EUROMET PR-K2.b

Comparison on spectral responsivity
(300 nm to 1 000 nm)

Final Report

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Pilot: Instituto de Optica "Daza de Valdés", CSIC. Formerly Instituto de Física Aplicada, CSIC
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SUMMARY

This report contains the results of the regional comparison EUROMET PR-K2.b. Ten laboratories took part in it, including the pilot. In general the results are consistent with a few exceptions as explained in the report.

The comparison gives international linkage in spectral responsivity from 300 nm to 1 000 nm to seven European laboratories: Bundesamt für Metrologie und Akkreditierung (METAS), Norwegian Metrology and Accreditation Service (Justervesenet), Central Office of Measures (GUM), National Institute of Metrology (INM-Romania), Optics Laboratory of TUBITAK-UME (UME), Czech Metrology Institute (CMI), Swedish National Testing and Research Institute (SP). Three laboratories provided the link to CCPR-K2.b: Bureau National de Metrologie (BNM-INM/CNAM), Instituto de Optica “Daza de Valdés” (IO-CSIC, acting as pilot) and NMi Van Swinden Laboratorium B.V. (NMi-VSL).

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1 Introduction

Under the Mutual Recognition Arrangement (MRA) the metrological equivalence of national measurement standards is determined by a set of key comparisons chosen and organized by the Consultative Committees of the CIPM working closely with the Regional Metrology Organizations (RMOs). At its meeting in March 1997, the Consultative Committee for Photometry and Radiometry (CCPR) identified several key comparisons in the field of optical radiation metrology, one of which concerns spectral responsivity.

The present report concerns the key comparison EUROMET PR-K2.b, international comparison of spectral responsivity measurements in the wavelength range 300 nm to 1000 nm, piloted by the Instituto de Óptica of CSIC (IO-CSIC). At the time of starting the comparison the pilot laboratory was recognised as Instituto de Fisica Aplicada (CSIC), but since them the laboratory has changed its name to Instituto de Óptica (CSIC). This is an administrative change not affecting the facilities nor capabilities of the laboratory.

The technical protocol was drawn up by a small working group comprising the BNM-INM (France), the VSL (Netherlands) and the IO-CSIC (pilot), following the protocol approved for the comparison CCPR-K2.b. All the three laboratories took part in the key comparison CCP-k2.b and will provide the linkage to that comparison.

This comparison has been carried out through the calibration of a group of transfer detectors: Single silicon photodiodes and trap detectors. The comparison was organized in a star form, carried out in two phases with two groups of participants.

The transfer detectors were sent to the first group in July 2003 and to the second group in December 2003 (three laboratories) and May 2004 (the other two laboratories).

For more details, please refer to the Technical Protocol of the comparison EUROMET PR-K2.b.

According to the guide for comparisons within EURAMET, after completion of the Pre-Draft A processes, the pilot laboratory distributed to all participants Draft A which disclosed the absolute results of the comparison with identification of all the participating labs. Pilot laboratory did not get any comments or questions on other participants’ uncertainty budget.

2 Participants

Participants in the comparison were grouped according to their readiness to do the measures at first or second round. The members of each group were:

Group 1: Bundesamt für Metrologie und Akkreditierung (METAS), Norwegian Metrology and Accreditation Service (Justervesenet), Central Office of Measures (GUM), National Institute of Metrology (INM-Romania).

Group 2: NMi Van Swinden Laboratorium B.V. (NMi-VSL), Optics Laboratory of TUBITAK-UME (UME), Czech Metrology Institute (CMI), Bureau National de Metrologie (BNM-INM/CNAM), Swedish National Testing and Research Institute (SP).

3 Comparison calendar

Measurements were done according to the following calendar:

- Group 1 between July and October 2003.
- Group 2: Two laboratories between December 2003 and February 2004, one laboratory between December 2003 and May 2004, another laboratory between May 2004 and December 2004 and the last one between May 2004 and April 2007.

Pilot measured the detectors before sending them to participants and after receiving them.

4 Principle of the comparison.

The comparison has been principally carried out through the calibration of the spectral responsivity of a group of transfer detectors, single silicon photodiodes and trap detectors. This type of detectors has shown excellent short and long-term stability.

Each participating laboratory has received a batch of detectors consisting of two single element photodiodes and two three-element reflection trap detectors The same type of detectors was used in an earlier comparison of spectral responsivity in similar conditions as for this comparison.

The comparison has taken the form of a star comparison, carried out in two phases. The calibrated detectors were distributed to the first group of participants. Participants then calibrated the detectors at the wavelengths required and returned the packages to the pilot laboratory to carry out a new calibration to monitor drift. The batches were then sent to the second group of participants, following the same procedure.

Within the Pilot Laboratory transfer detectors were compared with an IO-CSIC reference detector at each wavelength, before they were sent to the participating laboratory and after their return to check their stability. For every transfer detector at every wavelength its responsivity is calculated as the ratio of its response, I_t, to the response of the reference detector (under the same irradiation), I_r, times the responsivity of the reference detector, R_r:

$$R_t(\lambda) = \frac{I_t(\lambda)}{I_r(\lambda)} R_r(\lambda) \qquad (1)$$

This responsivity value is compared to that given by the participating laboratories.

4.1 Transfer detectors.

Detectors used in this comparison come from the batches used in the comparison CCPR-K2.b. This assures stability of the detectors, since all of them were checked for it then. Nevertheless the external reference of the devices was exchanged in order to keep the blindness of the comparison. Single elements detectors are identified by an F followed by a number, while trap detectors are identified by a T followed by a number.

4.2 Pilot’s experimental set-up

Spectral responsivity has been determined in the standard setup for determining responsivity at the pilot’s laboratory. The system is formed by two subsystems. One for the VIS and NIR ranges (450 nm to 1 000 nm) and another for the UV range: 300 nm to 400 nm. Both subsystems have got a radiation source (a 400 W QH incandescent lamp for the first and a Xe lamp for the UV), a 50 cm focal length single grating monochromator with the suitable second order blocking filters (an ARC Spectra Pro500 for the VIS an NIR and a SPEX 500 for the UV), a shutter for measuring dark signal, a beam splitter for monitoring temporal drift and a turn table to place detectors in the incident beam. The divergence of the beam impinging the detectors is less than 6 degrees (full cone) and the size of the spot onto the detectors is 4 mm x 4 mm in the VIS-NIR range and 3 mm x 3 mm in the UV range and the bandwidth was 1.4 nm. The photodiodes were connected to independent I/V preamplifiers to record their short circuit photocurrent as usual.

4.3 Uncertainties associated with the transfer at IO-CSIC

4.3.1 Stability of IO-CSIC responsivity scale.

The stability of responsivity scale of IO-CSIC is better than 0.1 times standard uncertainty of the scale. This stability is checked by comparing the different photodiodes where the scale is realized with a trap detector calibrated against the primary standard of the laboratory, a cryogenic substitution radiometer.

4.3.2 Stability of transfer device.

The possible drift δ of a transfer detector is determined as the relative change in responsivity when compared with the IO reference detectors before and after travelling:

$$\delta = \frac{R_{aft}(\lambda) - R_{bef}(\lambda)}{R_{bef}(\lambda)} \qquad (2)$$

The uncertainty u_{drift} associated with the possible drifts is estimated to be within ± δ/2 with a rectangular probability distribution. Then the uncertainty is given by:

$$u_{drift} = \frac{\delta}{2\sqrt{3}} \qquad (3)$$

The following table shows an average value of u_{drift} for every wavelength. None detector showed a drift significantly different from the average.

Table 1. Average uncertainty due to transfer detectors drift

Wavelength /nm	Standard uncertainty u_{drift}
300	9,6E-05
320	2,8E-04
340	1,0E-04
360	5,3E-04
380	2,9E-04
400	1,6E-04
450	9,9E-04
500	5,7E-04
550	5,0E-04
600	5,3E-04
650	5,8E-04

Wavelength /nm	Standard uncertainty u_{drift}
700	5,3E-04
750	5,9E-04
800	5,5E-04
850	5,7E-04
900	6,0E-04
950	6,8E-04
1 000	5,1E-04

4.3.3 Polarization effect.

Polarization effect on trap transfer has not been tested for this comparison. However it was tested in the comparison CCPR-K2.b and learnt that the uncertainty associated with the residual sensitivity to the polarization state of the beam for trap detectors is always under 0.05 %.

