in the wavelength range λ = 0.4–2.5 μm during calibration of the diffuse illuminant (DI) from the *Kameliya* complex are carried out with the use of a reference TRU 1100-2350

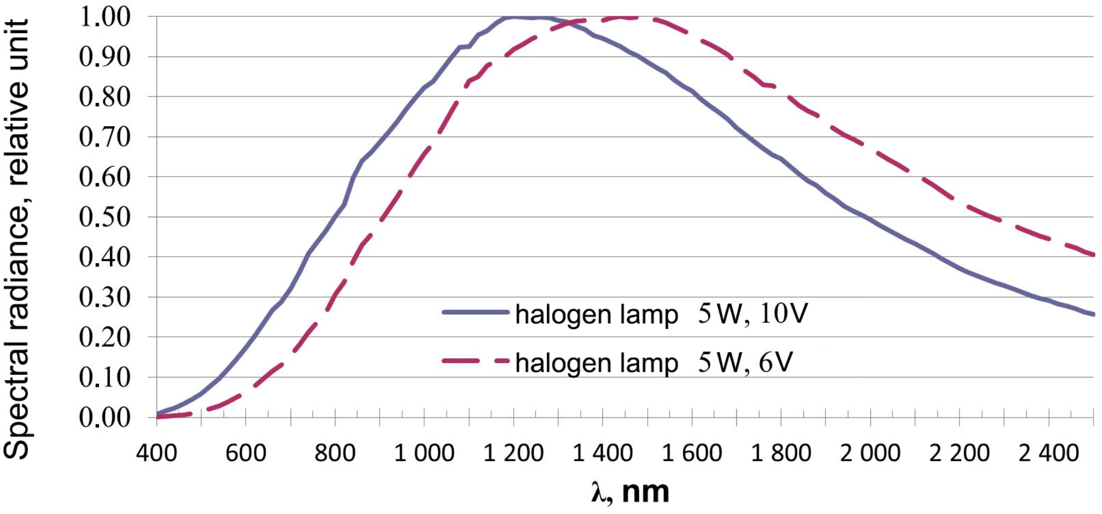


Fig. 5. Examples of relative spectral characteristics of radiation of a miniature halogen lamp with a rated power of 5 W (U_r = 12 V).

lamp (GOST 8.195-89 first category working standard), which is annually checked by VNIIOFI. The analysis of literature has shown the inconsistency of data on the distribution of brightness over the area of the ribbon lamp filament [6, 7].

The working area of the ribbon lamp filament of a TRU 1100-2350 is located opposite the pointer, facing the lamp envelope window (total ribbon size 2.8 x 20 mm). The limits of the working area are a distance of ±1 mm from the horizontal axis of the ribbon lamp filament, passing through the end of the pointer in accordance with the TU 16-546.108-76 technical specifications. In view of the strict requirements for the accuracy of SR absolute measurements, it is necessary to know how uneven the distribution of brightness across the lamp filament is.

Figure 6 illustrates a scheme for measuring the variance of lamp filament brightness. First of all, a laser module (operating at the wavelength λ = 637 nm) is installed behind the monochromator (MCh) entrance slit (opposite the center of the slit – Figure 6, laser). The entrance slit of the monochromator is limited in width to 0.6 mm and in height – to 0.5 mm.

