COOMET Supplementary Comparison

(Bilateral comparison between VNIIOFI, Russia and PTB, Germany)

COOMET.PR-S4

Laser Power Responsivity

(COOMET Project 461/RU/090)

Final Report

25 May 2011

Sergey A. Moskalyuk[1], Anatoly A. Liberman[1],Stefan Kück[2], Friedhelm Brandt[2]

[1] *Federal State-Owned Unitary Enterprise "All-Russian Research Institute for Optical and Physical Measurements"(VNIIOFI), 119361, Russia, Moscow, Ozernaia str., 46*

[2] *Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany*

Contents

1. Introduction

Physikalisch-Technische Bundesanstalt (PTB) and All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) agreed in December 2008 to conduct a bilateral comparison on the laser power responsivity at wavelengths of 532 nm / 530.9 nm, 1.064 µm and 10.6 µm. The aim of this comparison is to assess the equivalence of the laser power responsivity between two laboratories. (Note that VNIIOFI measurement results obtained at 532 nm were compared with PTB measurement results obtained at 530.9 nm. This is justified, because the wavelengths are rather close to each other and the responsivities of transfere detectors at these wavelengths differ by less than 0,001 %, which is less than uncertainty of the measurements).

The comparison was conducted within the COOMET regional metrological organization (COOMET project 461/RU/090) and was registered at BIPM KCDB as a supplementary comparison with the identification COOMET.PR-S4

2. Organization

2.1. Pilot

The VNIIOFI was a pilot laboratory in the comparison among the participants.

2.2. Participants' details

NMI Name (Country)	Personnel	Contact information
PTB (Germany)	Stefan Kück	Physikalisch-Technische Bundesanstalt FB 4.5 Optische Technologien AG 4.54 Laserradiometrie Bundesallee 100 38116 Braunschweig Telefon: +49 531 592-4500 Telefax: +49 531 592-694500 E-mail: stefan.kueck@ptb.de
VNIIOFI (Russia)	Anatoly Liberman	Federal State-Owned Unitary Enterprise "All-Russian Research Institute for Optical and Physical Measurements" Department of near-monochromatic optical radiation (F-2) 119361, Russia, Moscow, Ozernaia str., 46, tel: +7 495 437-34-47 fax: +7 495 437-34-47

2.3. Form of comparison

The comparison was carried out using two detector heads for measuring laser power. One detector head was supplied by PTB, and another detector head was supplied by VNIIOFI. The comparison took the form of the double sided type comparison. VNIIOFI calibrated the VNIIOFI detector head in December 2009 and then sent it to PTB. PTB calibrated both detector heads in December 2009 and then returned the package of both detectors to VNIIOFI. VNIIOFI calibrated both detector heads in May 2010 and then returned the PTB detector head to PTB. PTB recalibrated the PTB detector head in June 2010 to check the drift during the period.

Two detector heads were used: OPHIR 30A (PTB) and COHERENT PM10 (VNIIOFI).

Therefore, the consequence of the detectors measurements were the following:

For OPHIR 30A: PTB (Dec 2009) – VNIIOFI (May 2010) – PTB (Jun 2010)

For COHERENT PM10: VNIIOFI (Dec 2009) – PTB (Dec 2009) – VNIIOFI (May 2010)

PTB sent their measurement results to the pilot (VNIIOFI) in November 2010. VNIIOFI collected both measurement results and sent them to PTB. VNIIOFI as a pilot laboratory prepared the first version of the Draft A Report in October 2011.

3. Description of the artefacts

3.1. PTB Artefact

The PTB measurement artefact was a detector head of the OPHIR 30A type (Figure 1). The thermopile sensor of the detector has a series of bimetallic junctions. A temperature difference between any two junctions causes a voltage to be formed between the two junctions. Since the junctions are in series and the «hot» junctions are always on the inner, hotter side, and the «cold» junctions are on the outer, cooler side, radial heat flow on the disc causes a voltage proportional to the power input. Laser power impinges on the center of the thermopile sensor disk (on the reverse side of the thermopile), flows radically and is cooled on the periphery. The array of thermocouples measures the temperature gradient, which is proportional to the incident or absorbed power. In principle, the reading is not dependent on the ambient temperature since only the temperature difference affects the voltage generated and the voltage difference depends only on the heat flow, not on the ambient temperature. Since all the heat absorbed flows through the thermocouples (as long as the laser beam is inside the inner circle of hot junctions), the response of the detector is almost independent of beam size and position. If the beam is close to the edge of the inner circle, some thermocouples become hotter than others but since the sum of all of them is measured, the reading remains the same.

The detector was equipped with a posts and a post holder, as well as with a fixed cable with a 15-pin sub-D connector. The signal voltage was to be measured between the Pin 9 (+) and the Pin 1 (-). Connecting cables were provided by PTB.

OPHIR 30A specifications

CW & Single Pulse Measurements: 20mW – 30W, 6mJ – 30J

Recommended Use:	General Purpose
Special Features:	Fast response, wide dynamic range
Absorber:	Broadband, 0.19 – 20μm
Aperture:	18mm
Digital Power Scales:	30W / 3W
Maximum Average Power Density:	20KW / cm^2
Power Noise Level:	1mW
Response Time with Display (0 - 95 %):	0.8s
Linearity with Power:	±1 %
Energy Scales:	30J / 3J
Energy Threshold:	6mJ
Cooling:	Air Convection

Figure 1. Detector head of the OPHIR 30A.

3.2. VNIIOFI Artefact

The VNIIOFI measurement artefact was a detector head of the COHERENT PM10 type (Figure 2). The principle of work of the detector head PM10 is same as OPHIR 30A.The detector was equipped with a fixed cable with a 25-pin sub-D connector. The signal voltage was measured between the Pin 1 (+) and the Pin 14 (-).

COHERENT PM10 specifications

Wavelength Range:	0.19 – 11 μm
Max Power:	10 W
Max Intermittent Power (<5 min):	30 W
Resolution:	1 mW
Max Avg. Power Density:	26 kW/cm^2
Max Pulse Energy Density:	0.6 J/cm^2
Response Time:	2 sec
Detector Coating:	broadband
Detector Diameter:	19 mm
Probe Dimensions:	Ø 63 mm x 36 mm

Figure 2. Detector head of the COHERENT PM10 type.

4. Measurement at VNIIOFI

4.1. Primary standard

Figure 3 shows a block scheme of the National Primary standard GET 28-2009 of the unit of laser power used for the comparison.

