

VNIIOFI ACTIVITIES IN RADIOMETRY AND PHOTOMETRY

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Consultative Committee for Photometry and Radiometry (CCPR)

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TOTAL SPECTRAL RADIANCE FLUX (TSRF) REALIZATION

TSRF realization with spectro-radiometer and photometer

VNIIOFI carries out works on realization of independent methods for reproducing TSRF of incoherent optical radiation' sources - reference high-temperature blackbodies (BB), halogen lamps, and LED with quasi-Lambert spatial distribution of radiance. Schemes for measuring facilities use photometers, spectroradiometers and computer-controlled high-class goniometer designed and manufactured by GL-Optics (Poland).

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:

$$\Phi_l = 683 l^2 \int_{380}^{680} V(\lambda) \iint_{0,0}^{2\pi, \pi/2} \frac{i(\lambda, \theta, \varphi)}{k_0(\lambda)} \sin\theta d\theta d\varphi d\lambda$$

where $i(\lambda, \theta, \varphi)$ – is the signal measured by a spectroradiometer using a goniometer.

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

$$683 \int_{380}^{780} V(\lambda) I(\lambda, \theta, \varphi) d\Omega d\lambda \equiv \int_{\Omega_0} I(\theta, \varphi) d\Omega = \Phi_l$$

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

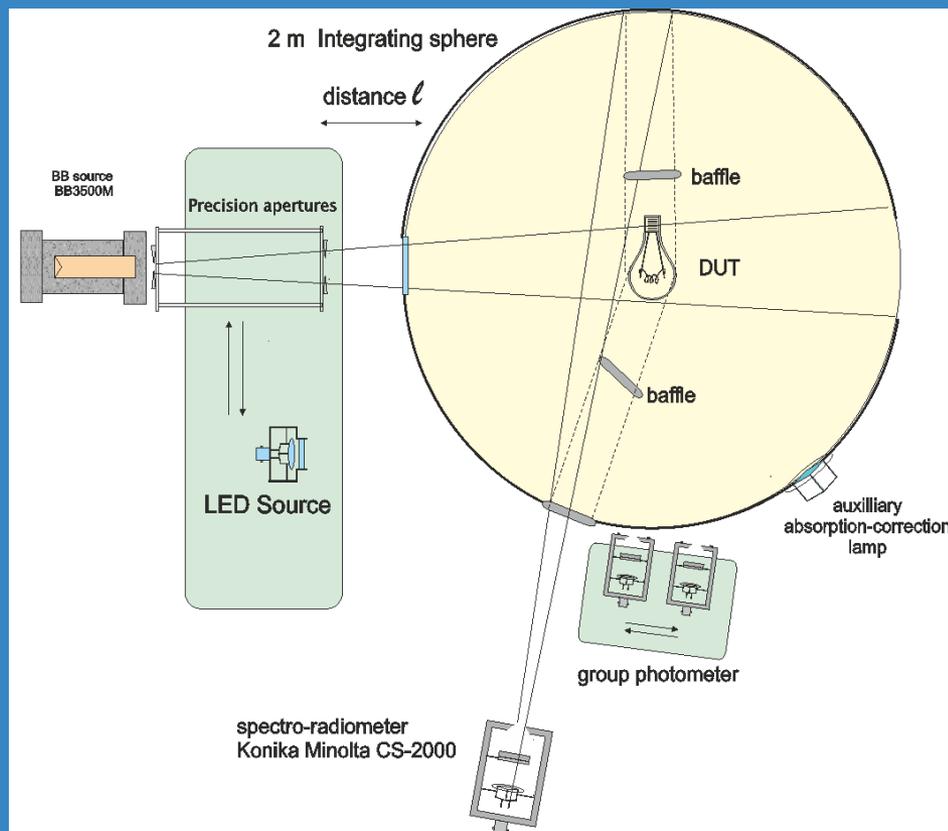
$$I_{rel}(\lambda, \theta, \varphi) = \frac{i(\lambda, \theta, \varphi)}{i(\lambda_0, \theta_0, \varphi_0)} = \frac{I(\lambda, \theta, \varphi)}{k_{scale}}$$

where $\lambda_0, \theta_0, \varphi_0$ – are the wavelength and the direction of observation chosen for calibration of the photometer against the BB, for example, those at which the measured signal is maximal. As a result, we find the required TSRF

$$\Phi(\lambda) = k_{scale} \cdot \int_{\Omega_0} I_{rel}(\lambda, \theta, \varphi) d\Omega$$

where the absolutizing factor measured by means of photometer, is as follows:

$$k_{scale} = \frac{\Phi_l}{683 \cdot \int_{380}^{780} V(\lambda) \int_{\Omega_0} I_{rel}(\lambda, \theta, \varphi) d\Omega d\lambda}$$

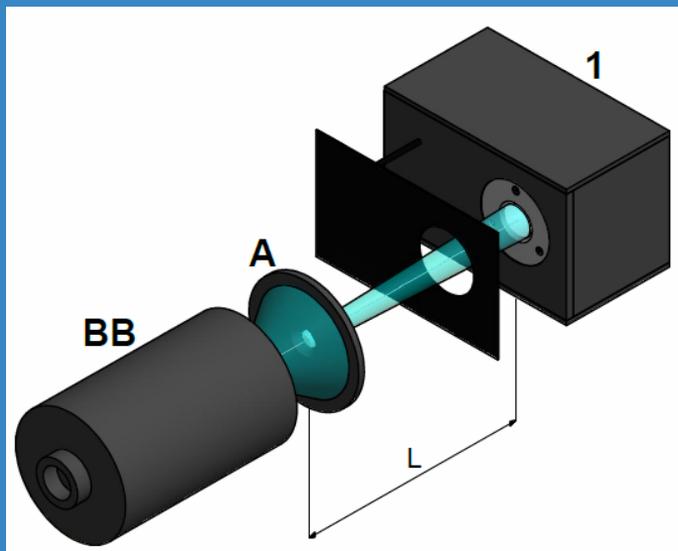
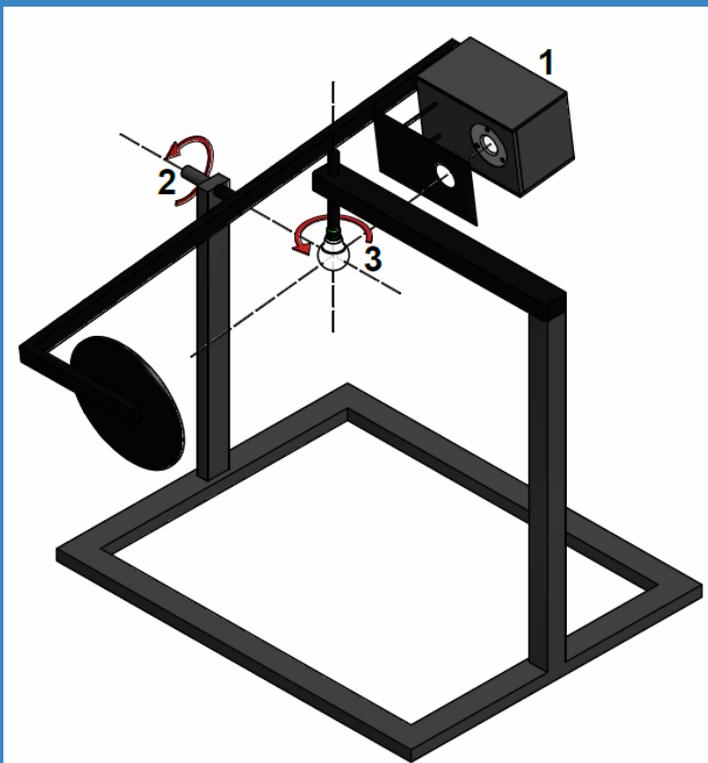


Scheme of TSRF realization from Blackbody or LED as an external source

TSRF REALIZATION ON THE BASIS OF GONIO-SPECTRORADIOMETER

The scheme of the TSRF realization from optical source in the form of a halogen lamp is based on a goniometer (made by GL Optic, Poland), which includes a 127-mm integrating sphere with a spectroradiometer (1) and a high-speed photometer class A - all elements are temperature stabilized.

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 by 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. Mounting unit enables precise fixation of a measuring unit to a goniometer arm, or to a calibration system based on BB source.