4.3.4 Linearity.

Previous tests have shown that, for a beam size of about 3 mm and an optical power of 20 µW or less, as used in this comparison, non-linearity effects are negligible compared with the other sources of uncertainty.

4.3.5 Monochromator wavelength calibration.

The wavelength selection system of the monochromator is calibrated by means of low pressure spectral lamps (Hg and Kr). The run-to-run repeatability was better than 0.05 nm and the wavelength deviation of the Monochromator setting from the reference value of the spectral line was less than ± 0.2 nm over the whole range.

Since detectors are compared for the same wavelength setting in the monochromator by using the turntable, wavelength uncertainty is mainly determined by the slope of the spectral responsivity curve of the single photodiodes and trap detectors. Relative standard uncertainty component due to wavelength uncertainty is given in the table below.

Table 2. Contribution to relative uncertainty of spectral responsivity due to wavelength uncertainty

Wavelength /nm	Trap detector $u_\lambda(R(\lambda))$	photodiode $u_\lambda(R(\lambda))$
300	3,87E-04	5,55E-04
320	5,43E-04	2,39E-04
340	4,27E-04	1,39E-04
360	6,23E-04	4,14E-04
380	7,20E-04	9,04E-04
400	5,38E-04	5,15E-04
450	4,27E-04	3,36E-04
500	3,62E-04	2,70E-04
550	3,27E-04	2,32E-04
600	2,92E-04	2,03E-04
650	2,73E-04	1,88E-04
700	2,51E-04	1,72E-04

Wavelength /nm	Trap detector $u_\lambda(R(\lambda))$	photodiode $u_\lambda(R(\lambda))$
750	2,35E-04	1,60E-04
800	2,16E-04	1,47E-04
850	2,07E-04	1,41E-04
900	1,83E-04	1,15E-04
950	2,26E-05	8,72E-05
1 000	2,35E-05	9,06E-05

4.3.6 Use of a monitor detector and noise reduction

A monitor detector was used to correct results for small drifts of the source at each wavelength. Temporal drift was completely negligible for the VIS-NIR subsystem and no correction was applied, while some correction was applied to the UV readings.

4.3.7 Inter-reflections detector/slits

Monochromator's slits were blackened to make negligible inter-reflections between them and single photodiodes whose reflectance is high compare to trap detectors.

4.3.8 Stray light

Stray light refers to the out-of-band radiation at the output of the monochromator. In the monochromator used for the comparison, the amount of stray light was measured by means of blocking filters, and was found to have no significant effect on the comparisons of detectors.

4.3.9 Bandwidth effects

For the bandwidths used in this comparison and the slope of the detectors being compared, the bandwidth effects are negligible.

4.3.10 Amplifier gain

Every detector was connected to an independent current-voltage amplifier. The amplifier's outputs were connected to a single voltmeter via low-noise scanner card. The uncertainty of photocurrent measurement is below 0.01 %.

4.3.11 Uniformity, spot size and alignment

The detectors were aligned in the beam axis to within 0.05 mm by using micrometric positioners. The uncertainty in alignment is manifested in the experimental dispersion of the results. Differences in spot size, spot non-uniformity or alignment method between the Pilot and the participants may introduce some bias in the comparison.

4.3.12 Beam divergence and vignetting

The output beam divergence was lower than the acceptance of the trap detectors. A small increase or decrease of this angle did not produce significant changes in the measured ratios. The vignetting effects are therefore estimated to be negligible for the detector comparisons.

4.3.13 Temperature

Transfer detectors' temperature was not measured in this comparison. Participating laboratories were asked to perform responsivity calibration in suitable laboratory accommodation maintained at a temperature as close as possible to 23 ºC. The exact temperature of the laboratory during the time of the measurements had to be reported with the calibration results, as established in the comparison protocol.

Reported temperatures range within (23 ± 1) ºC. Taking into account this range, no correction was applied for temperature variation.

4.3.14 Repeatability

The responsivity of every detector taking part in the comparison was measured at least three times respect to the IO transfer photodiode. The standard deviation of the successive R(λ) values within any period was calculated to estimate the repeatability. The average value of those standard deviations obtained at every wavelength is shown in Table 3 for single photodiodes and for traps. These values are used as an estimate of the uncertainty associated with the repeatability.

Table 3. Relative uncertainty due to repeatability of measurements

Wavelength /nm	Standard relative uncertainty for single diodes	Standard relative uncertainty for traps
300	2,0E-03	2,2E-03
320	2,0E-03	2,3E-03
340	1,8E-03	2,0E-03
360	2,0E-03	2,1E-03
380	2,0E-03	1,8E-03
400	1,5E-03	1,5E-03
450	1,4E-03	1,1E-03
500	8,3E-04	6,2E-04
550	7,7E-04	6,3E-04
600	4,9E-04	4,7E-04
650	5,6E-04	4,9E-04
700	5,2E-04	4,8E-04
750	4,6E-04	4,3E-04
800	5,3E-04	4,9E-04
850	4,2E-04	4,6E-04
900	4,8E-04	5,5E-04
950	5,3E-04	6,6E-04
1 000	6,0E-04	7,4E-04

4.3.15 Combined uncertainty associated with the transfer

The previous contributions have been added quadratically to obtain the combined transfer uncertainty as shown in table 4.

Table 4. Standard relative combined uncertainty for the transfer process

Wavelength /nm	Standard relative transfer uncertainty
300	2,2E-03
320	2,4E-03

Wavelength /nm	Standard relative transfer uncertainty
340	2,1E-03
360	2,2E-03
380	2,0E-03
400	1,6E-03
450	1,6E-03
500	9,2E-04
550	8,7E-04
600	7,7E-04
650	8,0E-04
700	7,6E-04
750	7,7E-04
800	7,7E-04
850	7,6E-04
900	8,3E-04
950	9,5E-04
1 000	9,0E-04

5 Participants results and uncertainties

Calibration reports of transfer detectors realized at every participating laboratory are enclosed as annexes at the end of this report. They contain information on the spectral responsivity values, their uncertainty, and the calibration traceability: primary standard, transfer standards, environmental conditions.

The reported combined relative standard uncertainties as a function of wavelength are summarized in Figure 1 for all the participants.

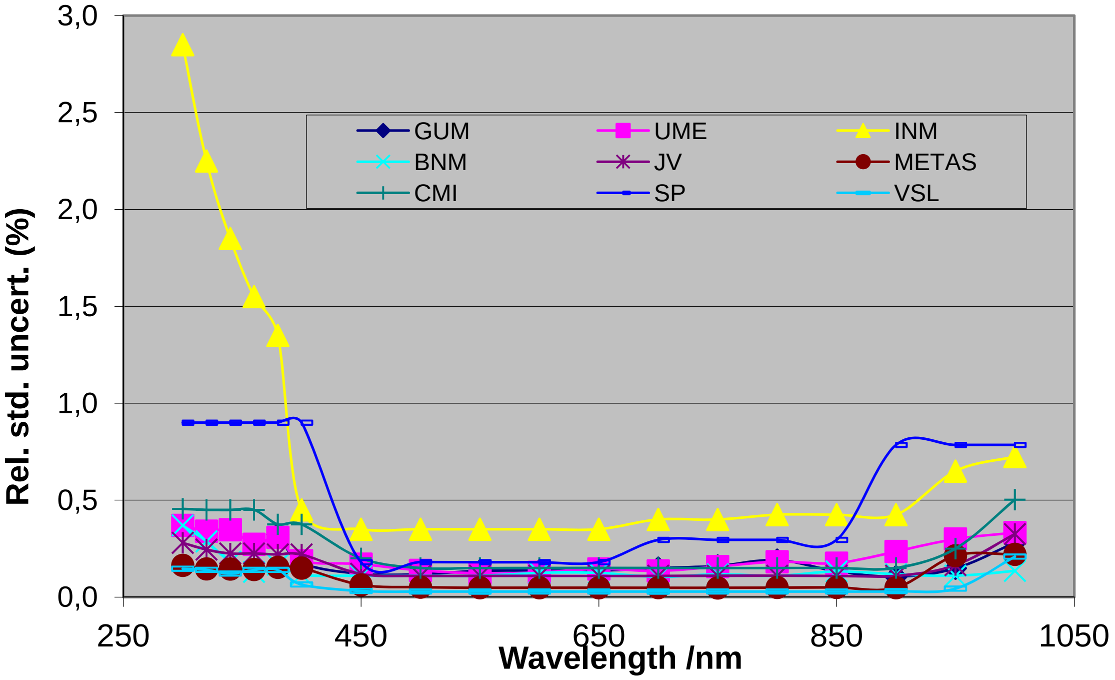


Figure 1. Average relative standard uncertainty of participating laboratories

6 Responsivity values of transfer detectors at the pilot laboratory

Responsivity values and their corresponding uncertainty obtained for every transfer detector and wavelength at the pilot laboratory are shown in the following tables and compared to the values given by the participating laboratories. The responsivity at the pilot laboratory is the average between the calibration done before sending the transfer detectors to the participating laboratory and after receiving them from the laboratory.