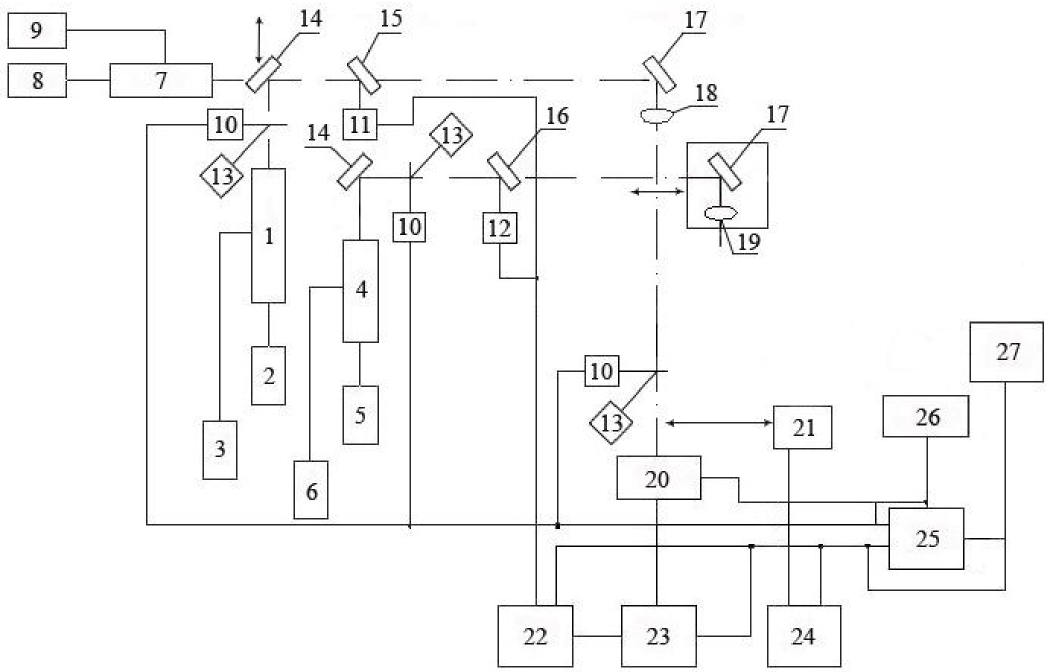

Figure.3. Block scheme of Primary standard of unit of laser power GET 28-2009.
1. Laser λ=0.532 μm; 2. Power module (λ=0.532 μm); 3. Chiller (λ=0.532 μm);
4. Laser λ=10.6 μm; 5. Power module (λ=10.6 μm); 6. Chiller (λ=10.6 μm);
7. Laser λ=1.064 μm; 8. Power module (λ=1,064 μm); 9. Chiller (λ=1.064 μm); 10. Shutter; 11. Monitor photo detector; 12. Monitor detector; 13. Beam trap; 14. Mirror; 15. Parallel-sided plate K-8; 16. Parallel-sided plate; 17. Mirror; 18. Lens K-8; 19. Lens AsGa; 20. Calorimeter PI-15; 21. Test detector; 22. Switching unit; 23. Multimeter Keithley 2002; 24. Multimeter Agilent 34420A; 25. Control module; 26. Module for electrical calibration; 27. Computer.

Tables 4.1 and 4.2 present the lasers used in the facility and the main specifications of the primary standard.

Table 4.1.Lasers are used in the Primary standard facility

Coherent Compass 1064 – 4000 M Diode – Pumped CW IR Laser (Nd: YAG)	
Wavelength	1064 nm
Power output	≤ 4 W
GL-10, “Plasma”, Russia CO_2 laser	
Wavelength	10.6 μm
Power output	≤ 10 W
Coherent Verdi™ V-8 Diode – Pumped Laser (Nd: YVO_4)	
Wavelength	532 nm
Power output	≤ 8 W

Table 4.2. The main specifications of the Primary standard GET 28-2009

Power range, W	$5 \cdot 10^{-3} \div 2.0$
Wavelengths, μm	0.532; 1.064; 10.6
Expanded uncertainty *U(k=2)* , %	0.1 (approximately)

The principle of laser power measurements is based on using a standard calorimeter with the method of substitution of optical power by electrical power. The standard calorimeter works on the calorimetric principle, which provides generation of a thermo-emf, which is proportional to the thermal current generated in a calorimeter head under the laser radiation.

The laser radiation hits a copper cone with a base diameter of 10 mm and with vertex angle of 15°. The surface of the cone is coated by paint with high absorption at the spectral range from 0.2 μm to 15 μm.

Figure 4 shows a scheme of the calorimeter.

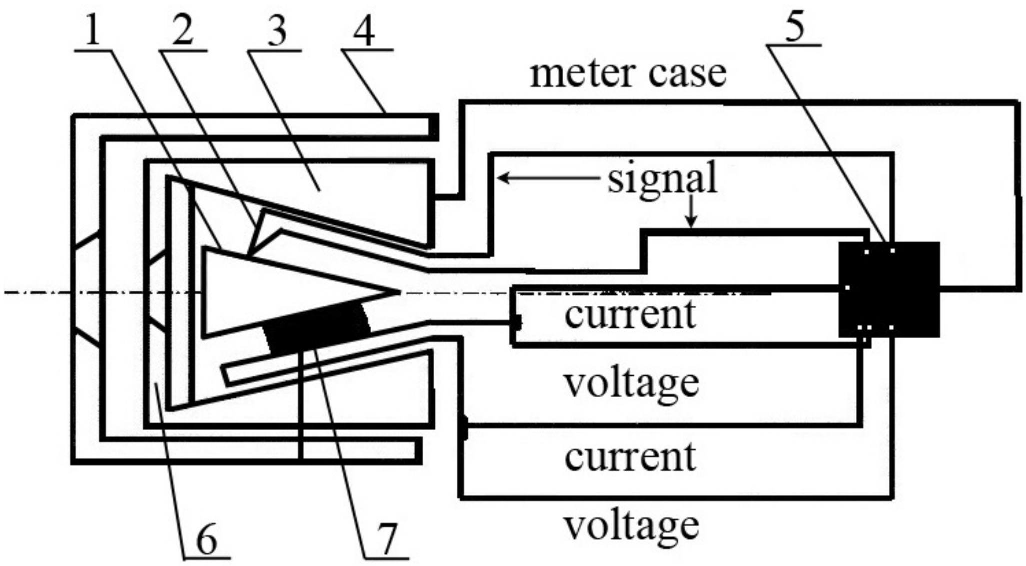

Figure 4. Scheme of calorimeter. 1 – receiving cone; 2 - thermobattery; 3 – internal passive thermostat; 4 – housing; 5. – connector PC-7; 6 – entrance aperture; 7 – winding.

4.2. Description of VNIIOFI measurement procedure

The comparison was carried out by means of calibration of two transfer detectors – the laser power meter heads: OPHIR 30A provided by PTB and COHERENT PM10 provided by VNIIOFI.

At VNIIOFI the transfer detectors were calibrated against the standard calorimeter PI-15 by means of alternate measuring of laser beam power using the Primary standard facility (Figure 3) described above. The calibration was done at three wavelengths: 0.532 μm, 1.064 μm and 10.6 μm.

To minimize an uncertainty associated the lasers stability monitor detectors used for monitoring a probable drift of the laser power during the calibration procedure. A silicon photodiode (marked as item 11 in Figure 3) was used as the monitor detector at the wavelengths of 0.532 μm and 1.064 μm. At the wavelength of 10.6 μm the monitor was a thermo detector of the COHERENT PM3 type (marked as item 12 in Figure 3).

The measurement procedure was identical at every wavelength and is illustrated by a time diagram shown in Figure 5.

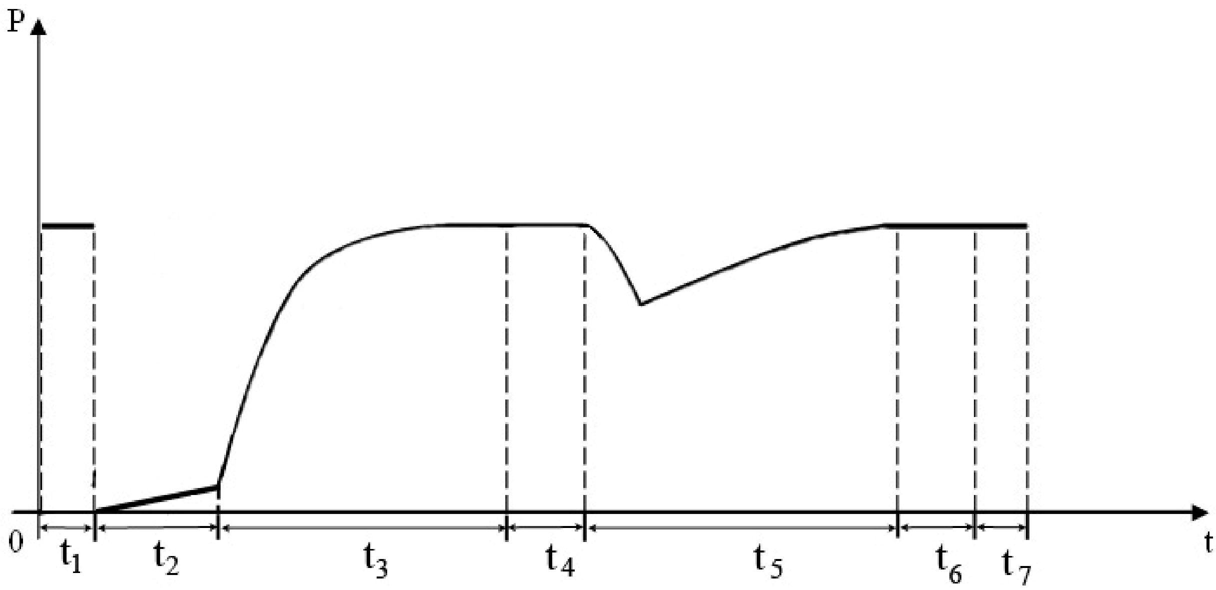

Figure 5. Time diagram of measurements.