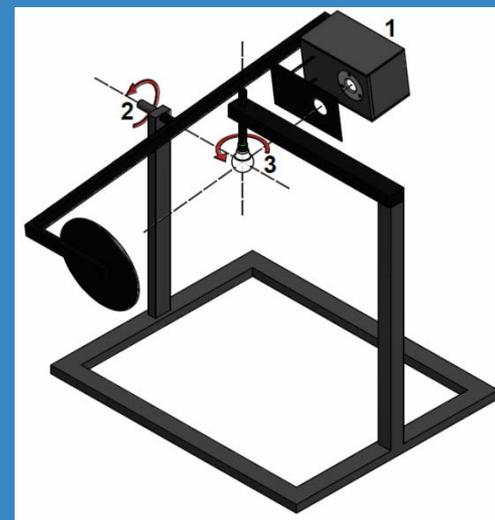
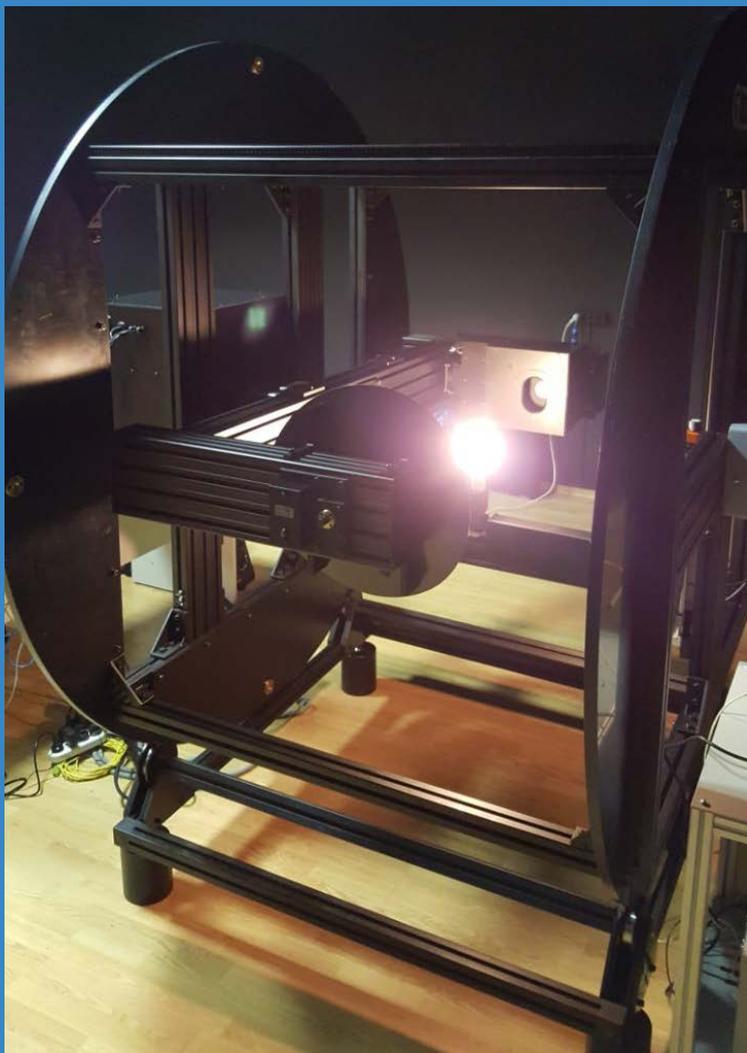


Scheme of calibration of the spectroradiometer and photometer located in the detector block (1), according to spectral characteristics, according to the reference BB with the radiation flux generator in the form of a block of precision apertures (A)

Computer-controlled high-class goniometer designed and manufactured by GL-Optics.

1) Integrating sphere with spectroradiometer and highspeed photometer (temperature-stabilized); 2) Main rotation axis - uniform rotation with a constant angular speed; 3) DUT slow uniform rotation with a constant angular speed

New Standard facility for Total Spectral Radiant Intensity



Spectral range: 350-1000 nm
Bandwidth: 3.5 nm
Measurand range: $10^6 - 5 \cdot 10^8$ W/m
Exp. Unc. (k=2): 0.5 % – 2 %

2

Facility for measuring the spectral sensitivity
of THz receivers

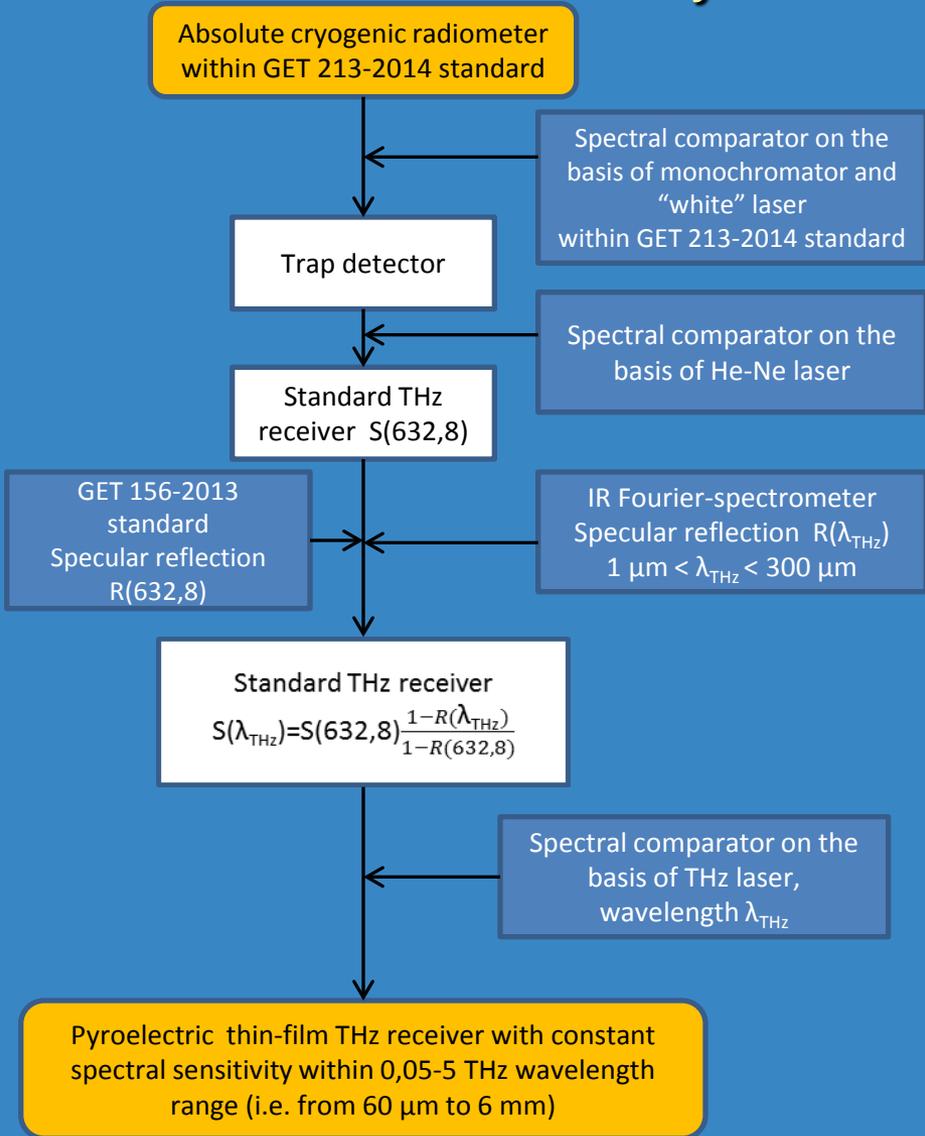
Reference facility for measuring the spectral sensitivity of THz receivers

At VNIIOFI, in 2018, at the improving the State primary standard of units of absolute and relative spectral sensitivity in the wavelength range from 0.25 to 14.00 μm GET 213-2014 in terms of expanding the spectral range to 300 μm (up to 1 THz) it was developed a block diagram of a reference facility for measuring the spectral sensitivity of THz receivers.

This facility provides traceability of the results of measuring spectral sensitivity to the primary standard based on a cryogenic radiometer.

According to the principle of operation, the reference facility is a spectrocomparator. An optical pumped molecular gas laser is used as a radiation source. The unit of spectral sensitivity is transmitted to the calibrated receiver from the reference THz range radiation receiver.

Reference facility for measuring the spectral sensitivity of THz receivers



The basic requirement for a reference receiver is that its spectral sensitivity must be known.

This is achieved as follows:

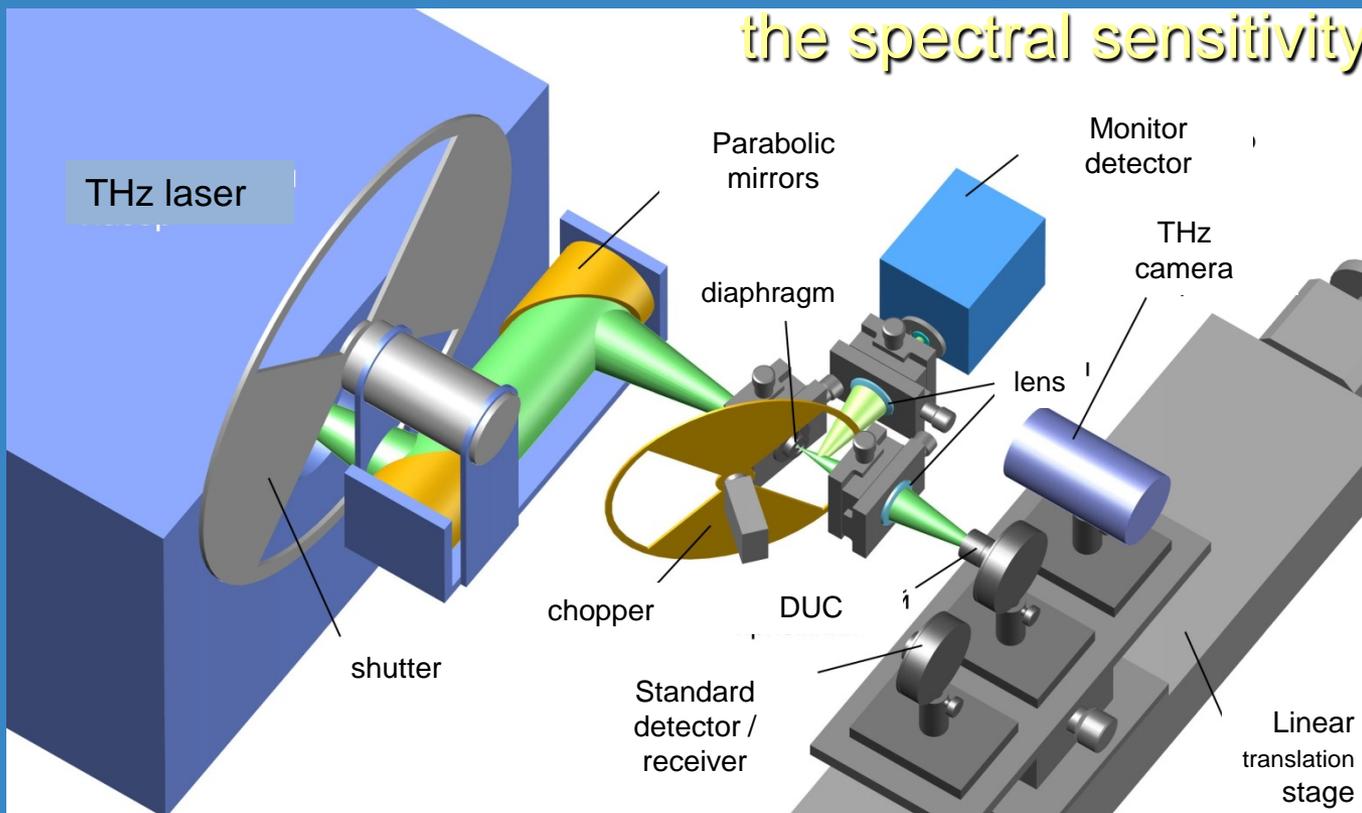
- the dependence of spectral sensitivity on the wavelength is determined on the basis of a physical model that allows you to find the spectral absorption coefficient of the receiver at different wavelengths by measuring the spectral reflection and transmission coefficients at these wavelengths;
- The spectral sensitivity of the reference receiver is measured at one selected wavelength with traceability to SI units.