6.1 Detectors measured by METAS

Table 5. Spectral responsivity of single photodiodes measured by METAS

	Detector F43				Detector F48			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300	0,131192	4,57E-04	0,129300	1,25E-03	0,133057	4,58E-04	0,131423	1,27E-03
320	0,143835	4,17E-04	0,141267	1,62E-03	0,145606	4,22E-04	0,143124	1,65E-03
340	0,149525	4,40E-04	0,148810	1,42E-03	0,151391	4,36E-04	0,150572	1,46E-03
360	0,146697	4,28E-04	0,144521	1,68E-03	0,148365	4,39E-04	0,146389	1,77E-03
380	0,157274	5,06E-04	0,156525	1,54E-03	0,158860	5,21E-04	0,158180	1,52E-03
400	0,181945	5,49E-04	0,179665	1,65E-03	0,183270	5,57E-04	0,181291	1,64E-03
450	0,223184	2,77E-04	0,221180	1,19E-03	0,224438	2,78E-04	0,222427	1,05E-03
500	0,255952	2,46E-04	0,253848	9,07E-04	0,257077	2,57E-04	0,255270	9,36E-04
550	0,286250	2,69E-04	0,283491	9,07E-04	0,287310	2,76E-04	0,284641	8,99E-04
600	0,315316	2,96E-04	0,312874	1,06E-03	0,316256	3,04E-04	0,314242	1,03E-03
650	0,343469	3,23E-04	0,341204	1,06E-03	0,344358	3,37E-04	0,342373	1,05E-03
700	0,371444	3,49E-04	0,368589	1,12E-03	0,372295	3,57E-04	0,369659	1,10E-03
750	0,399019	3,75E-04	0,395134	1,35E-03	0,399685	3,68E-04	0,396245	1,21E-03
800	0,426456	4,26E-04	0,423753	1,36E-03	0,427203	4,19E-04	0,424867	1,43E-03
850	0,453798	4,54E-04	0,451140	2,28E-03	0,454489	4,45E-04	0,452343	2,33E-03
900	0,481223	4,52E-04	0,476930	2,38E-03	0,481783	4,53E-04	0,478002	2,42E-03
950	0,505185	2,10E-03	0,499533	2,52E-03	0,506008	2,23E-03	0,500776	2,52E-03
1000	0,477788	2,05E-03	0,474792	2,45E-03	0,479618	2,12E-03	0,476937	2,46E-03

Table 6. Spectral responsivity of trap detectors measured by METAS

	Detector T04				Detector T17			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300	0,247502	7,72E-04	0,244197	2,43E-03	0,247159	7,51E-04	0,244365	2,33E-03
320	0,256389	7,44E-04	0,251458	3,09E-03	0,256170	7,48E-04	0,251492	3,00E-03
340	0,269138	7,64E-04	0,267042	2,52E-03	0,268967	7,85E-04	0,267395	2,63E-03
360	0,281783	7,72E-04	0,277435	3,49E-03	0,281643	7,77E-04	0,277168	3,41E-03
380	0,297204	8,62E-04	0,294981	3,01E-03	0,297067	8,56E-04	0,295767	2,94E-03
400	0,316919	9,32E-04	0,313208	2,94E-03	0,316860	9,38E-04	0,312549	2,97E-03
450	0,360062	4,54E-04	0,357920	1,72E-03	0,360012	4,61E-04	0,357560	1,66E-03
500	0,401159	4,09E-04	0,398194	1,41E-03	0,401131	4,41E-04	0,397964	1,45E-03
550	0,441971	4,24E-04	0,437996	1,43E-03	0,441947	4,42E-04	0,437793	1,44E-03
600	0,482709	4,63E-04	0,479178	1,46E-03	0,482673	4,73E-04	0,479267	1,53E-03
650	0,523062	5,02E-04	0,519943	1,69E-03	0,523033	5,02E-04	0,519905	1,56E-03
700	0,563566	5,64E-04	0,559644	1,62E-03	0,563471	5,52E-04	0,559343	1,62E-03

	Detector T04				Detector T17			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)
750	0,603588	5,79E-04	0,598490	1,80E-03	0,603739	5,68E-04	0,598485	1,96E-03
800	0,643891	6,57E-04	0,640621	2,05E-03	0,643903	6,18E-04	0,640290	2,08E-03
850	0,684052	6,84E-04	0,680752	3,46E-03	0,683888	6,70E-04	0,680736	3,45E-03
900	0,723981	7,24E-04	0,718538	3,67E-03	0,724117	7,10E-04	0,718297	3,63E-03
950	0,762481	3,26E-03	0,755314	3,83E-03	0,762899	3,23E-03	0,755074	3,74E-03
1000	0,754329	3,36E-03	0,752641	4,11E-03	0,755667	3,37E-03	0,753283	3,79E-03

6.2 Detectors measured by JV

Table 7. Spectral responsivity of single photodiodes measured by JV

	Detector F18				Detector F24			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)
300	0,131330	7,88E-04	0,130086	1,43E-03	0,133690	8,02E-04	0,132474	1,49E-03
320	0,144000	7,78E-04	0,141817	1,67E-03	0,146280	7,90E-04	0,143801	1,64E-03
340	0,149820	7,49E-04	0,149003	1,55E-03	0,151990	7,60E-04	0,151119	1,52E-03
360	0,146820	7,34E-04	0,144946	1,76E-03	0,148850	7,44E-04	0,146710	1,77E-03
380	0,157700	7,89E-04	0,157502	1,65E-03	0,159570	7,98E-04	0,158993	1,66E-03
400	0,181940	9,10E-04	0,179724	1,71E-03	0,183730	9,19E-04	0,181577	1,74E-03
450	0,223030	6,24E-04	0,221594	1,19E-03	0,224660	6,29E-04	0,223494	1,37E-03
500	0,255870	6,65E-04	0,254334	8,69E-04	0,257320	6,69E-04	0,255349	1,44E-03
550	0,286090	7,44E-04	0,283933	9,53E-04	0,287440	7,47E-04	0,285075	1,00E-03
600	0,314990	8,19E-04	0,313002	1,51E-03	0,316200	8,22E-04	0,314157	1,65E-03
650	0,343270	8,93E-04	0,341754	1,23E-03	0,344370	8,95E-04	0,342586	1,38E-03
700	0,371140	9,65E-04	0,368976	1,16E-03	0,372180	9,68E-04	0,370039	1,16E-03
750	0,398880	1,04E-03	0,395623	1,48E-03	0,399860	1,04E-03	0,395838	1,42E-03
800	0,426380	1,11E-03	0,424753	1,37E-03	0,427260	1,11E-03	0,425375	1,30E-03
850	0,453720	1,18E-03	0,452126	2,29E-03	0,454570	1,18E-03	0,452840	2,29E-03
900	0,481130	1,25E-03	0,478721	2,90E-03	0,481940	1,25E-03	0,478506	2,42E-03
950	0,505830	1,82E-03	0,501215	2,47E-03	0,506610	1,82E-03	0,501522	2,52E-03
1000	0,484590	3,20E-03	0,478919	2,37E-03	0,485970	3,21E-03	0,479377	2,40E-03