Figure 5 shows time diagram of measurements step by step: t_1 – evaluation of optical power by a monitor detector; t_2 – measurement of the zero level and drift by the colorimeter PI-15 (device 15 in Figure 3); t_3 – electrical substituting of the calorimeter; t_4 – measurement of the electrical substitution power by the colorimeter (U, I, S); t_5 –exposure of the calorimeter with a laser beam; t_6 – measurement of the laser power by the colorimeter and monitoring of the laser power stability using a monitor detector during the calibration measurements; t_7 – measurement of signals of the transfer detector and monitoring of the laser power stability.

The exposure time was at least 45 s for the OPHIR 30A detector and at least 30 s for the COHERENT PM10 detector before the detector voltage is reading. The offset voltage was also measured and subtracted.

The spectral responsivity of the detector is determined as a ratio of the output voltage of the transfer detector to the laser power measured by the calorimeter PI-15.

The calibration measurement was performed 5 times for each transfer detector following the VNIIOFI normal procedure of calibration. The mean value and the standard deviations of the measurements are calculated.

The measurement was performed automatically by computer controlled system.

Equation of measured spectral responsivity:

$s = \dfrac{U - U_0}{P_{st}}$; *U* – voltage (transfer standard readings); U_0 – offset voltage (transfer standard readings), P_{st} – power measured by the calorimeter PI-15.

4.3. Laboratory conditions

The laboratory temperature and humidity during the calibration were (21±1) °C and (60±20)%, respectively. The transfer detectors were kept at the laboratory conditions for more than one day before calibration.

4.4. Results of VNIIOFI measurements

4.4.1. VNIIOFI measurement of OPHIR 30A.

Table 4.3.Results of VNIIOFI measurement of OPHIR 30A (May 2010)

Laser	λ, μm	Power, W	Beam diam. mm	T ºC	N of Meas	*Respon sivity* *s*, mV/W	Standard unc. u(s),		k	Expanded unc. U(s),	
							%	mV/W		%	mV/W
Nd: YVO_4	0.532	0.96794	6	22.3	5	1.50698	0,202	0,0030	2,16	0,437	0,0066
Nd: YAG	1.064	0.98957	2	22.1	5	1.45652	0,114	0,0017	2,032	0,233	0,0034
CO_2	10.6	0.95398	6	22.4	5	1.54974	0,273	0,0042	2,201	0,601	0,0093

4.4.2. VNIIOFI measurement of COHERENT PM10

Table 4.4. Results of VNIIOFI 1-st measurement of COHERENT PM10 (December 2009)

Laser	λ, μm	Power, W	Beam diam. mm	T ºC	N of Meas	*Respon sivity* *s*, mV/W	Standard unc. u(s),		k	Expanded unc. U(s),	
							%	mV/W		%	mV/W
Nd: YVO_4	0.532	0.94775	6	19.8	5	1,70696	0,235	0,0040	2,179	0,512	0,0087
Nd: YAG	1.064	0.97287	2	19.6	5	1,67174	0,157	0,0026	2,12	0,333	0,0056
CO_2	10.6	0.91776	6	19.7	5	1.79004	1,324	0,0237	2,262	2,996	0,0536

Table 4.5. Results of VNIIOFI 2-nd measurement of COHERENT PM10 (May 2010)

Laser	λ, μm	Power, W	Beam diam. mm	T ºC	N of Meas	*Respon sivity* *s*, mV/W	Standard unc. u(s),		k	Expanded unc. U(s),	
							%	mV/W		%	mV/W
Nd: YVO_4	0.532	0.96794	6	22.3	5	1.71367	0,208	0,0036	2,179	0,453	0,0078
Nd: YAG	1.064	0.98957	2	22.1	5	1.6676	0,116	0,0019	2,032	0,236	0,0039
CO_2	10.6	0.95398	6	22.4	5	1.79132	0,450	0,0081	2,228	1,003	0,0180

4.4.3. Uncertainty budget

Table 4.6. Uncertainty of standard calorimeter PI-15:

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Voltage measurement on winding of the standard	∞	B	uniform	0.041
2	Voltage measurement on resistor of the standard	∞	B	uniform	0.029
3	Voltage measurement on thermobattery	∞	B	uniform	0.005
4	Absorption of the standard calorimeter	∞	B	uniform	0.017
5	Determination of the coefficient of equivalence of heat loss of the standard	∞	B	uniform	0.049
6	The correction of the temperature dependence of the standard	∞	B	uniform	0.017
7	The temperature dependence of the thermal source distribution	∞	B	uniform	0.029
	Type B total uncertainty	0.08			

Table 4.7. Uncertainty budget of VNIIOFI measurement of OPHIR 30A at wavelength 0.532 μm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.015
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.181
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.04
	Type A total uncertainty	0.186			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.202			
	Effective degrees of freedom	13			
	Expanded uncertainty (k = 2.16)	0.437			

Table 4.8. Uncertainty budget of VNIIOFI measurement of OPHIR 30A at wavelength 1.064 μm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.011
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.064
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.05
	Type A total uncertainty	0.082			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0,114			
	Effective degrees of freedom	34			
	Expanded uncertainty (k = 2.032)	0.233			

Table 4.9. Uncertainty budget of VNIIOFI measurement of OPHIR 30A at wavelength 10.6 μm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.021
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.231
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.12
	Type A total uncertainty	0,261			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.273			
	Effective degrees of freedom	11			
	Expanded uncertainty (k = 2.201)	0.601			

Table 4.10. Uncertainty budget of VNIIOFI 1-st measurement of COHERENT PM10 at wavelength 0.532 μm (Dec 2009)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.016
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.210
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.07
	Type A total uncertainty	0,221			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.235			
	Effective degrees of freedom	12			
	Expanded uncertainty (k = 2.179)	0.512			

Table 4.11. Uncertainty budget of VNIIOFI 1-st measurement of COHERENT PM10 at wavelength 1.064 μm (Dec 2009)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.012
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.09
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.10
	Type A total uncertainty	0,135			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.157			
	Effective degrees of freedom	16			
	Expanded uncertainty (k = 2.12)	0.333			

Table 4.12. Uncertainty budget of VNIIOFI 1-st measurement of COHERENT PM10 at wavelength 10.6 μm (Dec 2009)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.068
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	1.314
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.13
	Type A total uncertainty	1,322			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	1.324			
	Effective degrees of freedom	9			
	Expanded uncertainty (k = 2.262)	2.996			

Table 4.13. Uncertainty budget of VNIIOFI 2-nd measurement of COHERENT PM10 at wavelength 0.532 μm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.011
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.182
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.06
	Type A total uncertainty	0,192			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.208			
	Effective degrees of freedom	12			
	Expanded uncertainty (k = 2.179)	0.453			

Table 4.14. Uncertainty budget of VNIIOFI 2-nd measurement of COHERENT PM10 at wavelength 1.064 µm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.009
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.066
3	Calibration of voltmeter	∞	B	uniform	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.051
	Type A total uncertainty	0,084			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.116			
	Effective degrees of freedom	33			
	Expanded uncertainty (k = 2.032)	0.236			

Table 4.15. Uncertainty budget of VNIIOFI 2-nd measurement of COHERENT PM10 at wavelength 10.6 µm (May 2010)

№	Uncertainty source	Degree of freedom	Type	Probability distribution	Standard uncertainty (%)
1	Repeatability of standard calorimeter readings	4	A	normal	0.028
2	Repeatability of transfer standard readings (incl. zone nonuniform, laser stability, drift)	4	A	normal	0.432
3	Calibration of voltmeter	∞	B	normal	0.01
4	Repeatability of monitor detector readings	4	A	normal	0.093
	Type A total uncertainty	0,443			
	Type B total uncertainty	0.08			
	Combined standard uncertainty	0.450			
	Effective degrees of freedom	10			
	Expanded uncertainty (k = 2.228)	1.003			

5. Measurement at PTB

5.1. Description of the measurement facility and primary scale

Primary standard: Cryogenic radiometer
Transfer standard: Si-Trap-detector
Standard detector for laser radiometry: LM7 thermal cone detector. The last recalibration of LM7 was performed in May 2007

Traceability chain of laser radiometry at PTB is illustrated in Figure 6. The measurement facility is shown in Figures 7-9.