Then, based on the known spectral absorption coefficients at the selected wavelength and at the desired THz wavelength, the spectral sensitivity is recalculated for the desired wavelength.

This algorithm has already been implemented at the PTB (Germany).

The traceability of measurements of the spectral sensitivity of THz receivers to an absolute cryogenic radiometer

Block diagram of a setup for measuring the spectral sensitivity of THz radiation receivers

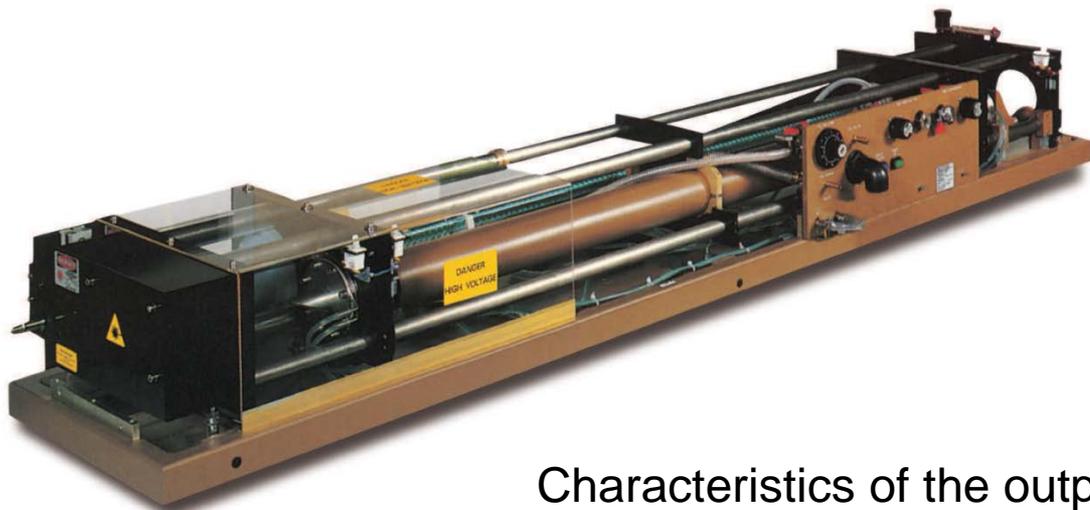


The absorption element of the receiver is a bulk layer of special glass with a polished front surface and gold coated back surface. The physical model of reflection and absorption of radiation used in this way allows using this receiver to reproduce and transmit a unit of spectral sensitivity in the range from 1 to 5 THz (from 60 to 300 μm), provided that its spectral sensitivity is measured at the same wavelength in the visible range.

The unit of spectral sensitivity in the THz range is transmitted on a reference installation for calibrating terahertz radiation receivers, which is essentially a spectral comparator based on a THz laser.

Basic elements of the reference THz-facility

Radiation source

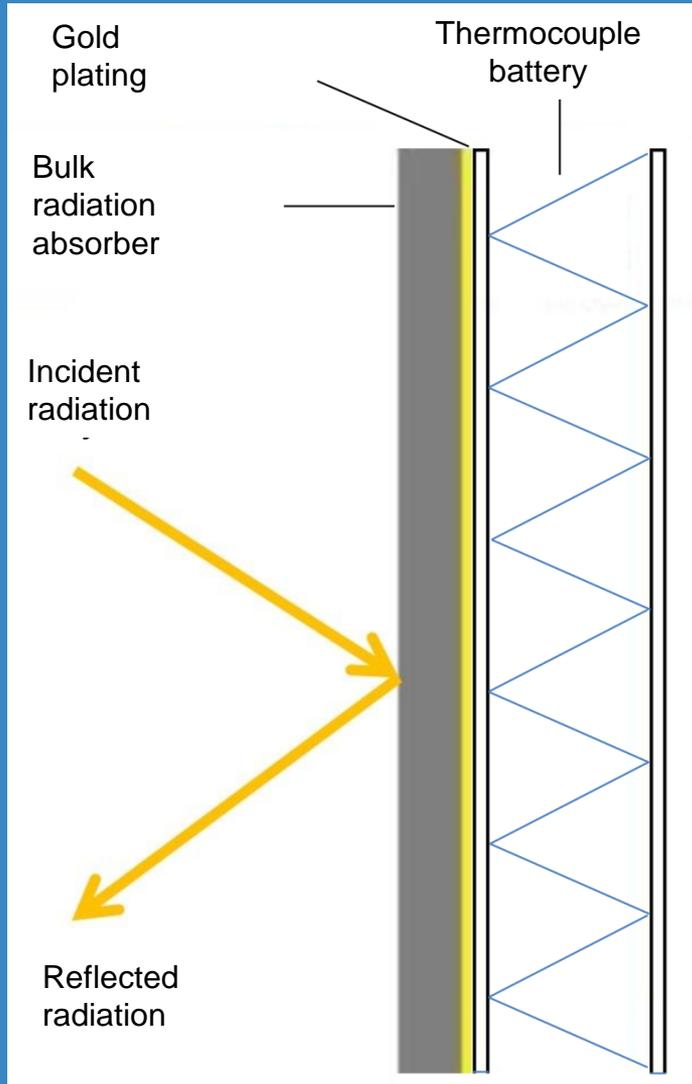


Characteristics of the output radiation of a THz laser in
the far IR region of the spectrum

Wavelength, μm	Far-infrared laser gas molecule	Pump line CO_2	Typical Power, mW
96,5	CH_3OH	9R10	60
118,8	CH_3OH	9R36	150
184,3	CH_2F_2	9R32	150
432,6	HCOOH	9R20	30
513,0	HCOOH	9R28	10

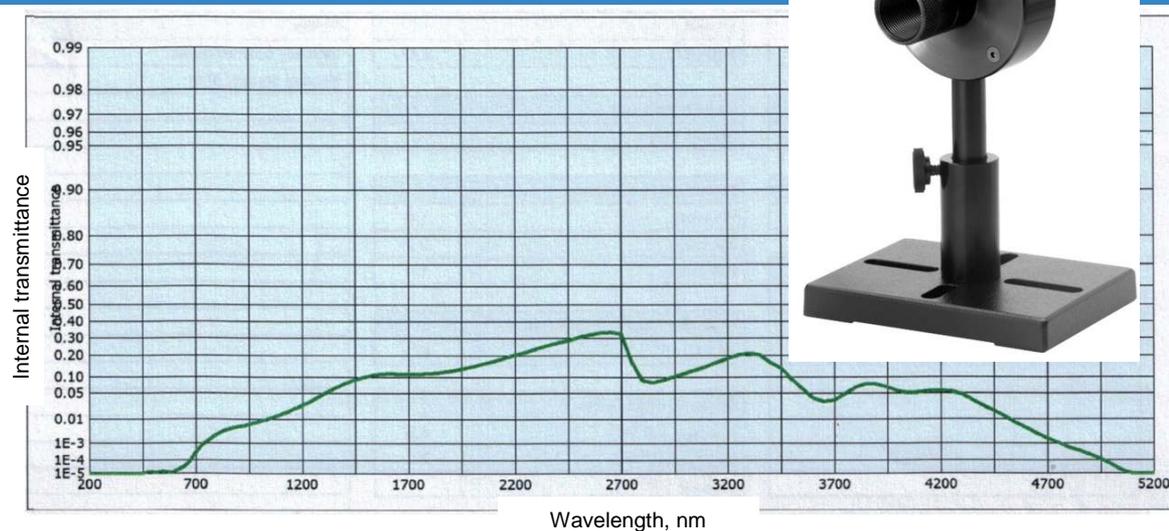
Basic elements of the reference THz-facility

Reference radiation receiver



Design of a THz reference thermocouple receiver

As a volumetric absorber of THz radiation, a disk with a diameter of 12 mm and a thickness of 0.6 mm made of polished Scott neutral glass NG1 glass with a gold coating on the back was used. This material is supposed to be used as a bulk absorber of THz radiation in the design of a reference THz radiation receiver.