Table 8.Spectral responsivity of trap detectors measured by JV

	Detector T06				Detector T13			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_P$ A/W	$Uncert_P$ (k=2)
300	0,246900	1,28E-03	0,244278	2,55E-03	0,247110	1,28E-03	0,244884	2,58E-03
320	0,256040	1,13E-03	0,251020	2,79E-03	0,256200	1,13E-03	0,251702	2,87E-03
340	0,268940	1,08E-03	0,266786	2,77E-03	0,269140	1,08E-03	0,267157	2,68E-03
360	0,281600	1,13E-03	0,276585	3,27E-03	0,281950	1,13E-03	0,277531	3,29E-03
380	0,297190	1,13E-03	0,296083	2,93E-03	0,297510	1,13E-03	0,296789	2,99E-03
400	0,316650	1,20E-03	0,312695	2,89E-03	0,316870	1,20E-03	0,313044	2,87E-03
450	0,359600	7,19E-04	0,357839	2,64E-03	0,359740	7,19E-04	0,356119	1,77E-03
500	0,400750	7,21E-04	0,397690	1,68E-03	0,400910	7,22E-04	0,396982	1,40E-03
550	0,441620	7,95E-04	0,437582	1,41E-03	0,441740	7,95E-04	0,437126	1,48E-03
600	0,482120	8,68E-04	0,478957	1,82E-03	0,482230	8,68E-04	0,478071	1,71E-03

	Detector T06				Detector T13			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
650	0,522620	9,41E-04	0,519613	1,80E-03	0,522740	9,41E-04	0,519133	1,72E-03
700	0,562970	1,01E-03	0,559110	1,75E-03	0,563110	1,01E-03	0,558301	1,70E-03
750	0,603460	1,09E-03	0,597831	2,26E-03	0,603560	1,09E-03	0,596912	2,11E-03
800	0,643750	1,16E-03	0,640234	2,01E-03	0,643860	1,16E-03	0,639126	2,18E-03
850	0,683920	1,23E-03	0,680393	3,46E-03	0,684100	1,23E-03	0,679394	4,29E-03
900	0,724300	1,30E-03	0,718259	3,72E-03	0,724430	1,30E-03	0,717091	4,78E-03
950	0,763480	2,29E-03	0,754951	3,93E-03	0,763630	2,29E-03	0,753466	4,97E-03
1000	0,762710	4,88E-03	0,752343	3,89E-03	0,762970	4,88E-03	0,750084	5,36E-03

6.3 Detectors measured by GUM

Table 9. Spectral responsivity of single photodiodes measured by GUM

	Detector F09				Detector F32			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300								
320								
340								
360								
380	0,159360	2,42E-04	0,158371	1,51E-03	0,157480	9,03E-04	0,156465	1,51E-03
400	0,183570	4,98E-04	0,181247	1,64E-03	0,181690	6,06E-04	0,179241	1,67E-03
450	0,224730	5,21E-04	0,222612	1,13E-03	0,222820	5,64E-04	0,221166	1,04E-03
500	0,257500	5,98E-04	0,255283	9,24E-04	0,255710	7,44E-04	0,253453	8,89E-04
550	0,287450	7,63E-04	0,285209	1,00E-03	0,285920	8,58E-04	0,283158	1,12E-03
600	0,316220	8,17E-04	0,314020	1,06E-03	0,314850	7,17E-04	0,312566	1,08E-03
650	0,344430	6,42E-04	0,342191	1,12E-03	0,343180	7,98E-04	0,340762	1,03E-03
700	0,372200	5,93E-04	0,369615	1,16E-03	0,370980	9,31E-04	0,368190	1,14E-03
750	0,399760	9,12E-04	0,396257	1,29E-03	0,398700	1,23E-03	0,394820	1,22E-03
800	0,427420	1,14E-03	0,424881	1,39E-03	0,426440	1,72E-03	0,423556	1,37E-03
850	0,454810	1,64E-03	0,452122	4,40E-03	0,453630	1,34E-03	0,450902	2,29E-03
900	0,482170	1,33E-03	0,477712	4,62E-03	0,481050	1,04E-03	0,476847	2,36E-03
950	0,506930	1,53E-03	0,500812	4,91E-03	0,505980	1,32E-03	0,499679	2,51E-03
1000	0,484600	2,38E-03	0,477209	4,67E-03	0,484140	2,43E-03	0,476303	2,79E-03

Table 10. Spectral responsivity of trap detectors measured by GUM

	Detector T07				Detector T16			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300								
320								
340								
360								
380	0,297860	3,28E-03	0,297383	2,80E-03	0,297790	2,25E-03	0,295794	2,80E-03
400	0,317430	1,31E-03	0,313617	2,95E-03	0,317550	1,25E-03	0,311999	2,99E-03
450	0,360360	5,72E-04	0,357598	1,66E-03	0,360220	1,13E-03	0,357472	2,20E-03
500	0,401460	3,85E-04	0,397836	1,35E-03	0,401350	1,32E-03	0,397771	1,97E-03

	Detector T07				Detector T16			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
550	0,442010	1,41E-03	0,437930	1,41E-03	0,441760	8,72E-04	0,437846	2,11E-03
600	0,482200	1,37E-03	0,478738	1,51E-03	0,482130	1,54E-03	0,479270	2,39E-03
650	0,522790	2,14E-03	0,519465	1,55E-03	0,522530	1,37E-03	0,519413	2,40E-03
700	0,562780	3,07E-03	0,559053	1,61E-03	0,562770	1,36E-03	0,559036	2,55E-03
750	0,602640	2,85E-03	0,597870	1,81E-03	0,602470	1,67E-03	0,597964	2,89E-03
800	0,642660	3,79E-03	0,640115	2,02E-03	0,642560	1,72E-03	0,640272	2,99E-03
850	0,684050	1,11E-03	0,680161	3,38E-03	0,683620	1,72E-03	0,680416	4,21E-03
900	0,723770	7,29E-04	0,718043	3,58E-03	0,723740	1,80E-03	0,718186	4,44E-03
950	0,762820	3,39E-03	0,754433	3,72E-03	0,762610	1,38E-03	0,754698	4,66E-03
1000	0,762180	6,01E-03	0,750675	4,13E-03	0,760650	3,53E-03	0,749603	5,06E-03

6.4 Detectors measured by INM-Romania

Table 11. Spectral responsivity of single photodiodes measured by INM-Romania

	Detector F19				Detector F45			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,128700	7,72E-03	0,132167	1,35E-03	0,124900	7,49E-03	0,128697	1,37E-03
320	0,141300	6,78E-03	0,143760	1,74E-03	0,137800	6,61E-03	0,140709	1,71E-03
340	0,149300	5,97E-03	0,151177	1,60E-03	0,145800	5,83E-03	0,148000	1,60E-03
360	0,142800	4,86E-03	0,146781	1,79E-03	0,140100	4,76E-03	0,143964	1,75E-03
380	0,153600	4,61E-03	0,158837	1,69E-03	0,150600	4,52E-03	0,156097	1,59E-03
400	0,182400	1,82E-03	0,181691	1,70E-03	0,179300	1,79E-03	0,179119	1,71E-03
450	0,225400	1,80E-03	0,223930	1,10E-03	0,222700	1,78E-03	0,220576	1,46E-03
500	0,258000	2,06E-03	0,255161	9,00E-04	0,255500	2,04E-03	0,252675	1,01E-03
550	0,287700	2,30E-03	0,284967	9,12E-04	0,285300	2,28E-03	0,283163	1,09E-03
600	0,316700	2,53E-03	0,314236	1,00E-03	0,314300	2,51E-03	0,312303	9,86E-04
650	0,344900	2,76E-03	0,342542	1,02E-03	0,342800	2,74E-03	0,340627	1,19E-03
700	0,372700	2,98E-03	0,369778	1,08E-03	0,370300	2,96E-03	0,368106	1,05E-03
750	0,400400	3,20E-03	0,396278	1,30E-03	0,397900	3,18E-03	0,394930	1,26E-03
800	0,427800	3,85E-03	0,424967	1,41E-03	0,425200	3,83E-03	0,423226	1,56E-03
850	0,454900	4,09E-03	0,452135	2,28E-03	0,452300	4,07E-03	0,450556	2,42E-03
900	0,477800	4,30E-03	0,477946	2,45E-03	0,475300	4,28E-03	0,476280	2,53E-03
950	0,495600	6,94E-03	0,500708	2,52E-03	0,492900	6,90E-03	0,499122	2,68E-03
1000	0,477300	7,16E-03	0,477842	3,81E-03	0,475100	7,13E-03	0,476365	3,51E-03