Uncertainty estimation was based on the PTB Quality management system, work instruction ("Arbeitsanweisung") "QM-AA-4.13K-Ar-Kr-HeNe", Version 3 from August 2005. Uncertainty tables are attached.

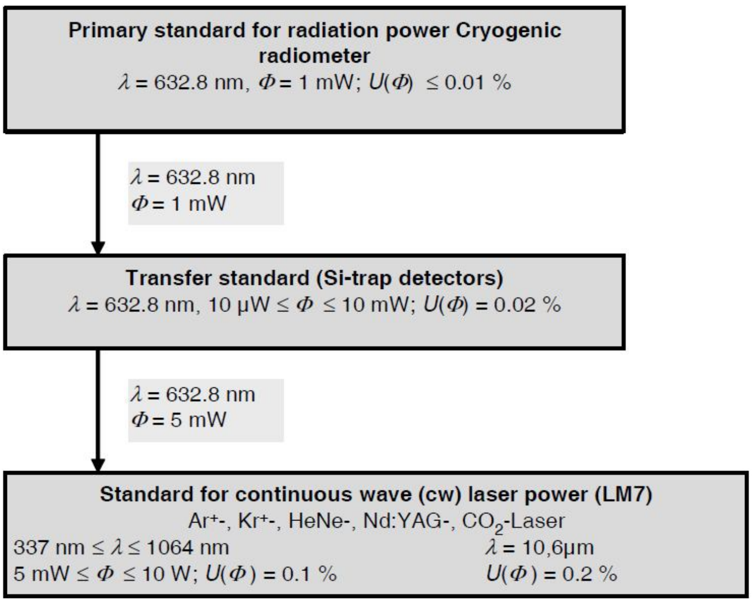

Figure 6. Traceability chain of laser radiometry at PTB

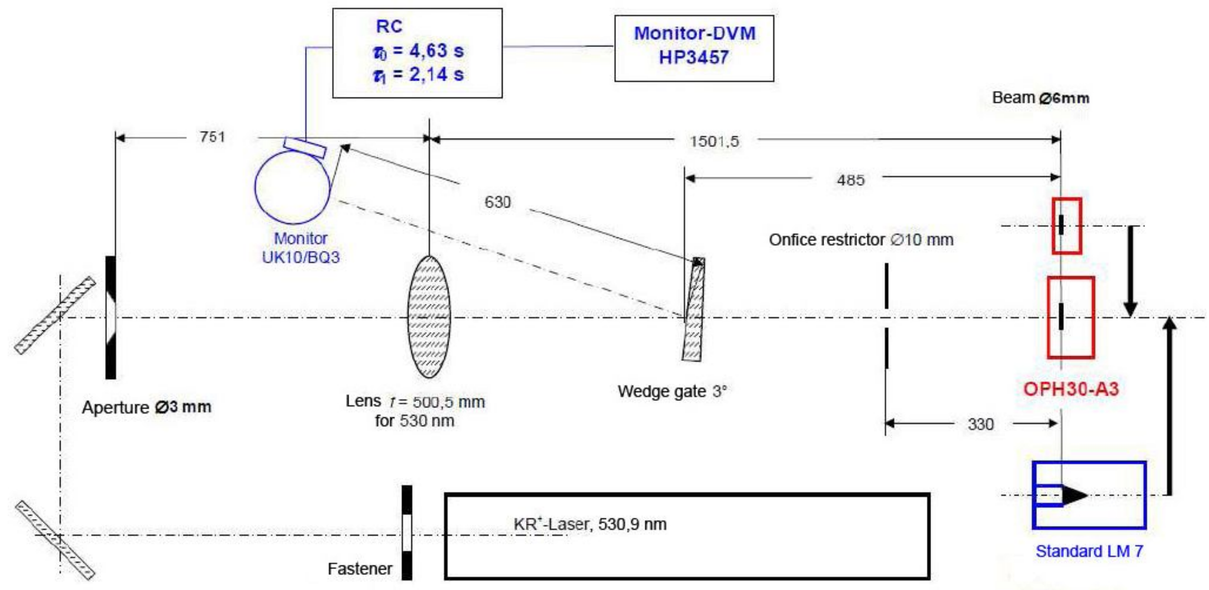

Figure 7. Setup for the calibration of the COHERENT PM10 and OPHIR 30A detectors at 530.9 nm

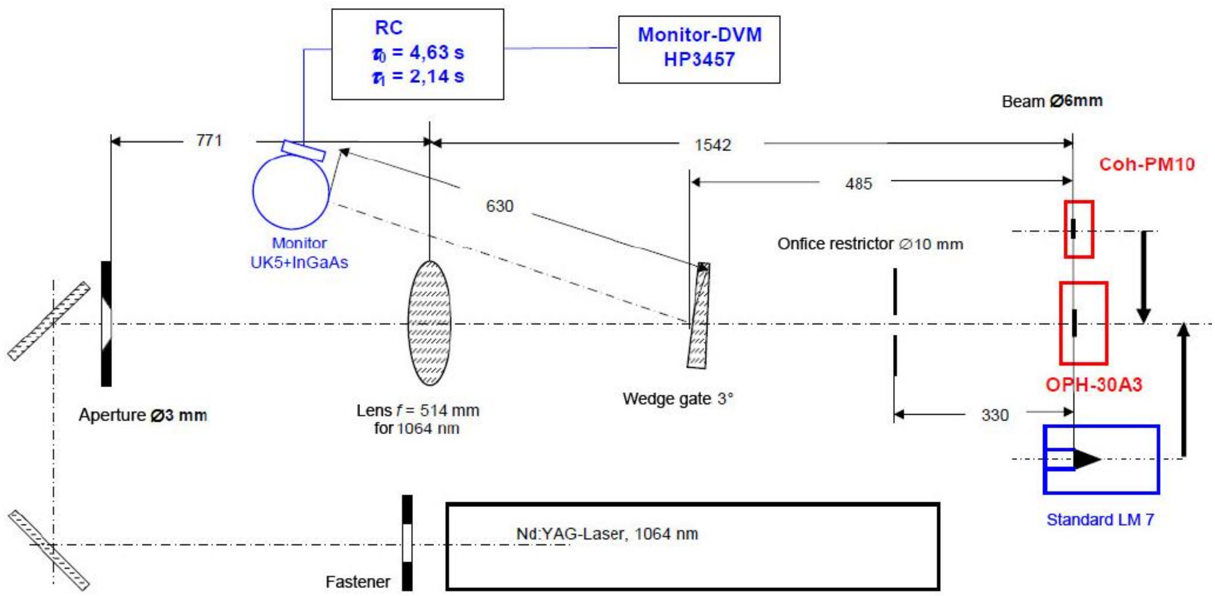

Figure 8. Setup for the calibration of the COHERENT PM10 and OPHIR 30A detectors at 1064 nm