Dependence of the internal transmittance of a plane-parallel wafer of NG1 glass 1 mm thick on the wavelength

Basic elements of the reference THz-facility

Radiation receivers

If the spectral sensitivity $S(\lambda_0)$ of the reference receiver is measured at a wavelength λ_0 of the visible range with reference to a cryogenic radiometer, the spectral reflection coefficients of a gilded disk NG1 at a wavelength of λ_0 and the required wavelength λ_{THz} of the THz range, then the spectral sensitivity $S(\lambda_{\text{THz}})$ at this λ_{THz} wavelength is determined from the relation:

$$\frac{S(\lambda_0)}{1-R(\lambda_0)} = \frac{S(\lambda_{\text{THz}})}{1-R(\lambda_{\text{THz}})}$$



Appearance of the reference and
calibrated receivers on the translation
stage



Appearance of a THz pyroelectric camera
for visualization of terahertz radiation

3

In-flight calibration of Earth Observation Instruments

Development of the novel space-borne standard blackbodies that incorporate the phase transition phenomenon

Current techniques cannot ensure proper verification of stability and consistency of radiometric scales at the stated level. Potentially this task can be solved through the development of the novel space-borne standard blackbodies that incorporate the phase transition phenomenon.

For this purpose individual substances and eutectic alloys with the phase transition temperatures lying in the dynamic range of temperature measurements with Earth observation systems ($\sim 230\div 350$ K) are to be studied.

Investigations in this field at VNIIOFI were started from laboratory experiments with the suitable phase-change materials (PCMs), and further proceeded with flight tests of the PCMs and the novel space-borne fixed-point BB prototypes (with different PCMs) in zero-gravity environment.

PURPOSE:

Studies of the effect of zero-gravity on the temperature characteristics of phase transitions to be used as the fixed points in the calibration of equipment for radiometric measurements within the framework of Global Earth Observation System (GEOSS);

The **FIRST FLIGHT TEST** of the prototype of the novel high-stable space-borne calibration blackbody incorporating the phase transition phenomenon.



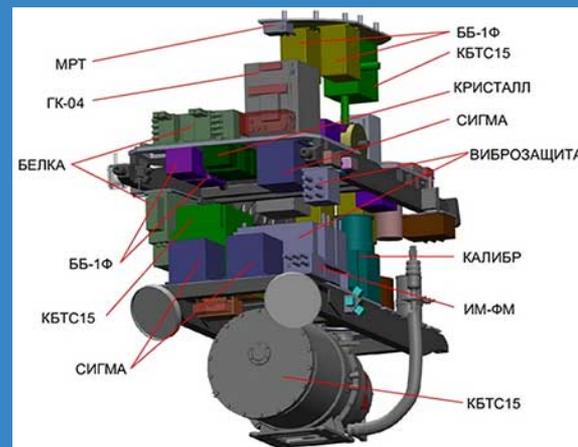
The device KALIBR designed for the flight test on board the "PHOTON-M" No.4 spacecraft

a – prototype of the novel space-borne calibrator based upon the phase transition (the Ga fixed-point blackbody)

b – control unit



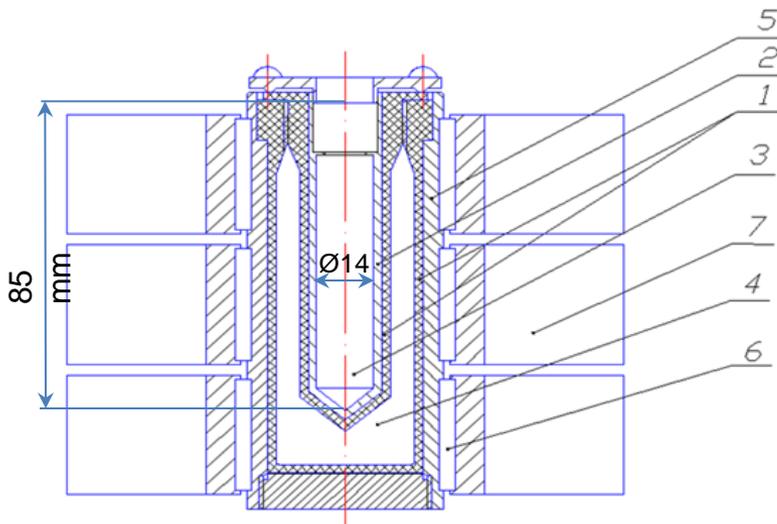
"PHOTON-M" No.4 spacecraft



Placement of scientific equipment inside the lander of "PHOTON-M" No.4 spacecraft

SPACE EXPERIMENT “KALIBR”

The first space experiment with the novel high-stable space-borne fixed-point blackbody prototype KALIBR was carried out by VNIIOFI and Central Research Institute of Machine Building (TSNIIMASH, Russia) on board the “PHOTON-M” No.4 spacecraft in 2014.

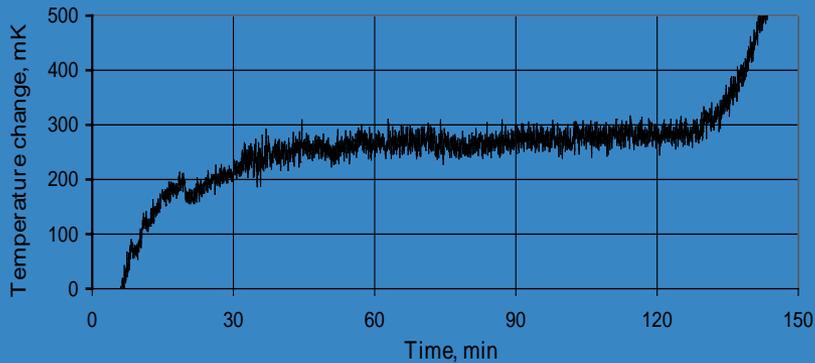


Scheme drawing of the prospective space-borne blackbody test model KALIBR utilizing the Gallium as a phase-change material:

1- Teflon cell; 2 – Metallic inlay; 3 – Cavity;
4 – Phase change material (Ga); 5 – Heat exchanger;
6 – Thermoelectric module; 7 – Heat sink

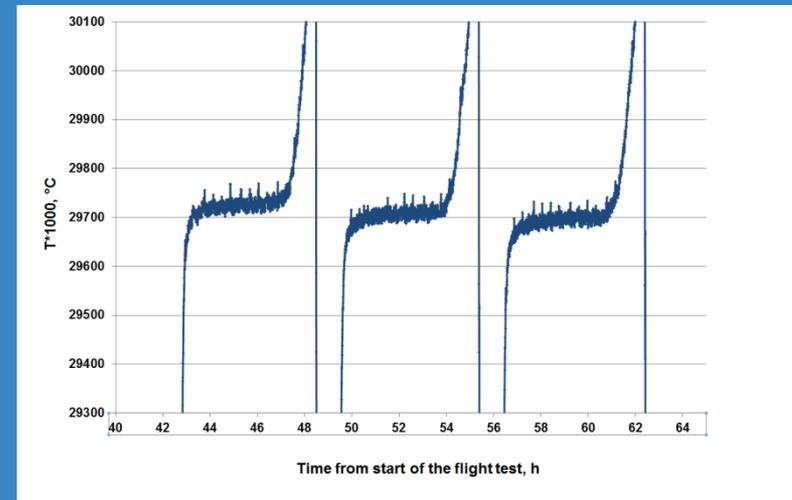
SPACE EXPERIMENT "KALIBR"

Pre-flight studies:



Stabilization of the space-borne
BB test model **KALIBR** cavity
temperature during the Gallium
melt transition

Flight test:

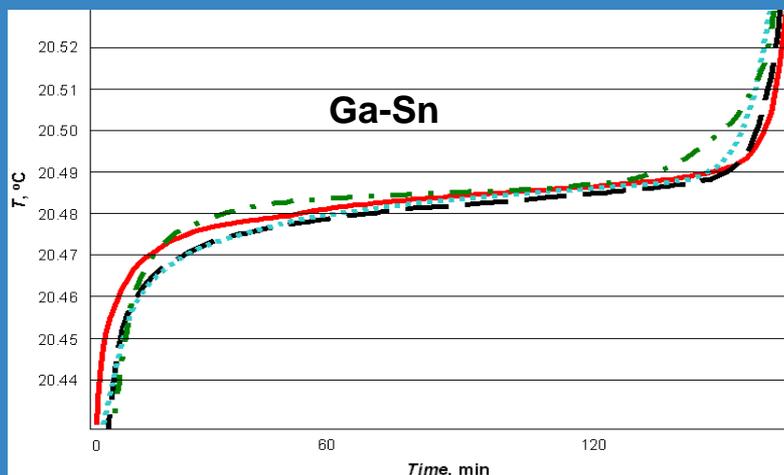


Typical series of Ga melting plateaus
obtained under zero-gravity conditions in
flight test

Obtained in zero-gravity melting plateaus
demonstrate rather good repeatability:
about 15 mK (1σ)

“REPER-KALIBR” experiment (1st STAGE)

Pre-flight laboratory studies of the phase-change materials selected for the flight test (Ga-based eutectics)