Table 12. Spectral responsivity of trap detectors measured by INM-Romania

	Detector T10				Detector T12			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,234600	1,27E-02	0,244195	2,65E-03	0,230400	1,24E-02	0,245312	2,41E-03
320	0,245300	1,03E-02	0,251156	3,04E-03	0,245500	1,03E-02	0,251911	2,82E-03
340	0,261800	8,90E-03	0,266503	2,82E-03	0,261300	8,88E-03	0,267800	2,58E-03
360	0,268500	7,52E-03	0,275867	3,50E-03	0,267800	7,50E-03	0,276958	3,16E-03
380	0,285600	6,85E-03	0,295361	3,10E-03	0,285600	6,85E-03	0,296882	2,86E-03
400	0,314300	2,51E-03	0,312428	2,92E-03	0,314400	2,52E-03	0,313808	2,70E-03

	Detector T10				Detector T12			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
450	0,361100	2,17E-03	0,355752	1,80E-03	0,360900	2,17E-03	0,358271	1,75E-03
500	0,402000	2,41E-03	0,396188	1,50E-03	0,401900	2,41E-03	0,397419	1,47E-03
550	0,442200	2,65E-03	0,436403	1,51E-03	0,441900	2,65E-03	0,437804	1,57E-03
600	0,483000	2,90E-03	0,477685	1,56E-03	0,482500	2,90E-03	0,479022	1,63E-03
650	0,523400	3,14E-03	0,518182	1,57E-03	0,523100	3,14E-03	0,519647	1,67E-03
700	0,563100	4,50E-03	0,557404	1,61E-03	0,562800	4,50E-03	0,558969	1,73E-03
750	0,603100	4,82E-03	0,596066	1,82E-03	0,603300	4,83E-03	0,597632	1,83E-03
800	0,643200	5,15E-03	0,638235	2,13E-03	0,643000	5,14E-03	0,640017	2,23E-03
850	0,683000	5,46E-03	0,678139	3,42E-03	0,682900	5,46E-03	0,680014	3,51E-03
900	0,716300	5,73E-03	0,715865	3,55E-03	0,716300	5,73E-03	0,717890	3,66E-03
950	0,744800	8,94E-03	0,752278	3,75E-03	0,744900	8,94E-03	0,754358	3,87E-03
1000	0,748800	1,05E-02	0,747798	4,29E-03	0,749800	1,05E-02	0,749934	4,42E-03

6.5 Detectors measured by NMi-VSL

Table 13. Spectral responsivity of single photodiodes measured by NMi-VSL

	Detector F21				Detector F34			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,131430	4,47E-04	0,130162	1,23E-03	0,131290	4,36E-04	0,129856	1,24E-03
320	0,143780	4,11E-04	0,141845	1,56E-03	0,143700	3,97E-04	0,141621	1,56E-03
340	0,149650	3,83E-04	0,149312	1,41E-03	0,149550	4,01E-04	0,149018	1,44E-03
360	0,146700	4,49E-04	0,145088	1,65E-03	0,146650	4,49E-04	0,144982	1,47E-03
380	0,157680	4,64E-04	0,157083	1,49E-03	0,157600	4,48E-04	0,156865	1,55E-03
400	0,181970	2,62E-04	0,179978	1,63E-03	0,181950	2,29E-04	0,179926	1,62E-03
450	0,223420	1,56E-04	0,221713	6,31E-04	0,223340	1,56E-04	0,221466	6,48E-04
500	0,256390	1,69E-04	0,254125	6,86E-04	0,256270	1,69E-04	0,253896	7,02E-04
550	0,286590	1,83E-04	0,283770	7,54E-04	0,286470	1,83E-04	0,283520	7,67E-04
600	0,315480	2,02E-04	0,313132	8,38E-04	0,315330	2,02E-04	0,312901	8,41E-04
650	0,343710	2,20E-04	0,341443	9,13E-04	0,343580	2,20E-04	0,341215	9,20E-04
700	0,371550	2,38E-04	0,368826	9,75E-04	0,371420	2,38E-04	0,368551	9,90E-04
750	0,399200	2,63E-04	0,395489	1,05E-03	0,399050	2,55E-04	0,395214	1,06E-03
800	0,426600	2,82E-04	0,424271	1,13E-03	0,426480	2,73E-04	0,424000	1,14E-03
850	0,453870	2,90E-04	0,451647	2,22E-03	0,453770	2,90E-04	0,451428	2,22E-03
900	0,481110	3,37E-04	0,477366	2,34E-03	0,481040	3,37E-04	0,477108	2,35E-03
950	0,505420	5,36E-04	0,500311	2,46E-03	0,505380	5,36E-04	0,500027	2,46E-03
1000	0,482210	2,10E-03	0,477865	2,43E-03	0,482230	2,10E-03	0,477038	2,37E-03

Table 14. Spectral responsivity of trap detectors measured by NMi-VSL

	Detector T11				Detector T14			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,246530	6,36E-04	0,243722	2,68E-03	0,246530	5,97E-04	0,244310	2,29E-03
320	0,255230	7,25E-04	0,250737	2,94E-03	0,255240	7,15E-04	0,251129	2,77E-03
340	0,268160	6,01E-04	0,266070	2,78E-03	0,268290	6,06E-04	0,266863	2,54E-03
360	0,280830	7,02E-04	0,276948	3,10E-03	0,280890	7,30E-04	0,277126	2,78E-03

	Detector T11				Detector T14			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
380	0,296900	8,14E-04	0,294693	3,24E-03	0,297060	8,02E-04	0,295345	2,89E-03
400	0,316410	4,11E-04	0,312374	2,99E-03	0,316470	3,86E-04	0,312844	2,87E-03
450	0,359820	2,09E-04	0,355781	1,10E-03	0,359800	2,01E-04	0,356038	1,07E-03
500	0,401260	2,09E-04	0,396585	1,20E-03	0,401190	2,01E-04	0,396681	1,18E-03
550	0,442040	2,21E-04	0,436554	1,21E-03	0,441960	2,21E-04	0,436667	1,24E-03
600	0,482540	2,41E-04	0,477774	1,40E-03	0,482460	2,51E-04	0,477839	1,41E-03
650	0,522970	2,72E-04	0,518408	1,46E-03	0,522890	2,61E-04	0,518539	1,52E-03
700	0,563310	2,82E-04	0,557854	1,57E-03	0,563230	2,82E-04	0,558043	1,63E-03
750	0,603620	3,02E-04	0,596600	1,69E-03	0,603530	3,14E-04	0,596872	1,68E-03
800	0,643860	3,35E-04	0,638694	1,85E-03	0,643720	3,35E-04	0,638962	1,80E-03
850	0,684030	3,56E-04	0,678653	3,48E-03	0,683900	3,56E-04	0,679335	3,60E-03
900	0,724170	3,77E-04	0,716198	3,71E-03	0,724050	3,77E-04	0,716839	3,97E-03
950	0,762960	5,19E-04	0,752703	3,96E-03	0,762910	5,34E-04	0,753453	5,22E-03
1000	0,760720	3,04E-03	0,750783	4,85E-03	0,760110	3,04E-03	0,753168	8,52E-03

6.6 Detectors measured by UME

Table 15. Spectral responsivity of single photodiodes measured by UME.