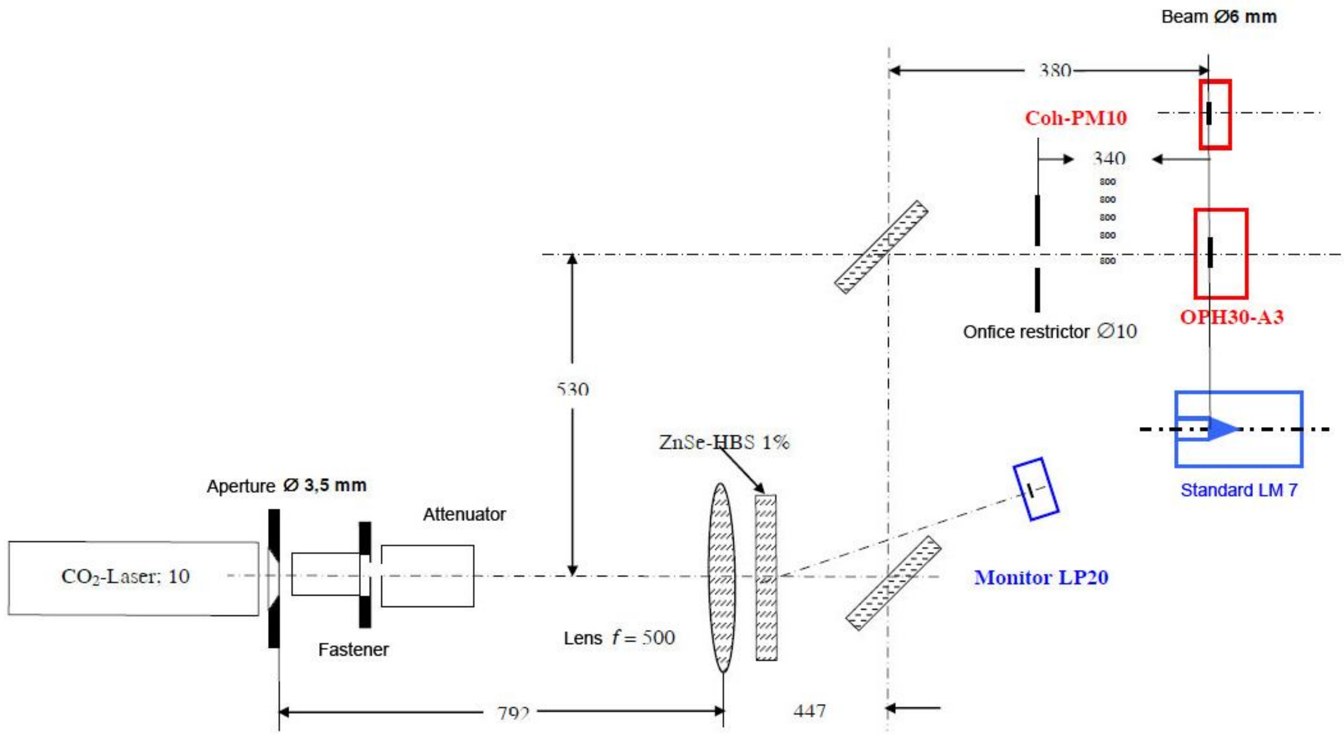

Figure 9. Setup for the calibration of the COHERENT PM10 and OPHIR 30A detectors at 10.6 µm

5.2. Results of PTB measurements

5.2.1. PTB measurement of the COHERENT PM10.

Table 5.1. Results of the measurements of the COHERENT PM10 detector at PTB, December 2009

λ, µm	Power, W	*s*, mV/W	u(s), %	u(s), mV/W	k	U(s), %	U(s), mV/W
0.5309	1.0	1.7120	0.12	0.0020	2.1	0.24	0.0041
1.064	1.0	1.6781	0.15	0.0025	2.4	0.35	0.0059
10.6	1.0	1.7915	0.12	0.0022	2.0	0.24	0.0043

5.2.2. PTB measurement of the OPHIR 30A.

Table 5.2. Results of the measurements of the OPHIR 30A detector at PTB, December 2009

λ, µm	Power, W	*s*, mV/W	u(s)	u(s), mV/W	k	U(s)	U(s), mV/W
0.5309	1.0	1.5015	0.09 %	0.0013	2.0	0.17 %	0.0026
1.064	1.0	1.4653	0.09 %	0.0013	2.0	0.17 %	0.0025
10.6	1.0	1.5546	0.14 %	0.0021	2.0	0.27 %	0.0042

Table 5.3. Results of the measurements of the OPHIR 30A detector at PTB, June 2010

λ, μm	Power, W	*s*, mV/W	u(s)	u(s), mV/W	k	U(s)	U(s), mV/W
0.5309	1.0	1.5025	0.09 %	0.0013	2.0	0.17 %	0.0026
1.064	1.0	1.4659	0.09 %	0.0013	2.0	0.17 %	0.0025
10.6	1.0	1.5568	0.18 %	0.0028	2.1	0.38 %	0.0059

5.2.3. Uncertainty budget

Table 5.4. Description of uncertaintu budget

Quantity	Type	Unit	Definition
s_k	Result	mV/W	corrected spectral responsivity
s_{Pr}	A	mV/W	measured spectral responsivity
F_{VN}	B		factor for the voltage measurement of the standard LM 7
F_{VPr}	B		factor for the voltage measurement of detector
F_{s0}	A		factor for the normalized spectral responsivity of the standard LM 7
F_k	A		factor for the correction factor of the standard LM 7
F_α	B		factor for the absorption of the standard LM 7
F_H	B		factor of the inhomogeneity of the standard LM 7
F_S	B		factor for stray light
$F_{\beta T\phi}$	B		factor for the correction of the temperature dependence of the standard LM 7

Model Equation:

$s_k=s_{Pr}*F_{s0}*F_{VN}*F_{VPr}*F_\alpha*F_k*F_H*F_S*F_{\beta T\phi}$;

Table 5.5. Uncertainty budget of PTB measurement of COHERENT PM10 at wavelength 530.9 nm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.71202 mV/W	0.0736 %	4	1.0	$1.3\cdot10^{-3}$ mV/W	43.5 %
F_{VN}	1.000000	0.0231 %	infinity	1.7	$400\cdot10^{-6}$ mV/W	4.3 %
F_{VPr}	1.000000	0.0231 %	infinity	1.7	$400\cdot10^{-6}$ mV/W	4.3 %
F_{s0}	1.000000	0.0420 %	49	1.7	$720\cdot10^{-6}$ mV/W	14.2 %
F_k	1.000000	0.0600 %	130	1.7	$1.0\cdot10^{-3}$ mV/W	28.9 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.7	$120\cdot10^{-6}$ mV/W	0.4 %
F_H	1.000000	0.0144 %	infinity	1.7	$250\cdot10^{-6}$ mV/W	1.7 %
F_S	1.000000	0.0144 %	infinity	1.7	$250\cdot10^{-6}$ mV/W	1.7 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.7	$200\cdot10^{-6}$ mV/W	1.1 %
s_k	1.7120 mV/W	0.112 %	20			

Result: Quantity: s_k
Value: 1.7120 mV/W
Relative Expanded Uncertainty: 0.24 %
Coverage Factor: 2.1
Coverage: t-table 95%

Table 5.6. Uncertainty budget of PTB measurement of COHERENT PM10 at wavelength 1064 nm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.67813 mV/W	0.120 %	4	1.0	$2.0\cdot10^{-3}$ mV/W	67.3 %
F_{VN}	1.000000	0.0231 %	infinity	1.7	$390\cdot10^{-6}$ mV/W	2.5 %
F_{VPr}	1.000000	0.0231 %	infinity	1.7	$390\cdot10^{-6}$ mV/W	2.5 %
F_{s0}	1.000000	0.0420 %	49	1.7	$700\cdot10^{-6}$ mV/W	8.2 %
F_k	1.000000	0.0600 %	130	1.7	$1.0\cdot10^{-3}$ mV/W	16.7 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.7	$120\cdot10^{-6}$ mV/W	0.2 %
F_H	1.000000	0.0144 %	infinity	1.7	$240\cdot10^{-6}$ mV/W	1.0 %
F_S	1.000000	0.0144 %	infinity	1.7	$240\cdot10^{-6}$ mV/W	1.0 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.7	$190\cdot10^{-6}$ mV/W	0.6 %
s_k	1.6781 mV/W	0.147 %	8			

Result: Quantity: s_k
Value: 1.6781 mV/W
Relative Expanded Uncertainty: 0.35 %
Coverage Factor: 2.4
Coverage: t-table 95%

Table 5.7. Uncertainty budget of PTB measurement of COHERENT PM10 at wavelength 10.6 µm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.791530 mV/W	0.0458 %	3	1.0	$820\cdot10^{-6}$ mV/W	14.1 %
F_{VN}	1.000000	0.0231 %	infinity	1.8	$410\cdot10^{-6}$ mV/W	3.6 %
F_{VPr}	1.000000	0.0289 %	infinity	1.8	$520\cdot10^{-6}$ mV/W	5.6 %
F_{s0}	1.000000	0.0420 %	49	1.8	$750\cdot10^{-6}$ mV/W	11.8 %
F_k	1.000000	0.0600 %	130	1.8	$1.1\cdot10^{-3}$ mV/W	24.1 %
F_α	1.000000	0.0491 %	infinity	1.8	$880\cdot10^{-6}$ mV/W	16.2 %
F_H	1.000000	0.0577 %	infinity	1.8	$1.0\cdot10^{-3}$ mV/W	22.4 %
F_S	1.000000	0.0144 %	infinity	1.8	$260\cdot10^{-6}$ mV/W	1.4 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.8	$210\cdot10^{-6}$ mV/W	0.9 %
s_k	1.7915 mV/W	0.122 %	140			