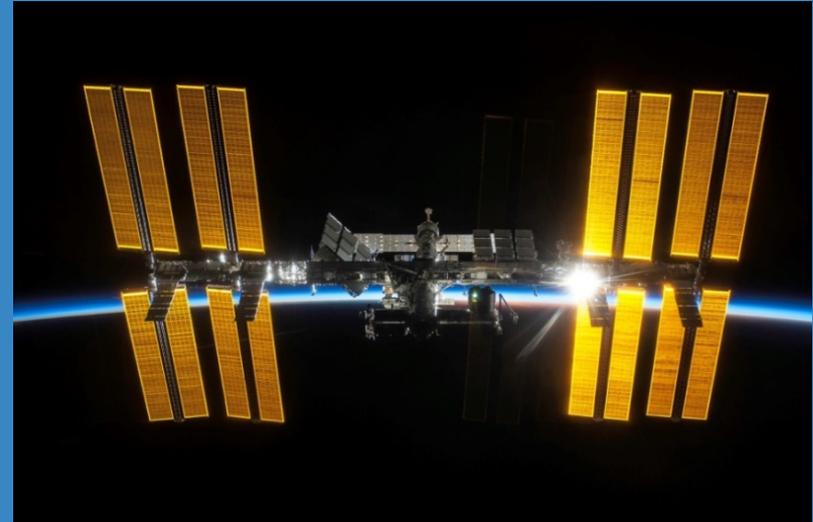
Demonstration of the selected PCMs melting plateaus repeatability by example of Ga-Sn eutectic alloy.
(at realization in small-sized cells)

Substance	Melting temperature (approximate) K	Repeatability (δ) (individual sequences) mK	Overall repeatability (δ_{ov}) mK
Ga	302.91	1 – 1.5	2.5
Ga-In	288.81	1 – 2	3.0
Ga-Sn	293.63	1 - 2	3.0

Repeatability of fixed points of the most promising PCMs to be studied in “REPER-KALIBR “flight test.
(at realization in small-sized cells)

Pre-flight preparation: development of the equipment

Flight test “REPER-KALIBR” with the PCM’s potentially suitable for on-orbit temperature and radiometric references - *within the dynamic temperature range* - is being prepared at VNIIOFI and Russian Space Corporation “Energia”.



The equipment to be delivered to the ISS for realization “REPER-KALIBR” experiment with Ga-based eutectics (1st stage)

- 1 – Control block
- 2 – Container for changeable thermal blocks (individual block for every PCM to be studied)

For the 1-st stage of the “REPER-KALIBR” flight test of Ga and Gallium-based eutectics Ga-In, Ga-Sn, Ga-Zn ($\sim 288\div 298$ K) filling the gap in the ITS-90 temperature scale between the TPW and the melting point of Ga were selected.



The thermal block of the equipment for realizing the flight test on board the ISS. (1-st stage)



The thermal block's Teflon cell for filling with Ga and Ga-based eutectics to be studied in zero-gravity

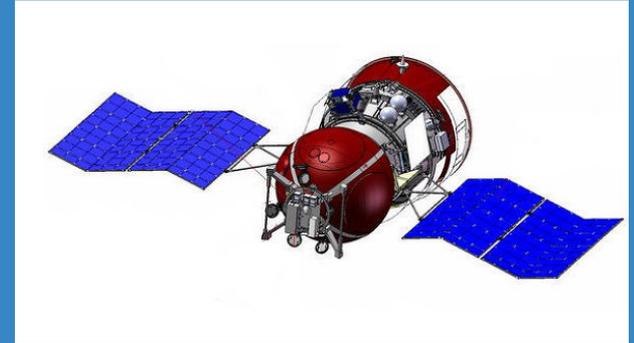
For the 2-nd stage eutectic alloy In-Bi (~ 345.7 K) and H_2O (273.15 K) were selected. That will allow to significantly extend a prospective "on-orbit temperature scale" in the directions of both lower and higher temperatures **within the dynamic temperature range ($\sim 230\div 350$ K).**

SPACE EXPERIMENT "KALIBR-2"

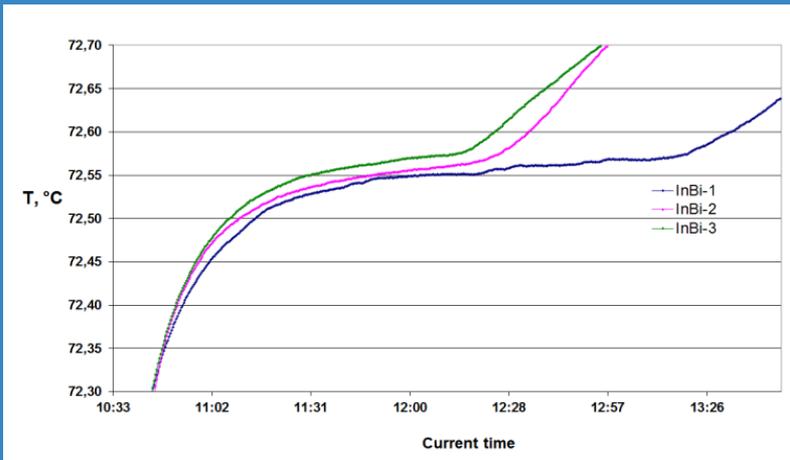
Pre-flight laboratory studies

In-Bi eutectic alloy was selected as a phase-change material for the novel high-stable space-borne blackbody prototype KALIBR-2

Eutectic alloy	Cell marking	Alloy mass, g	Composition, mass%	Nominal eutectic composition, mass%
In-Bi	InBi-1	150	33,27% Bi	~ 33,26 % Bi
	InBi-2	150	37,1% Bi	
	InBi-3	150	24% Bi	



In-Bi fixed points in small-sized cells



Typical melting plateaus of InBi-1, InBi-2, InBi-3 fixed points (at realization in small cells)



The spacecraft model "Bion-M"

Conclusion:

Development of the novel space-borne standard blackbodies incorporating the phase transition phenomenon

The experiment on board the "Foton-M" No.4 spacecraft with the Ga fixed-point BB (~ 302.9 K) is the first step to establishing "on-orbit radiometric temperature scale" based on the space-borne low-temperature fixed-point standard blackbodies.

The next important step in this direction will be experiment with the space-borne blackbody test model KALIBR-2 (on board the "Bion-M" No.4 spacecraft) utilizing the fixed point of eutectic alloy In-Bi of higher temperature (~ 345.7 K).

Establishing "on-orbit radiometric temperature scale" is targeted at ensuring compatibility of data on different IR instruments **within the dynamic range of temperature measurements with Earth observation systems (~ 230÷350 K).**

A number of onboard reference blackbodies utilizing suitable PCMs, including Ga (PCM of the KALIBR) and alloy In-Bi (PCM of the prospective KALIBR-2), should be developed to achieve this goal.

Dates of the SPACE EXPERIMENT "KALIBR-2"

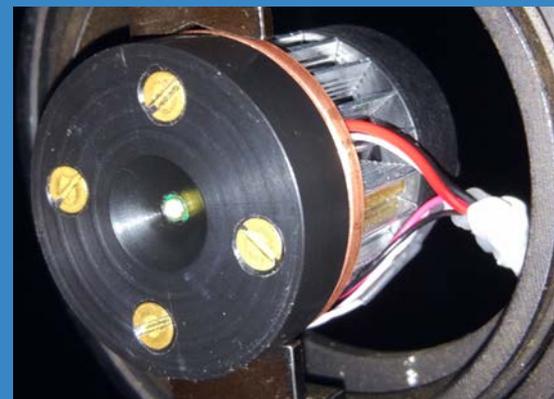
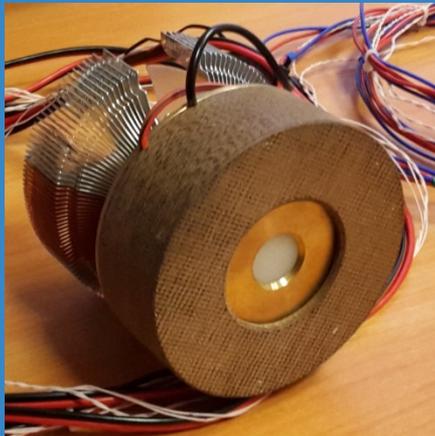
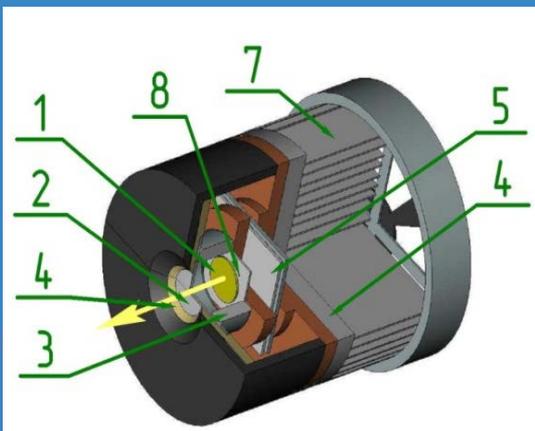
- Equipment delivery to the ISS (International Space Station) for carrying out stage 1 of the REPER-KALIBR Space experiment is scheduled for April 2020.
- Space experiment KALIBR-2 at the Bion-M spacecraft No. 2 for testing the weightless prototype of an onboard black body under zero gravity conditions, with a simultaneous study of the effect of weightlessness on the phase transition of its working substance - the In-Bi eutectic alloy - is planned for 2023.
- Phase 2 of the REPER-KALIBR Space experiment at the ISS is planned for 2024.

4

High power LED standard light sources for
photometric applications

High power LED standard light sources for photometric applications

High power LED light sources have been developed as possible new VNIIOFI standard sources for luminous intensity, luminous flux and colour measurements. Stability and repeatability of the sources were investigated and demonstrated high accuracy.