	Detector F09				Detector F32			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,131600	1,08E-03	0,132014	9,43E-04	0,131400	8,67E-04	0,129418	9,37E-04
320	0,131800	1,03E-03	0,143679	1,14E-03	0,131500	6,58E-04	0,141270	1,13E-03
340	0,128900	8,77E-04	0,150872	1,03E-03	0,128400	9,50E-04	0,148592	1,01E-03
360	0,149100	7,16E-04	0,146764	1,26E-03	0,148600	8,32E-04	0,144700	1,20E-03
380	0,160000	8,00E-04	0,158495	1,14E-03	0,159500	1,02E-03	0,156659	1,12E-03
400	0,184000	9,57E-04	0,181623	1,19E-03	0,183500	3,67E-04	0,179743	1,20E-03
450	0,222700	6,24E-04	0,222824	7,54E-04	0,222200	7,55E-04	0,220513	7,08E-04
500	0,255700	6,65E-04	0,255168	8,19E-04	0,255200	6,64E-04	0,253140	7,88E-04
550	0,285700	7,43E-04	0,284992	8,66E-04	0,285200	7,99E-04	0,282950	8,26E-04
600	0,314700	8,18E-04	0,314372	9,74E-04	0,314300	8,80E-04	0,312386	9,25E-04
650	0,342900	8,92E-04	0,342757	1,07E-03	0,342400	8,90E-04	0,340859	9,98E-04
700	0,371300	1,04E-03	0,370325	1,08E-03	0,370800	8,90E-04	0,368354	1,03E-03
750	0,398800	1,20E-03	0,396775	1,27E-03	0,398500	1,43E-03	0,394959	1,17E-03
800	0,426000	1,36E-03	0,425572	1,28E-03	0,425800	1,87E-03	0,423904	1,22E-03
850	0,453500	1,63E-03	0,452923	1,53E-01	0,453400	1,72E-03	0,451463	2,26E-03
900	0,481200	2,98E-03	0,478667	1,61E-01	0,480900	1,25E-03	0,477340	2,40E-03
950	0,505600	3,54E-03	0,501640	1,69E-01	0,505200	3,23E-03	0,500396	2,50E-03
1000	0,492200	3,84E-03	0,477601	1,61E-01	0,491900	3,25E-03	0,476774	2,40E-03

Table 16. Spectral responsivity of trap detectors measured by UME

	Detector T07				Detector T16			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,248000	1,88E-03	0,246697	1,79E-03	0,247600	1,78E-03	0,245509	1,82E-03
320	0,257700	1,96E-03	0,253225	2,01E-03	0,256700	1,75E-03	0,252280	2,13E-03

	Detector T07				Detector T16			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	$Uncert_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	$Uncert_{P}$ (k=2)
340	0,270100	1,78E-03	0,268737	1,88E-03	0,269000	1,88E-03	0,267617	1,93E-03
360	0,282500	1,64E-03	0,278941	2,33E-03	0,281200	1,57E-03	0,277993	2,44E-03
380	0,298300	1,97E-03	0,297757	2,12E-03	0,296900	1,96E-03	0,296315	2,12E-03
400	0,317800	1,08E-03	0,314671	2,12E-03	0,316700	1,39E-03	0,313250	2,20E-03
450	0,360300	1,30E-03	0,354986	1,04E-03	0,359800	1,37E-03	0,354913	1,62E-03
500	0,401200	1,28E-03	0,395878	1,12E-03	0,400900	1,04E-03	0,395746	1,72E-03
550	0,442100	9,73E-04	0,435853	1,23E-03	0,441800	9,72E-04	0,435871	1,88E-03
600	0,482900	1,16E-03	0,477196	1,30E-03	0,482500	1,16E-03	0,477078	2,04E-03
650	0,522900	1,67E-03	0,517577	1,44E-03	0,522800	1,67E-03	0,517377	2,24E-03
700	0,564400	1,69E-03	0,557223	1,52E-03	0,563400	1,46E-03	0,556992	2,37E-03
750	0,603100	1,69E-03	0,595832	1,63E-03	0,603300	1,93E-03	0,595552	2,56E-03
800	0,643300	2,19E-03	0,637968	1,73E-03	0,643700	2,32E-03	0,637576	2,72E-03
850	0,683900	2,05E-03	0,678213	3,40E-03	0,684000	2,46E-03	0,677717	4,19E-03
900	0,725200	3,63E-03	0,715617	3,64E-03	0,724500	3,62E-03	0,715058	4,50E-03
950	0,754900	4,08E-03	0,751908	3,81E-03	0,754500	3,92E-03	0,751523	4,69E-03
1000	0,678600	4,21E-03	0,749070	3,95E-03	0,675100	4,05E-03	0,746766	4,75E-03

6.7 Detectors measured by CMI

Table 17. Spectral responsivity of single photodiodes measured by CMI

	Detector F43				Detector F48			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	$Uncert_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	$Uncert_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	$Uncert_{P}$ (k=2)
300	0,130680	1,18E-03	0,129912	9,12E-04	0,132450	1,22E-03	0,131936	9,34E-04
320	0,143570	1,29E-03	0,141754	1,12E-03	0,145380	1,31E-03	0,143618	1,16E-03
340	0,149400	1,34E-03	0,149298	1,02E-03	0,151110	1,36E-03	0,151104	1,04E-03
360	0,146470	1,32E-03	0,145046	1,22E-03	0,148040	1,33E-03	0,146736	1,25E-03
380	0,157640	1,18E-03	0,157007	1,10E-03	0,159020	1,20E-03	0,158576	1,12E-03
400	0,181860	1,36E-03	0,180213	1,20E-03	0,183190	1,37E-03	0,181527	1,22E-03
450	0,223160	8,93E-04	0,221390	7,25E-04	0,224350	8,97E-04	0,222392	6,56E-04
500	0,256080	7,68E-04	0,254018	7,61E-04	0,257150	7,71E-04	0,254989	7,05E-04
550	0,286310	8,59E-04	0,283923	8,28E-04	0,287260	8,62E-04	0,284756	8,27E-04
600	0,315250	9,46E-04	0,313401	8,90E-04	0,316120	9,48E-04	0,314124	8,79E-04
650	0,343330	1,03E-03	0,341860	9,36E-04	0,344110	1,03E-03	0,342441	9,50E-04
700	0,371310	1,11E-03	0,369312	1,03E-03	0,372020	1,12E-03	0,369853	1,01E-03
750	0,399060	1,20E-03	0,396112	1,15E-03	0,399700	1,20E-03	0,396562	1,07E-03
800	0,426550	1,28E-03	0,424983	1,18E-03	0,427130	1,28E-03	0,425282	1,16E-03
850	0,454050	1,36E-03	0,452528	2,27E-03	0,454560	1,36E-03	0,452796	2,26E-03
900	0,481410	1,44E-03	0,478356	2,41E-03	0,481840	1,45E-03	0,478500	2,40E-03
950	0,505630	2,53E-03	0,500921	2,50E-03	0,506270	2,53E-03	0,501104	2,52E-03
1000	0,481780	4,91E-03	0,475433	2,38E-03	0,483650	4,84E-03	0,477094	2,39E-03

Table 18. Spectral responsivity of trap detectors measured by CMI

	Detector T04				Detector T17			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,246170	2,26E-03	0,245788	1,72E-03	0,246290	2,22E-03	0,246055	1,74E-03
320	0,256260	2,31E-03	0,252770	2,05E-03	0,256330	2,31E-03	0,252777	2,03E-03
340	0,269370	2,42E-03	0,268132	1,81E-03	0,269480	2,43E-03	0,268237	1,90E-03
360	0,282610	2,54E-03	0,278106	2,32E-03	0,282730	2,54E-03	0,278025	2,37E-03
380	0,296960	2,23E-03	0,296932	2,05E-03	0,297140	2,23E-03	0,297009	2,13E-03
400	0,316570	2,37E-03	0,313956	2,11E-03	0,316700	2,38E-03	0,313954	2,15E-03
450	0,359720	1,44E-03	0,354407	1,11E-03	0,359950	1,44E-03	0,354436	1,02E-03
500	0,401110	1,20E-03	0,395534	1,17E-03	0,401380	1,20E-03	0,395546	1,10E-03
550	0,441770	1,33E-03	0,435817	1,31E-03	0,442210	1,33E-03	0,435736	1,23E-03
600	0,482270	1,45E-03	0,477090	1,46E-03	0,482710	1,45E-03	0,476945	1,35E-03
650	0,522450	1,57E-03	0,517453	1,50E-03	0,522940	1,57E-03	0,517418	1,49E-03
700	0,562870	1,69E-03	0,557144	1,63E-03	0,563420	1,69E-03	0,557096	1,61E-03
750	0,603320	1,81E-03	0,595819	1,75E-03	0,603930	1,81E-03	0,595757	1,67E-03
800	0,643600	1,93E-03	0,638067	1,85E-03	0,644230	1,93E-03	0,637923	1,79E-03
850	0,684030	2,05E-03	0,677915	3,51E-03	0,684650	2,05E-03	0,677687	3,43E-03
900	0,724260	2,17E-03	0,715361	3,68E-03	0,724900	2,17E-03	0,715055	3,64E-03
950	0,763340	3,82E-03	0,751773	3,92E-03	0,764000	3,82E-03	0,751507	3,75E-03
1000	0,761670	7,62E-03	0,747669	4,12E-03	0,762720	7,63E-03	0,748255	3,78E-03