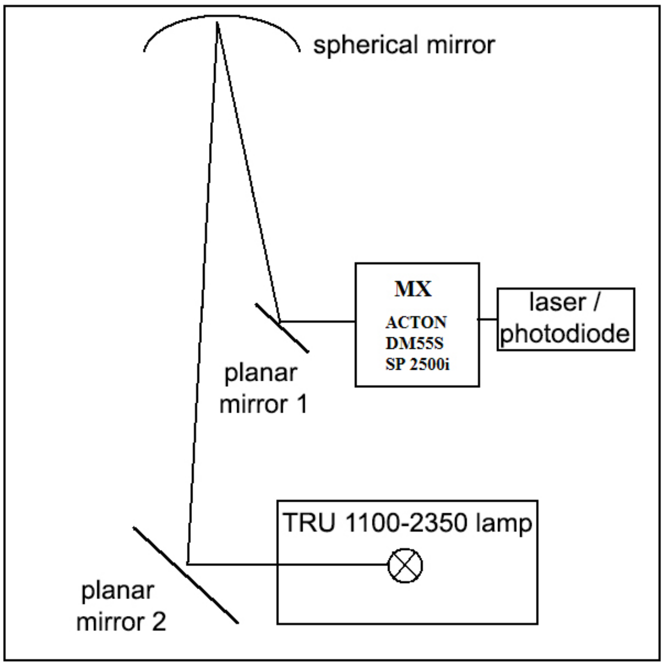


Fig. 6. Scheme for measuring the relative distribution of brightness across the area of a TRU 1100-2350 lamp filament.

After setting the monochromator wavelength to λ = 637 nm, the spot is aimed at the center of the mirrors horizontally and vertically (planar mirrors 1 and 2, spherical mirror) by adjusting the position of the mirrors and placing the laser spot in the center of the filament,

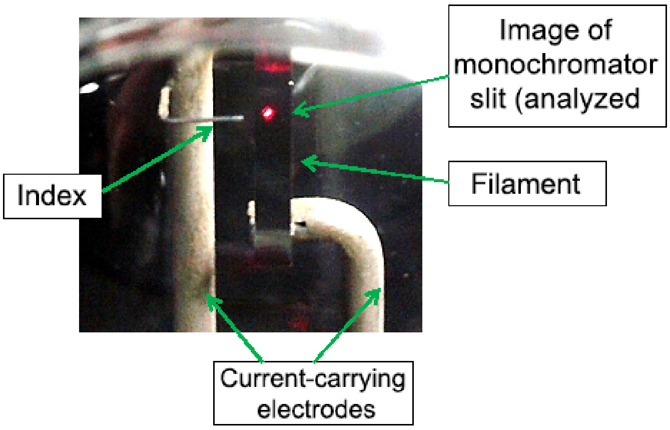


Fig. 7. Image of the monochromator slit in the plane of the filament during laser beam exposure (λ = 637 nm).

Later, the laser is turned on and a SZU 1337-1010BR photodiode (PD) is installed behind the exit slit of the monochromator (the laser module is not moved). The TRU 1100-2350 lamp is turned on (the rated current is 25 A ± 0.001 A) and the PD signal for a set point on the filament for λ = 980 nm (maximum SR for DI) with the help of an AGILENT 34401A multimeter. Analogous measurements are conducted at four more points of the filament body horizontally, and for each such point there are four more vertical points secured via shifting the laser light spot by movements of the lamp (Figures 8, 9).

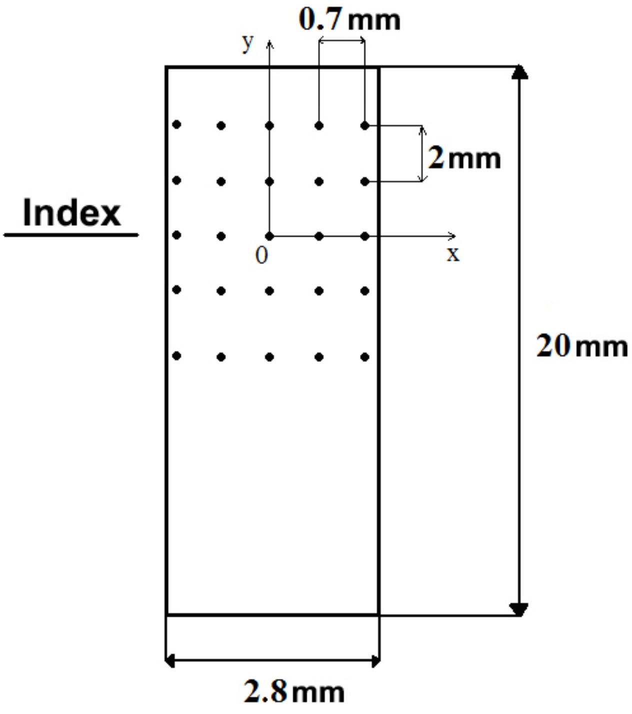


Fig. 8. Position of points for measuring the brightness across TRU 1100-2350 lamp filament.