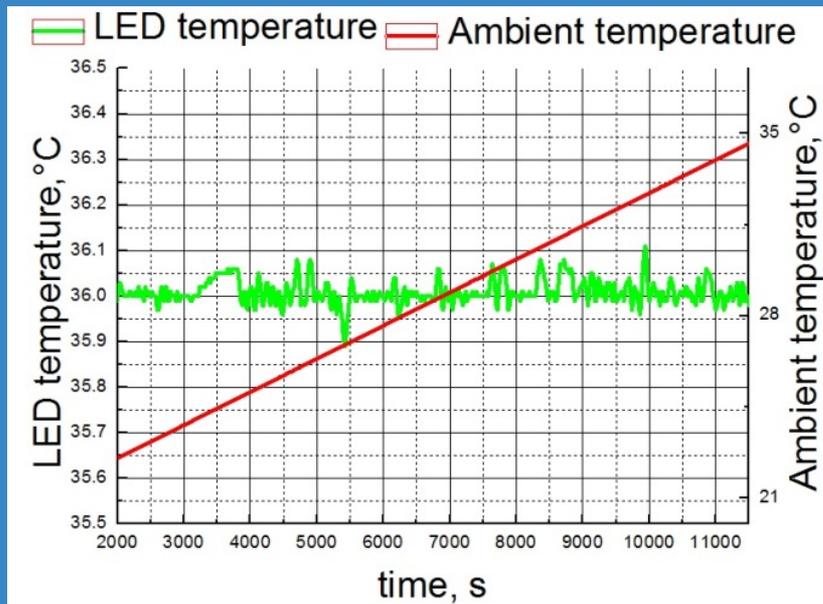
Scheme and external view of a standard LED source designed at VNIIOFI.

- 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.

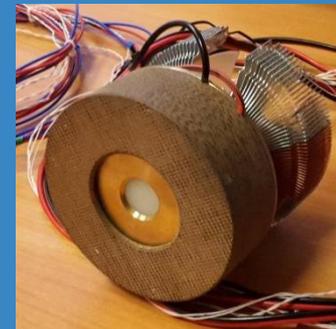
The design of quasi-lambertian high power LED sources for COB type LEDs has been developed. Two white LED sources have been built with luminous intensity of 500-1000 cd and luminous flux of 1500-2500 lm and photometric stability of 0.02% for approximately 10 h.

The developed LED sources can be used as standard photometric sources and may, in future, replace incandescent lamps.

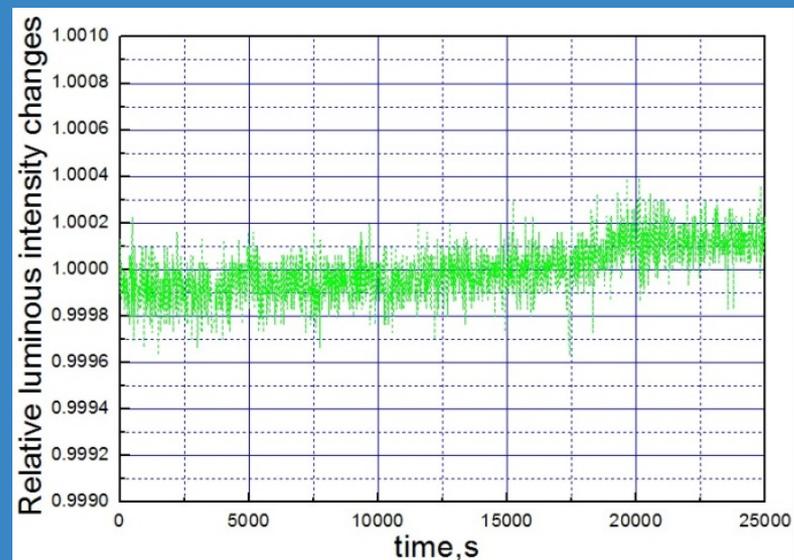
Development of Standard high-power LED sources (Chip-on-board)



Relation of LED temperature stability from ambient temperature (green - LED temperature, red - ambient temperature)

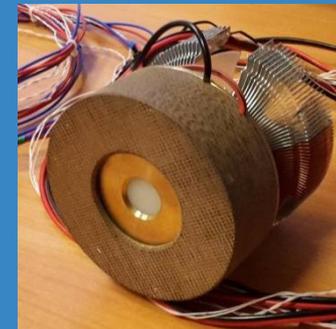
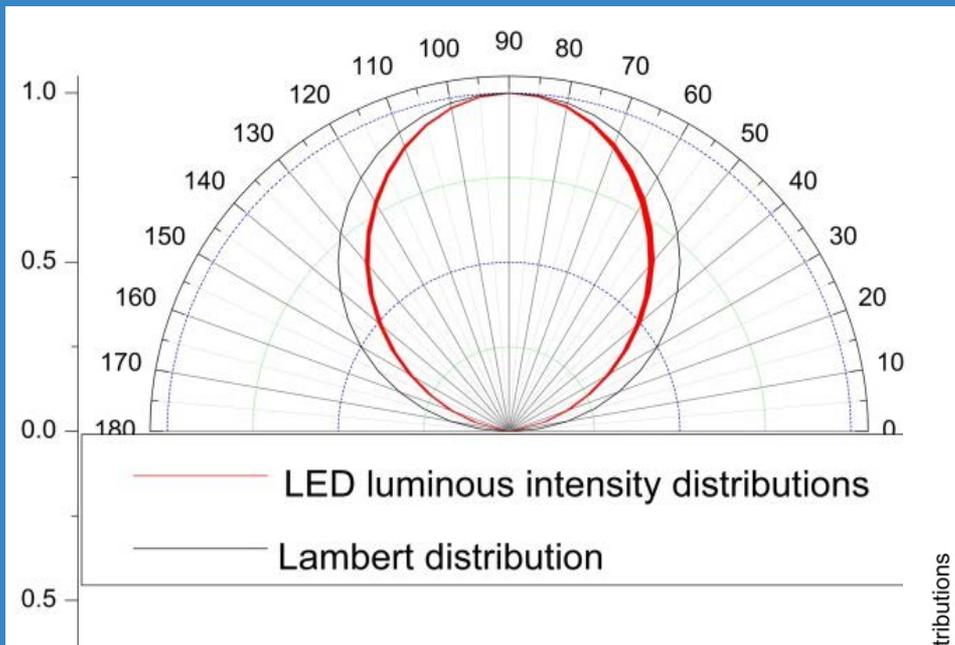


Relative change of luminous intensity.

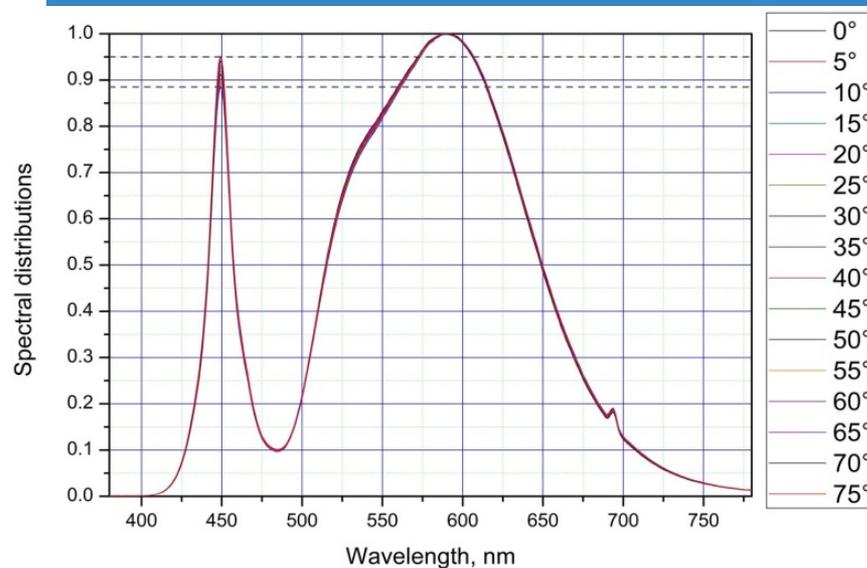


Standard high-power LED sources

Luminous intensity angle distribution



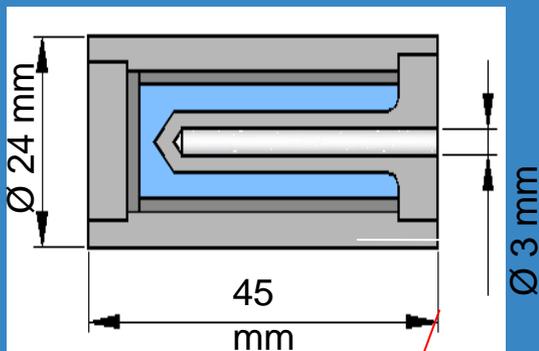
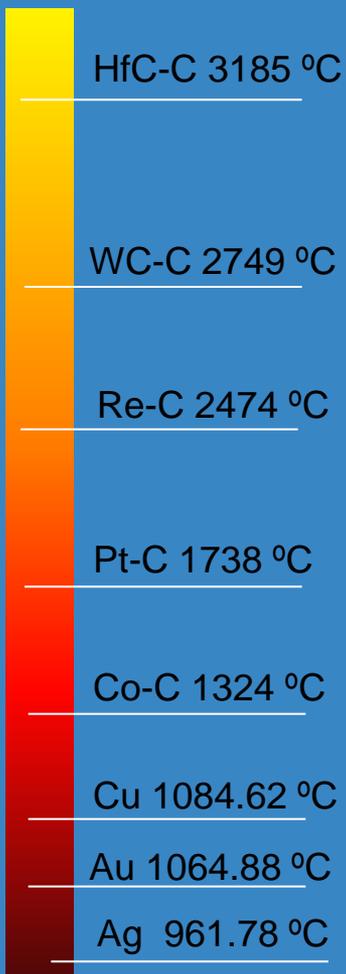
Dependences of the spectrum distributions from angle.