6.8 Detectors measured by BNM-INM/CNAM

Table 19. Spectral responsivity of single photodiodes measured by BNM-INM/CNAM

	Detector F19				Detector F45			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert$_{LAB}$ (k=2)	$R(\lambda)_{P}$ A/W	Uncert$_{P}$ (k=2)
300	0,132850	9,83E-04	0,132247	1,05E-03	0,129450	9,58E-04	0,128824	1,10E-03
320	0,145630	7,57E-04	0,144142	1,34E-03	0,142250	7,40E-04	0,140792	1,30E-03
340	0,151650	3,64E-04	0,151372	1,20E-03	0,148460	3,56E-04	0,148202	1,20E-03
360	0,148010	3,85E-04	0,147250	1,35E-03	0,145020	3,77E-04	0,144320	1,33E-03
380	0,158630	5,71E-04	0,158915	1,28E-03	0,155890	5,61E-04	0,156213	1,22E-03
400	0,183470	4,04E-04	0,181852	1,31E-03	0,180740	3,98E-04	0,179385	1,30E-03
450	0,224410	4,94E-04	0,223559	7,72E-04	0,221860	4,88E-04	0,220121	9,99E-04
500	0,257090	5,66E-04	0,256024	7,90E-04	0,254900	5,61E-04	0,253073	8,07E-04
550	0,287190	6,32E-04	0,285779	8,74E-04	0,285040	6,27E-04	0,283319	8,77E-04
600	0,315980	8,22E-04	0,315200	1,03E-03	0,313980	8,16E-04	0,312609	9,42E-04
650	0,343740	8,94E-04	0,343670	1,01E-03	0,341910	8,89E-04	0,341103	1,05E-03
700	0,371760	8,18E-04	0,371063	1,12E-03	0,370080	8,14E-04	0,368775	1,08E-03
750	0,399400	9,59E-04	0,397825	1,18E-03	0,397710	9,55E-04	0,395826	1,19E-03
800	0,427070	9,40E-04	0,426405	1,33E-03	0,425590	9,36E-04	0,423890	1,33E-03
850	0,454230	1,27E-03	0,454156	2,49E-03	0,452780	1,27E-03	0,451080	2,39E-03
900	0,481890	1,16E-03	0,479956	2,64E-03	0,480680	1,15E-03	0,476988	2,54E-03
950	0,505820	1,11E-03	0,503503	2,92E-03	0,504680	1,11E-03	0,500087	2,65E-03
1000	0,486720	1,36E-03	0,479107	3,42E-03	0,486420	1,36E-03	0,476390	2,41E-03

Table 20. Spectral responsivity of trap detectors measured by BNM-INM/CNAM

	Detector T10				Detector T12			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300	0,246460	1,82E-03	0,244927	2,02E-03	0,246660	1,83E-03	0,246170	1,76E-03
320	0,255410	1,89E-03	0,251967	2,31E-03	0,255570	1,33E-03	0,252822	2,06E-03
340	0,269190	1,99E-03	0,267315	2,07E-03	0,269260	6,46E-04	0,268370	1,86E-03
360	0,280300	7,29E-04	0,277269	2,58E-03	0,280480	7,29E-04	0,278373	2,33E-03
380	0,296370	7,71E-04	0,296207	2,36E-03	0,296440	1,07E-03	0,297226	2,03E-03
400	0,316130	8,22E-04	0,312969	2,22E-03	0,316210	6,96E-04	0,314148	2,03E-03
450	0,359180	7,90E-04	0,353757	1,39E-03	0,358980	7,90E-04	0,354967	1,19E-03
500	0,400530	8,81E-04	0,394740	1,40E-03	0,400520	8,81E-04	0,395867	1,24E-03
550	0,441350	9,71E-04	0,434787	1,52E-03	0,440810	9,70E-04	0,435910	1,32E-03
600	0,481770	1,06E-03	0,476066	1,61E-03	0,481530	1,25E-03	0,477264	1,45E-03
650	0,521680	1,15E-03	0,516402	1,69E-03	0,521540	1,36E-03	0,517606	1,59E-03
700	0,562320	1,24E-03	0,556098	1,76E-03	0,562190	9,70E-04	0,557288	1,66E-03
750	0,602720	1,33E-03	0,594634	1,87E-03	0,602540	1,45E-03	0,596030	1,72E-03
800	0,643380	1,42E-03	0,636442	1,98E-03	0,643200	1,42E-03	0,637945	1,84E-03
850	0,683320	1,50E-03	0,676656	3,65E-03	0,683130	1,91E-03	0,678417	3,40E-03
900	0,724140	1,59E-03	0,713796	3,66E-03	0,723880	1,74E-03	0,715790	3,72E-03
950	0,762290	1,68E-03	0,749799	4,01E-03	0,762110	1,68E-03	0,751556	3,78E-03
1000	0,766560	1,69E-03	0,745831	4,31E-03	0,767060	2,30E-03	0,747940	4,37E-03

6.9 Detectors measured by SP

Table 21. Spectral responsivity of single photodiodes measured by SP

	Detector F21				Detector F34			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_{P}$ A/W	Uncert_{P} (k=2)
300	0,131100	2,28E-03	0,130162	1,23E-03	0,131100	2,28E-03	0,129856	1,24E-03
320	0,144200	2,51E-03	0,141845	1,56E-03	0,144400	2,51E-03	0,141621	1,56E-03
340	0,150000	2,61E-03	0,149312	1,41E-03	0,150200	2,61E-03	0,149018	1,44E-03
360	0,147300	2,56E-03	0,145088	1,65E-03	0,147400	2,56E-03	0,144982	1,47E-03
380	0,158000	2,75E-03	0,157083	1,49E-03	0,158200	2,75E-03	0,156865	1,55E-03
400	0,182400	3,17E-03	0,179978	1,63E-03	0,182600	3,18E-03	0,179926	1,62E-03
450	0,223500	1,03E-03	0,221713	6,31E-04	0,223700	1,03E-03	0,221466	6,48E-04
500	0,256400	1,18E-03	0,254125	6,86E-04	0,256600	1,18E-03	0,253896	7,02E-04
550	0,286600	1,32E-03	0,283770	7,54E-04	0,286800	1,32E-03	0,283520	7,67E-04
600	0,315600	1,45E-03	0,313132	8,38E-04	0,315800	1,45E-03	0,312901	8,41E-04
650	0,343800	1,58E-03	0,341443	9,13E-04	0,344200	1,58E-03	0,341215	9,20E-04
700	0,371700	2,53E-03	0,368826	9,75E-04	0,372000	2,53E-03	0,368551	9,90E-04
750	0,399600	2,72E-03	0,395489	1,05E-03	0,399400	2,72E-03	0,395214	1,06E-03
800	0,427200	2,90E-03	0,424271	1,13E-03	0,427100	2,90E-03	0,424000	1,14E-03
850	0,454300	3,09E-03	0,451647	2,22E-03	0,454400	3,09E-03	0,451428	2,22E-03
900	0,481200	7,51E-03	0,477366	2,34E-03	0,481700	7,51E-03	0,477108	2,35E-03
950	0,507400	7,92E-03	0,500311	2,46E-03	0,507800	7,92E-03	0,500027	2,46E-03
1000	0,490000	7,64E-03	0,477865	2,43E-03	0,490200	7,65E-03	0,477038	2,37E-03