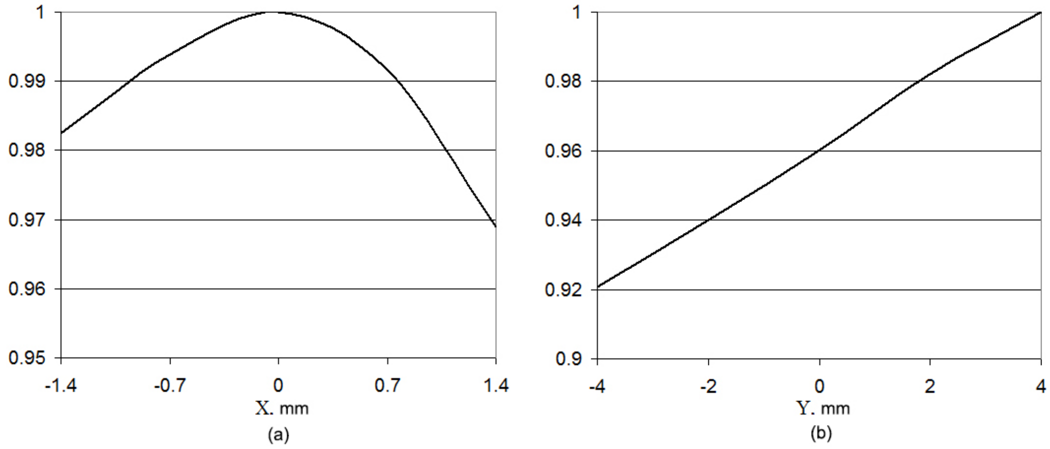


Fig. 9. Relative brightness distribution of TRU 1100-2350 lamp filament: (a) over ribbon width at index level, along axis X (Y = 0); (b) over ribbon height, along central Y axis (X = 0).

The obtained data reflects the existing non-uniformity of brightness along the vertical axis Y of the lamp filament body (about 8% for the measured area of the filament body, Figure 8, Figure 9b), while the brightness decreases in the direction from the top of the ribbon to the bottom. In the working area opposite the index along axis X, the non-uniformity is no more than 3% for the total width of the ribbon (Figure 8, Figure 9b), while the maximum brightness corresponds to the central point along the width of the ribbon.

Thus, the conducted measurements have demonstrated that implementing the given method and taking into account the measured brightness distribution near the working area of the lamp filament ensure the absolutizing of the DI. This is achieved by transmitting the SR from the reference TRU 1100-2350 lamp with high accuracy owing to the capability to position on the center of the working area of the lamp filament with an accuracy of no less than ±0.5 mm.

Conclusion

The results of modernizing the *Kameliya* measurement complex and the development of new methods of measuring spectral-energetic characteristics of optoelectronic ERS-equipment presented in the paper have ensured the practical implementation of optical circuits for taking the relative spectral characteristics of MSD. These methods have also proved to be adequate for measuring the transmission and reflection spectra (for various angles) of optical elements and optical blocks or ERS equipment in the range λ = 0.4–14 μm.

The new capabilities of the *Kameliya* complex have provided measurements for each of the seven IR channels of the fully manufactured light-splitting unit MSU-GS [1] (for the Electro-L No. 2 spacecraft), as well as for all six channels (three IR-channels) of the fully manufactured MSU-MR [2] (for the Meteor-M No. 2 spacecraft).

Apart from that, a method for measuring the spectral characteristics of optical emission sources (λ = 0.4–14 μm) in the range λ = 2.5–14 μm with the help of which the emission spectra of halogen lamps, light-emitting diode sources, gas discharge lamps were measured, has been developed.

Further upgrading of the *Kameliya* radiometric complex of JSC "Russian Space Systems" depends on the overall state of the metrological base in the space industry and in the country as a whole. The creation of advanced reference, measurement and testing equipment, especially in the IR part of the spectrum, as well as the development of a corresponding regulatory framework for competitive ERS equipment, which is an important government task, requires organizational decisions and financial support on a regular basis.

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