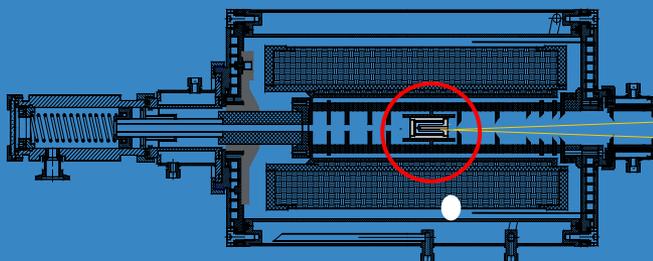
5

LARGE-AREA HTFP CELLS FOR IRRADIANCE-MODE MEASUREMENTS

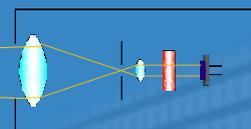
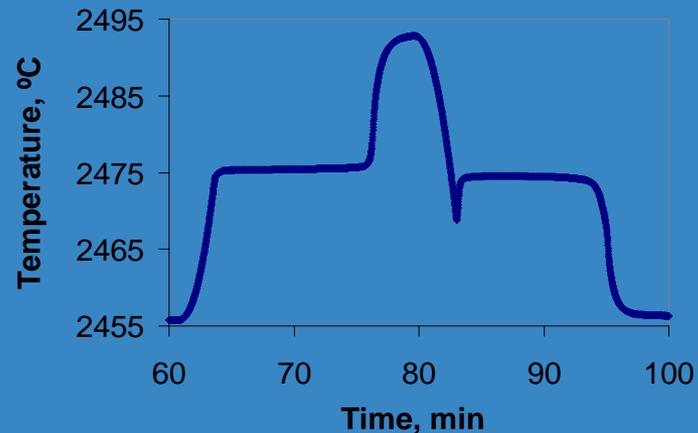
High-Temperature Fixed Points



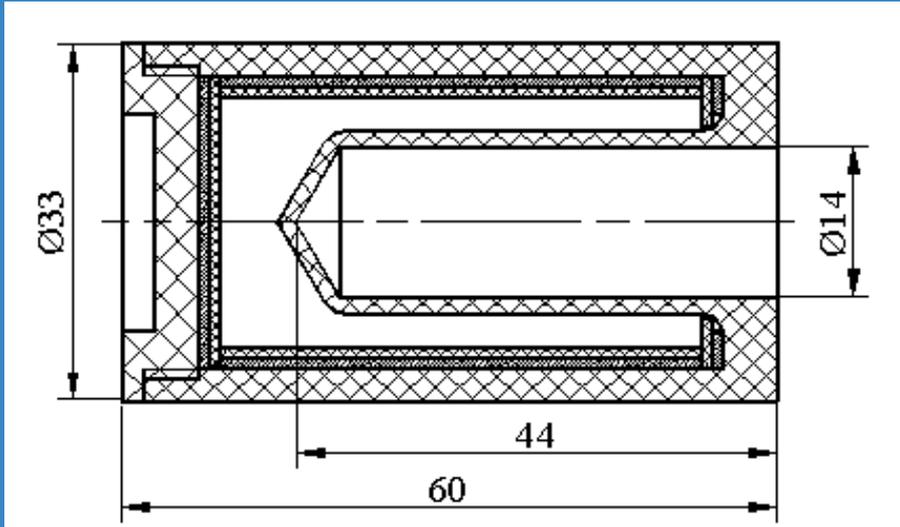
Eutectic alloy



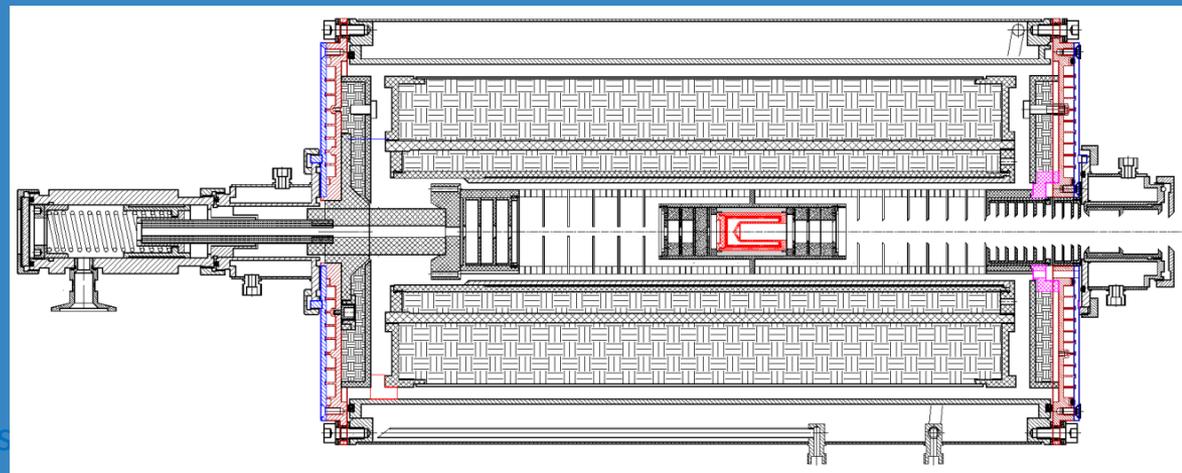
Inflection point



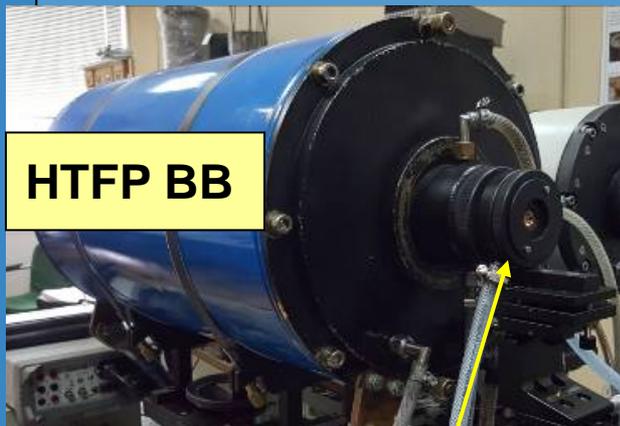
Design: Dimensions.