Result: Quantity: s_k
Value: 1.7915 mV/W
Relative Expanded Uncertainty: 0.24 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.8. Uncertainty budget of PTB 1-st measurement of OPHIR 30A at wavelength 530,9 nm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.501490 mV/W	8.6610^{-3} %	3	1.0	$130 \cdot 10^{-6}$ mV/W	1.1 %
F_{VN}	1.000000	0.0231 %	infinity	1.5	$350 \cdot 10^{-6}$ mV/W	7.5 %
F_{VPr}	1.000000	0.0231 %	infinity	1.5	$350 \cdot 10^{-6}$ mV/W	7.5 %
F_{s0}	1.000000	0.0420 %	49	1.5	$630 \cdot 10^{-6}$ mV/W	24.8 %
F_k	1.000000	0.0600 %	130	1.5	$900 \cdot 10^{-6}$ mV/W	50.7 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.5	$100 \cdot 10^{-6}$ mV/W	0.7 %
F_H	1.000000	0.0144 %	infinity	1.5	$220 \cdot 10^{-6}$ mV/W	2.9 %
F_S	1.000000	0.0144 %	infinity	1.5	$220 \cdot 10^{-6}$ mV/W	2.9 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.5	$170 \cdot 10^{-6}$ mV/W	1.9 %
s_k	1.5015 mV/W	0.0843 %	310			

Result: Quantity: s_k
Value: 1.5015 mV/W
Relative Expanded Uncertainty: 0.17 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.9. Uncertainty budget of PTB 1-st measurement of OPHIR 30A at wavelength 1064 nm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.465320 mV/W	0.0157 %	3	1.0	$230 \cdot 10^{-6}$ mV/W	3.4 %
F_{VN}	1.000000	0.0231 %	infinity	1.5	$340 \cdot 10^{-6}$ mV/W	7.3 %
F_{VPr}	1.000000	0.0231 %	infinity	1.5	$340 \cdot 10^{-6}$ mV/W	7.3 %
F_{s0}	1.000000	0.0420 %	49	1.5	$620 \cdot 10^{-6}$ mV/W	24.2 %
F_k	1.000000	0.0600 %	130	1.5	$880 \cdot 10^{-6}$ mV/W	49.5 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.5	$100 \cdot 10^{-6}$ mV/W	0.7 %
F_H	1.000000	0.0144 %	infinity	1.5	$210 \cdot 10^{-6}$ mV/W	2.9 %
F_S	1.000000	0.0144 %	infinity	1.5	$210 \cdot 10^{-6}$ mV/W	2.9 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.5	$170 \cdot 10^{-6}$ mV/W	1.8 %
s_k	1.4653 mV/W	0.0853 %	290			

Result: Quantity: s_k
Value: 1.4653 mV/W
Relative Expanded Uncertainty: 0.17 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.10. Uncertainty budget of PTB 1-st measurement of OPHIR 30A at wavelength 10.6 μm at 1 W (Date: December 2009)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.55456 mV/W	0.0798 %	6	1.0	$1.2\cdot10^{-3}$ mV/W	33.7 %
F_{VN}	1.000000	0.0231 %	infinity	1.6	$360\cdot10^{-6}$ mV/W	2.8 %
F_{VPr}	1.000000	0.0231 %	infinity	1.6	$360\cdot10^{-6}$ mV/W	2.8 %
F_{s0}	1.000000	0.0420 %	49	1.6	$650\cdot10^{-6}$ mV/W	9.3 %
F_k	1.000000	0.0600 %	130	1.6	$930\cdot10^{-6}$ mV/W	19.1 %
F_α	1.000000	0.0491 %	infinity	1.6	$760\cdot10^{-6}$ mV/W	12.8 %
F_H	1.000000	0.0577 %	infinity	1.6	$900\cdot10^{-6}$ mV/W	17.7 %
F_S	1.000000	0.0144 %	infinity	1.6	$220\cdot10^{-6}$ mV/W	1.1 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.6	$180\cdot10^{-6}$ mV/W	0.7 %
s_k	1.5546 mV/W	0.137 %	51			

Result: Quantity: s_k
Value: 1.5546 mV/W
Relative Expanded Uncertainty: 0.27 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.11. Uncertainty budget of PTB 2-nd measurement of OPHIR 30A at wavelength 530.9 nm at 1 W (Date: June 2010)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.502510 mV/W	0.0106 %	3	1.0	$160\cdot10^{-6}$ mV/W	1.5 %
F_{VN}	1.000000	0.0173 %	infinity	1.5	$260\cdot10^{-6}$ mV/W	4.0 %
F_{VPr}	1.000000	0.0173 %	infinity	1.5	$260\cdot10^{-6}$ mV/W	4.0 %
F_{s0}	1.000000	0.0500 %	66	1.5	$750\cdot10^{-6}$ mV/W	33.7 %
F_k	1.000000	0.0600 %	130	1.5	$900\cdot10^{-6}$ mV/W	48.6 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.5	$100\cdot10^{-6}$ mV/W	0.6 %
F_H	1.000000	0.0144 %	infinity	1.5	$220\cdot10^{-6}$ mV/W	2.8 %
F_S	1.000000	0.0144 %	infinity	1.5	$220\cdot10^{-6}$ mV/W	2.8 %
$F_{\beta T\phi}$	1.000000	0.0115 %	infinity	1.5	$170\cdot10^{-6}$ mV/W	1.8 %
s_k	1.5025 mV/W	0.0861 %	280			

Result: Quantity: s_k
Value: 1.5025 mV/W
Relative Expanded Uncertainty: 0.17 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.12. Uncertainty budget of PTB 2-nd measurement of OPHIR 30A at wavelength 1064 nm at 1 W (Date: June 2010)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.465910 mV/W	0.0123 %	3	1.0	$180 \cdot 10^{-6}$ mV/W	2.0 %
F_{VN}	1.000000	0.0173 %	infinity	1.5	$250 \cdot 10^{-6}$ mV/W	4.0 %
F_{VPr}	1.000000	0.0173 %	infinity	1.5	$250 \cdot 10^{-6}$ mV/W	4.0 %
F_{s0}	1.000000	0.0500 %	66	1.5	$730 \cdot 10^{-6}$ mV/W	33.6 %
F_k	1.000000	0.0600 %	130	1.5	$880 \cdot 10^{-6}$ mV/W	48.3 %
F_α	1.0000000	6.9310^{-3} %	infinity	1.5	$100 \cdot 10^{-6}$ mV/W	0.6 %
F_H	1.000000	0.0144 %	infinity	1.5	$210 \cdot 10^{-6}$ mV/W	2.8 %
F_S	1.000000	0.0144 %	infinity	1.5	$210 \cdot 10^{-6}$ mV/W	2.8 %
$F_{\beta T \phi}$	1.000000	0.0115 %	infinity	1.5	$170 \cdot 10^{-6}$ mV/W	1.8 %
s_k	1.4659 mV/W	0.0863 %	270			

Result: Quantity: s_k
Value: 1.4659 mV/W
Relative Expanded Uncertainty: 0.17 %
Coverage Factor: 2.0
Coverage: t-table 95%

Table 5.13. Uncertainty budget of PTB 2-nd measurement of OPHIR 30A at wavelength 10.6 μm at 1 W (Date: June 2010)

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
s_{Pr}	1.55684 mV/W	0.136 %	7	1.0	$2.1 \cdot 10^{-3}$ mV/W	57.8 %
F_{VN}	1.000000	0.0173 %	infinity	1.6	$270 \cdot 10^{-6}$ mV/W	0.9 %
F_{VPr}	1.000000	0.0173 %	infinity	1.6	$270 \cdot 10^{-6}$ mV/W	0.9 %
F_{s0}	1.000000	0.0500 %	66	1.6	$780 \cdot 10^{-6}$ mV/W	7.9 %
F_k	1.000000	0.0600 %	130	1.6	$930 \cdot 10^{-6}$ mV/W	11.3 %
F_α	1.000000	0.0491 %	infinity	1.6	$760 \cdot 10^{-6}$ mV/W	7.6 %
F_H	1.000000	0.0577 %	infinity	1.6	$900 \cdot 10^{-6}$ mV/W	10.5 %
F_S	1.000000	0.0289 %	infinity	1.6	$450 \cdot 10^{-6}$ mV/W	2.6 %
$F_{\beta T \phi}$	1.000000	0.0115 %	infinity	1.6	$180 \cdot 10^{-6}$ mV/W	0.4 %
s_k	1.5568 mV/W	0.178 %	20			

Result: Quantity: s_k
Value: 1.5568 mV/W
Relative Expanded Uncertainty: 0.38 %
Coverage Factor: 2.1
Coverage: t-table 95%

6. Results

6.1. Summary of participants measurements results

Summary of participants measurements results are presented in Tables 6.1 and 6.2.