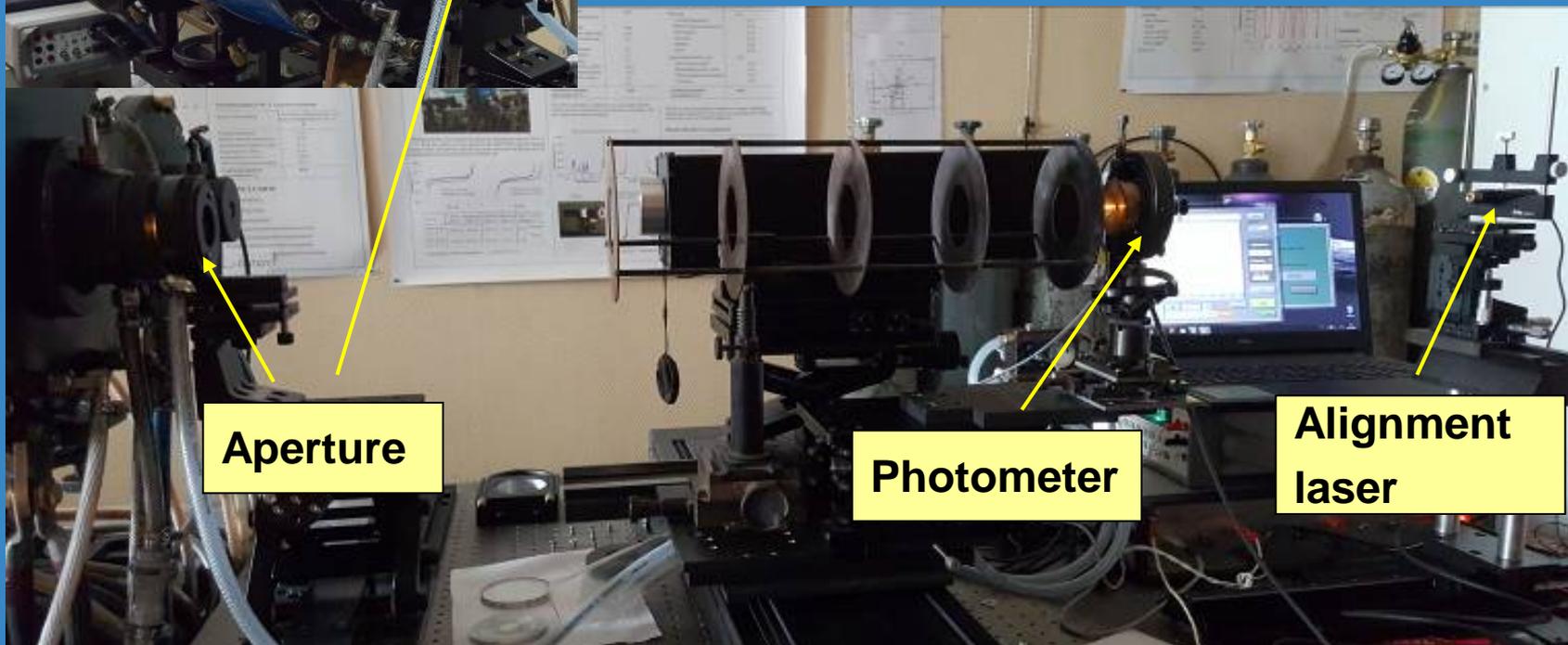
large aperture



Irradiance mode



HTFP BB



Aperture

Photometer

Alignment
laser

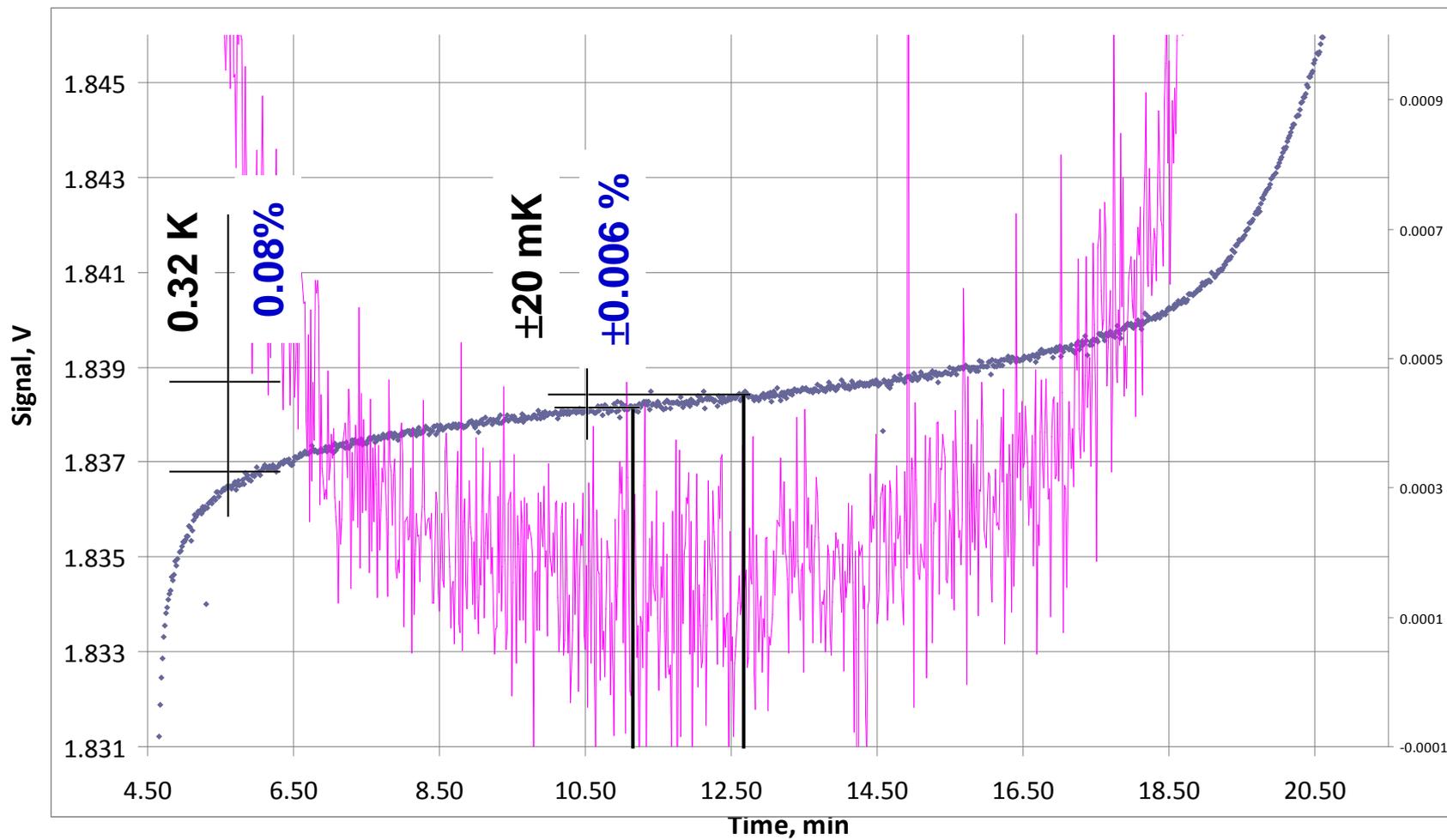
5 mm

$d \sim 700$ mm

5 mm

Inradiance mode. Measurements

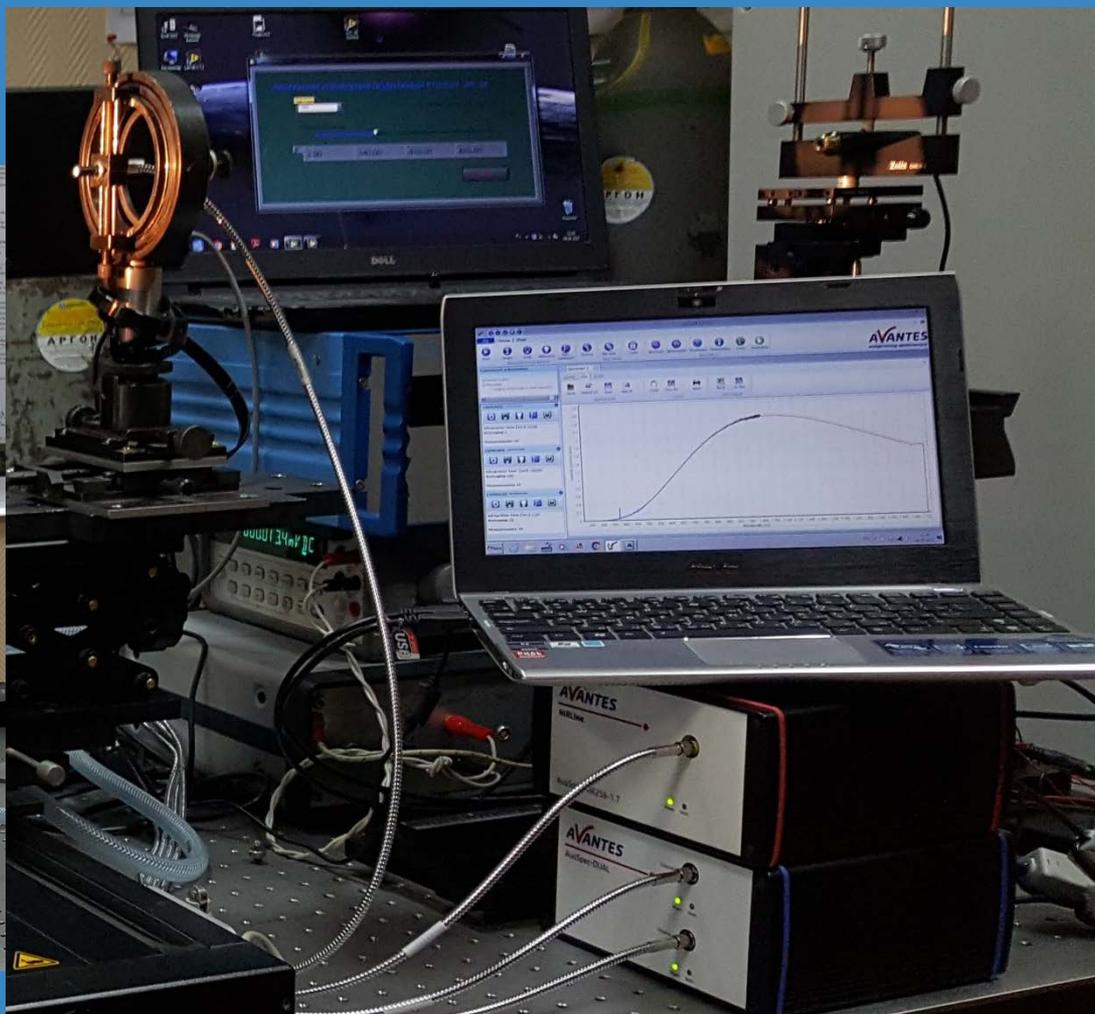
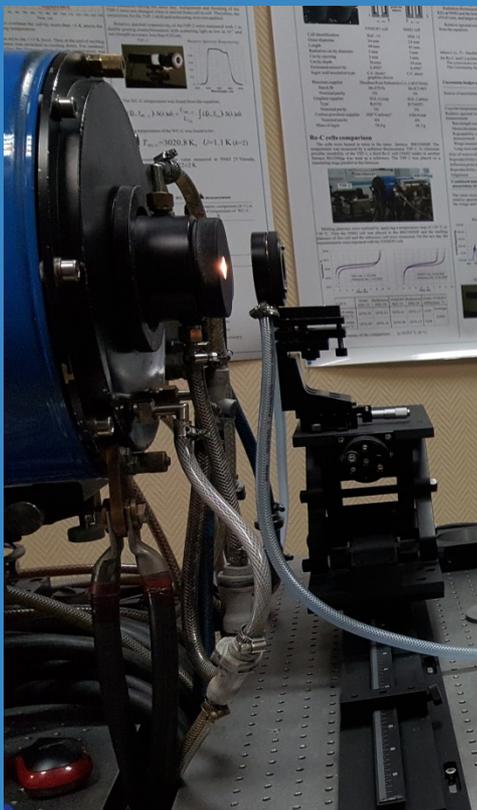
Re-C (2748 K) Filter Radiometer 510 nm. 5 mm, d=700 mm



Irradiance mode.

Calibrating SpectroRadiometer

WC-C (3021 K)



Uncertainty Budget

	$u(k=1), K$		
<u>Small cell</u>			
T_{Re-C} (E. Woolliams)	0.177		
Others	0.13		
<u>Large-to Small Comp.</u>	0.10		
<u>Large cell</u>			
POI identification	0.02		
Furnace effect	0.05		
Stability	0.05	<u>555 nm</u>	<u>300 nm</u>
<u>Combined</u>	0.251	0.09%	0.16%
Aperture		0.02%	0.02%
Distance		0.02%	0.02%
		0.09%	0.16%
	$U(k=2)$	0.18%	0.32%
	Stability	0.07%	0.10%