Table 6.1. Results of participants measurements for OPHIR 30A

N	Date and Place	*λ*, µm	*s*, mV/W	Coverage factor *k*	Standard uncertainty, %	Relative Expanded Uncertainty, %
1	**December 2009 PTB**	**0,5309**	**1,5015**	**2,0**	**0.09**	**0,17**
2	*May 2010 VNIIOFI*	*0,532*	*1,5070*	*2,2*	*0.20*	*0,44*
3	**June 2010 PTB**	**0,5309**	**1,5025**	**2,0**	**0.09**	**0,17**
4	**December 2009 PTB**	**1,064**	**1,4653**	**2,0**	**0.09**	**0,17**
5	*May 2010 VNIIOFI*	*1,064*	*1,4565*	*2,0*	*0.11*	*0,23*
6	**June 2010 PTB**	**1,064**	**1,4659**	**2,0**	**0.09**	**0,17**
7	**December 2009 PTB**	**10,6**	**1,5546**	**2,0**	**0.14**	**0,27**
8	*May 2010 VNIIOFI*	*10,6*	*1,5498*	*2,2*	*0.27*	*0,60*
9	**June 2010 PTB**	**10,6**	**1,5568**	**2,1**	**0.18**	**0,38**

Table 6.2. Results of participants measurements for COHERENT PM10

N	Date and Place	*λ*, µm	*s*, mV/W	Expansion factor *k*	Standard uncertainty, %	Relative Expanded Uncertainty, %
1	**December 2009 VNIIOFI**	**0,532**	**1,7070**	**2,2**	**0.24**	**0,51**
2	*December 2009 PTB*	*0,5309*	*1,7120*	*2,1*	*0.12*	*0,16*
3	**May 2010 VNIIOFI**	**0,532**	**1,7137**	**2,2**	**0.21**	**0,45**
4	**December 2009 VNIIOFI**	**1,064**	**1,6717**	**2,1**	**0.16**	**0,33**
5	*December 2009 PTB*	*1,064*	*1,6781*	*2,4*	*0.15*	*0,35*
6	**May 2010 VNIIOFI**	**1,064**	**1,6676**	**2,0**	**0.12**	**0,24**
7	**December 2009 VNIIOFI**	**10,6**	**1,7900**	**2,3**	**1.32**	**3,00**
8	*December 2009 PTB*	*10,6*	*1,7915*	*2,0*	*0.12*	*0,24*
9	**May 2010 VNIIOFI**	**10,6**	**1,7913**	**2,2**	**0.45**	**1,00**

6.2. Comparison results

The comparison results are evaluated separately for each detector and wavelength as the relative difference between VNIIOFI and PTB measurements:

$$\Delta_{VNIIOFI-PTB} = \frac{s_{VNIIOFI} - s_{PTB}}{s_{PTB}} \quad (6.1)$$

where $S_{VNIIOFI}$ and S_{PTB} are detector responcivities measured by VNIIOFI and PTB, respectively.
For COHERENT PM10 the $S_{VNIIOFI}$ values are calculated as an average between the first (Dec 2009) and the second (May 2010) VNIIOFI measurements:

$$s_{VNIIOFI} = \frac{s^1_{VNIIOFI} + s^2_{VNIIOFI}}{2} \tag{6.2}$$

For OPHIR 30A the S_{PTB} values are calculated as an average between the first (Dec 2009) and the second (Jun 2010) PTB measurements:

$$s_{PTB} = \frac{s^1_{PTB} + s^2_{PTB}}{2} \tag{6.3}$$

The standard uncertainties $u_{VNIIOFI\text{-}PTB}$ of the differences $\Delta_{VNIIOFI\text{-}PTB}$ are evaluated as

$$u_{VNIIOFI-PTB} = \sqrt{u^2_{VNIIOFI} + u^2_{PTB} + u^2_{tr}} \tag{6.4}$$

where $u_{vniiofi}$ and u_{ptb} are combined standard uncertainties declared by VNIIOFI and PTB, respectively (see Tables 6.1 and 6.2), and u_{tr} is a standard uncertainty associated with instability of the transfer detector during transportation.

For COHERENT PM10 the $u_{vniiofi}$ uncertainnty is calculated as an average between the standard uncertainties estimated by VNIIOFI for its first (Dec 2009) and second (May 2010) measurements:

$$u_{VNIIOFI} = \frac{u^1_{VNIIOFI} + u^2_{VNIIOFI}}{2} \tag{6.5}$$

For OPHIR 30A the u_{PTB} uncertainty is calculated as an average between standard uncertainties estimated by PTB for its first (Dec 2009) and second (Jun 2010) measurements:

$$u_{PTB} = \frac{u^1_{PTB} + u^2_{PTB}}{2} \tag{6.6}$$

The (relative) standard uncertainty, associated with stability of the transfer detector during transportation is calculated as:

$$u_{tr} = \frac{|\Delta_{rel}|}{2 \cdot \sqrt{3}} \tag{6.7}$$

where $\Delta_{rel} = \frac{(s_{after} - s_{before})}{s_{before}}$ - the relative change in the responsivity of detector head after and before travel.
Results of calculations of u_{tr} are presented in Tables 6.3 and 6.4.

Table 6.3. Results of calculation of u_{tr} for OPHIR 30A

λ, µm	**0,5309 / 0,532**	**1,064**	**10,6**
Δ_{rel}	0,07 %	0,04 %	0,14 %
u_{tr}	0,02 %	0,01 %	0,04 %

Table 6.4. Results of calculation of u_{tr} for COHERENT PM10

λ, µm	**0,5309 / 0,532**	**1,064**	**10,6**
Δ_{rel}	0,39 %	0,25 %	0,07 %
u_{tr}	0,11 %	0,07 %	0,02 %

Results of calculations of the standard uncertainties $u_{VNIIOFI\text{-}PTB}$ of the differences $\Delta_{VNIIOFI\text{-}PTB}$ are presented in Tables 6.5 and 6.6.

Table 6.5. Results of calculation of the standard uncertainty $u_{VNIIOFI\text{-}PTB}$ for OPHIR 30A

λ, µm	0,5309 / 0,532	1,064	10,6
$\Delta_{VNIIOFI\text{-}PTB}$	0,33 %	-0,62 %	-0,38 %
$u_{VNIIOFI}$	0.20 %	0.11 %	0.27 %
u_{PTB}	0.09 %	0.09 %	0,16 %
u_{tr}	0,02 %	0,01 %	0,04 %
Relative combined standard uncertainties of the comparison $u_{VNIIOFI\text{-}PTB}$	0,22 %	0,14 %	0,32 %

Table 6.6. Results of calculation of the standard uncertainty $u_{VNIIOFI\text{-}PTB}$ for COHERENT PM10

λ, µm	**0,5309 / 0,532**	**1,064**	**10,6**
$\Delta_{VNIIOFI\text{-}PTB}$	-0,10 %	-0,50 %	-0,05 %
$u_{VNIIOFI}$	0,22 %	0,14 %	0,89 %
u_{PTB}	0,12 %	0,15 %	0,12 %
u_{tr}	0,11 %	0,07 %	0,02 %
Relative combined standard uncertainties of the comparison $u_{VNIIOFI\text{-}PTB}$	0,27 %	0,22 %	0,90 %

The relative differences of the comparison are shown in Figures 10-11. The short horizontal lines near points shows relative differences of standard uncertainties, the short horizontal lines across the differences shows relative differences of expanded standard uncertainties.

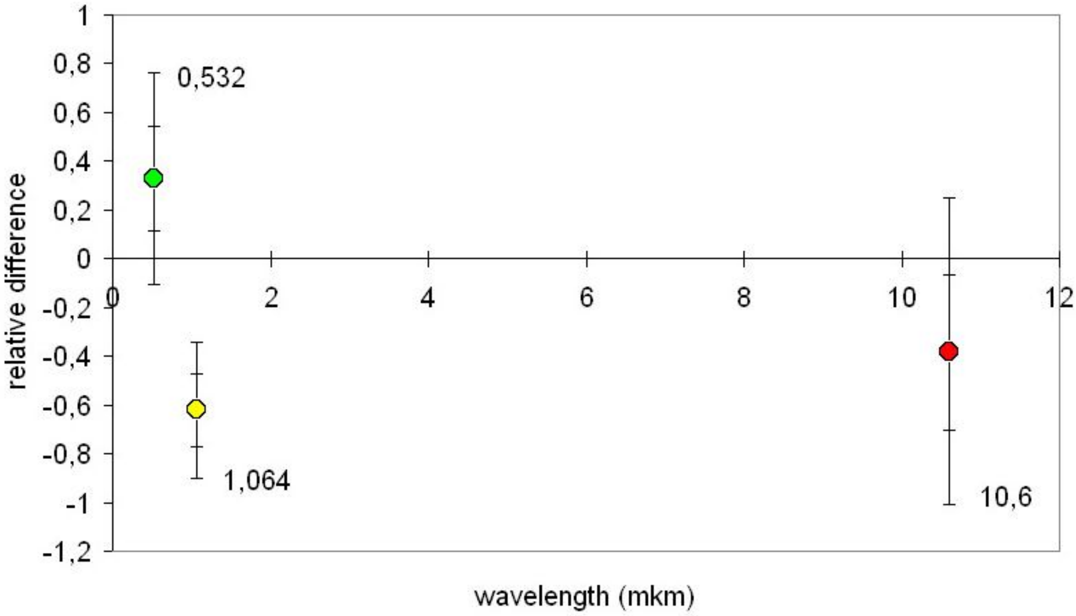

Figure 10. Relative difference, results for OPHIR 30A

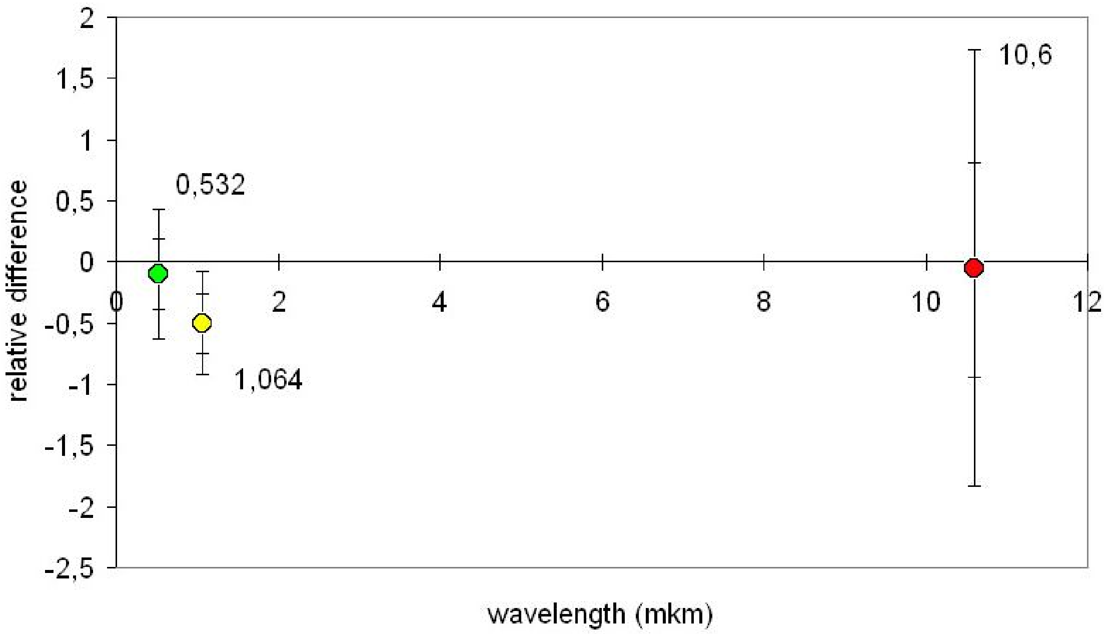

Figure 11. Relative difference, results for COHERENT 10 PM

6.3. Link with EUROMET.PR-S2

The results obtained by VNIIOFI with OPHIR 30A at wavelengths 0,532 μm, 1,064 μm and 10,6 μm can be linked to the EUROMET.PR-S2 [2] reference values via the PTB results.
For a given wavelength, the difference $\Delta_{VNIIOFI\text{-}Ref}$ from the EUROMET.PR-S2 reference value is given by:

$$\Delta_{VNIIOFI-\mathrm{Re}f} = \Delta_{VNIIOFI-PTB} + \Delta_{PTB-\mathrm{Re}f} \quad (6.3)$$

where $\Delta_{VNIIOFI\text{-}PTB}$ is defined by equation $\Delta_{VNIIOFI-PTB} = \dfrac{s_{VNIIOFi} - s_{PTB}}{s_{PTB}}$ and $\Delta_{\text{-}PTB\text{-}Ref}$ is the deviation of the PTB result from EUROMET.PR-S2 reference value at this wavelength.
The uncertainty $u_{VNIIOFI\text{-}Ref}$ associated with $\Delta_{VNIIOFI\text{-}Ref}$ is determined by the uncertainty of this supplementary comparison ($u_{VNIIOFI\text{-}PTB}$) and the uncertainty associated with $\Delta_{PTB\text{-}Ref}$ in EUROMET.PR-S2 ($u_{PTB\text{-}Ref}$):

$$u_{VNIIOFI-\mathrm{Re}f} = \sqrt{u^2_{VNIIOFI-PTB} + u^2_{PTB-\mathrm{Re}f}} \quad (6.4).$$

The relative differences of the PTB results to the reference values of EUROMET.PR-S2 and associated uncertainties are given in Table 6.3.
Table 6.3 – relative differences and associated uncertainties of PTB results to EUROMET.PR-S2 reference values

λ, μm	**0,5145**	**1,064**	**10,6**
$\Delta_{PTB\text{-}Ref}$	0,36 %	0,22 %	-0,11 %
$u_{\text{PTB-Ref}}$	0,1 %	0,13 %	0,16 %

The relative difference between the VNIIOFI value and the EUROMET.PR-S2 reference value, $\Delta_{VNIIOFI\text{-}Ref}$, at each wavelength and the associated uncertainty $u_{VNIIOFI\text{-}Ref}$ given in Table 6.4.
Table 6.4 – VNIIOFI results linking to EUROMET.PR-S2 comparison reference values

λ, μm	**0,5309 / 0,532**	**1,064**	**10,6**
$\Delta_{VNIIOFI\text{-}Ref}$	0,69 %	-0,4 %	-0,49 %
$u_{VNIIOFI\text{-}Ref}$	0,24 %	0,19 %	0,36 %

It should be noted that for the linkage the results obtained at 0.5309 μm were compared with the results at 0.5145 μm, the wavelength actually used in the EUROMET.PR-S2 comparison. This is justified, because these wavelengths are rather close to each other.

7. Conclusions

The results of this comparison demonstrate essentially an agreement between the results obtained at the two participating laboratories, i.e. PTB, Germany, and VNIIOFI, Russia. Furthermore, the link between the laser radiometry laboratory of VNIIOFI with the EUROMET.PR-S2 supplementary comparison reference value was established. We explain what the results on the wavelength of 1064 nm were not so close because the diameter of the laser beam at VNIIOFI was 2 mm whereas, while at PTB the diameter of the laser beam was about 6 mm. Thus divergences of results were depended on the zone nonuniform of the detector heads.

8. References

1] “ISO, Guide to the Expression of Uncertainty in Measurement”, International Organization for Standardization, Geneva, Switzerland, 1993.
2] Responsivity of detectors for radiant power of lasers, Final report, link http://kcdb.bipm.org/appendixB/appbresults/EUROMET.PR-S2/EUROMET.PR-S2_final_report.pdf