Table 22. Spectral responsivity of trap detectors measured by SP

	Detector T11				Detector T14			
Wavel (nm)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_P$ A/W	Uncert_P (k=2)	$R(\lambda)_{LAB}$ A/W	Uncert_{LAB} (k=2)	$R(\lambda)_P$ A/W	Uncert_P (k=2)
300	0,246200	4,58E-03	0,243722	2,68E-03	0,246300	4,58E-03	0,244310	2,29E-03
320	0,255900	4,76E-03	0,250737	2,94E-03	0,256100	4,76E-03	0,251129	2,77E-03
340	0,269000	5,00E-03	0,266070	2,78E-03	0,269100	5,01E-03	0,266863	2,54E-03
360	0,281800	5,24E-03	0,276948	3,10E-03	0,282000	5,25E-03	0,277126	2,78E-03
380	0,296900	5,52E-03	0,294693	3,24E-03	0,297000	5,52E-03	0,295345	2,89E-03
400	0,316700	5,89E-03	0,312374	2,99E-03	0,317000	5,90E-03	0,312844	2,87E-03
450	0,359400	9,34E-04	0,355781	1,10E-03	0,359400	9,34E-04	0,356038	1,07E-03
500	0,400500	1,04E-03	0,396585	1,20E-03	0,400600	1,04E-03	0,396681	1,18E-03
550	0,441500	1,15E-03	0,436554	1,21E-03	0,441600	1,15E-03	0,436667	1,24E-03
600	0,482000	1,25E-03	0,477774	1,40E-03	0,482100	1,25E-03	0,477839	1,41E-03
650	0,522300	1,36E-03	0,518408	1,46E-03	0,522400	1,36E-03	0,518539	1,52E-03
700	0,562600	2,81E-03	0,557854	1,57E-03	0,562700	2,81E-03	0,558043	1,63E-03
750	0,602800	3,01E-03	0,596600	1,69E-03	0,603000	3,02E-03	0,596872	1,68E-03
800	0,642800	3,21E-03	0,638694	1,85E-03	0,643100	3,22E-03	0,638962	1,80E-03
850	0,682800	3,41E-03	0,678653	3,48E-03	0,683200	3,42E-03	0,679335	3,60E-03
900	0,722700	1,14E-02	0,716198	3,71E-03	0,723200	1,14E-02	0,716839	3,97E-03
950	0,762000	1,20E-02	0,752703	3,96E-03	0,762700	1,21E-02	0,753453	5,22E-03
1000	0,765200	1,21E-02	0,750783	4,85E-03	0,766300	1,21E-02	0,753168	8,52E-03

7 Data analysis of the comparison

Data analysis has been conducted according to the EUROMET Guidelines on Conducting Comparisons, which refers to the “Guidelines for CCPR Comparison Report Preparation”. The analysis follows the procedure given in appendix B of that document.

The following table summarizes the symbols used in this chapter and their meanings.

Table 23. Symbols used in equations of this chapter

Symbol	Meaning
$R_{i,j}(\lambda)$	Spectral responsivity measured by every laboratory for each detector
$R^P_{i,j}(\lambda)$	Spectral responsivity measured by pilot for each detector
$\Delta_{i,j}$	Relative difference between NMi *i* and pilot for detector *j*
$u_{rel,add}(R_{i,j}(\lambda))$	Additional uncertainty from transfer
Δ_i	Average relative difference for NMi *i*
$u_{cut\text{-}off}$	Uncertainty cut-off

Symbol	Meaning
$u_{rel,adj}$	Adjusted relative standard uncertainty for every participant
$u_{\mathrm{T}}(\Delta_{\mathrm{i}})$	Transfer uncertainty component in $u(\Delta_{\mathrm{i}})$
$u_{adj}(\Delta_{\mathrm{i}})$	Uncertainty of Δ_i after cut-off
w_i	weights for every NMI
$\Delta_{EURAMET\text{-}RV}$	Key comparison reference value (EURAMET-RV)
$u(\Delta_{EURAMET\text{-}RV})$	Uncertainty of the EURAMET-RV
$\mathrm{D_i}$	Unilateral degree of equivalence
U_i	Expanded uncertainty of EURAMET-DoE
X^2_{obs}	Observed chi-squared
$D_{i,m}$	Bilateral degree of equivalence between NMI *I* and NMI *m*
$U_{i,m}$	Expanded uncertainty of bilateral degree of equivalence

7.1 Calculation of the EURAMET-RV

The following steps have been done to calculate the EURAMET-RV:

a) For each NMI i for each detector j, the relative difference $\Delta_{\mathrm{i,j}}$ between NMI measurement, $R_{i,j}(\lambda)$, and Pilot measurement, $R^P_{i,j}(\lambda)$, is given by,

$$\Delta_{i,j}(\lambda) = \frac{R_{i,j}(\lambda)}{R^P_{i,j}(\lambda)} - 1 \qquad (4)$$

and its uncertainty by

$$u\left(\Delta_{i,j}(\lambda)\right) = \sqrt{u^2_{rel}\left(R_{i,j}(\lambda)\right) + u^2_{rel}\left(R^{PR}_{i,j}(\lambda)\right) + u^2_{rel,add}\left(R_{i,j}(\lambda)\right)} \qquad (5)$$

Where $u_{rel,add}(R_{i,j}(\lambda))$ is an additional uncertainty arising from the comparison transfer: artefacts drift, different measurement conditions between the pilot and the laboratory, etc. In this case this value has been taken as the combined uncertainty associated with the transfer (see 3.1.15, Table 4). The term $u^2_{rel}(R^{PR}_{i,\ j})$ rather than $u^2_{rel}(R^P_{i,\ j})$ is used for Pilot lab uncertainty because Pilot measurements $R^P_{i,\ j}$ are strongly correlated with each other, and only uncorrelated components in Pilot measurements contribute when $\Delta_{\mathrm{i,\ j}}$ are further reduced to calculate EURAMET-DoE. Only uncertainty of responsivity scale and standard deviation of measurements are included in the estimate of $u^2_{rel}(R^P_{i,j})$.

b) For each NMI i, the relative differences Δ_{i} (average of the four detectors) are obtained by

$$\Delta_i = \frac{1}{4}\sum_{j=1}^{4}\Delta_{i,j} \qquad (6)$$

and its uncertainty by

$$u(\Delta_i) = \frac{1}{4}\sum_{j=1}^{4}u(\Delta_{i,j}) \qquad (7)$$

because it is assumed that the results from the four detectors measured by the same NMI are nearly fully correlated.

For Pilot laboratory i = 0 is used hereinafter, $\Delta_0 = 0$ and $u(\Delta_0) = u_{rel}\left(\bar{R}^P\right)$ where $u_{rel}\left(\bar{R}^P\right)$ is the average total uncertainty of all measurements at Pilot lab:

$$u_{rel}\left(\bar{R}^P\right) = \frac{1}{4N}\sum_{i=1}^{N}\sum_{j=1}^{4}u_{rel}\left(R_{i,j}^P\right) \qquad (8)$$

Where N is the number of participating laboratories.

Average relative differences and their uncertainties corresponding to every laboratory are shown in the next tables and in Figures 2 to 5.

Table 24. Average relative differences of every participant with respect to the pilot

Wavelength / nm	METAS	JV	GUM	INM-Ro	NMi-VSL
300	0,01301	0,00986		-0,03895	0,01035
320	0,01843	0,01778		-0,02164	0,01565
340	0,00600	0,00687		-0,01730	0,00476
360	0,01509	0,01571		-0,02843	0,01255
380	0,00525	0,00304	0,00527	-0,03481	0,00545
400	0,01231	0,01244	0,01411	0,00320	0,01171
450	0,00774	0,00670	0,00810	0,00964	0,00952
500	0,00769	0,00784	0,00892	0,01206	0,01035
550	0,00942	0,00892	0,00897	0,00994	0,01126
600	0,00717	0,00704	0,00688	0,00816	0,00873
650	0,00611	0,00559	0,00651	0,00749	0,00769
700	0,00732	0,00679	0,00698	0,00773	0,00856
750	0,00895	0,00974	0,00855	0,00980	0,01050
800	0,00566	0,00529	0,00508	0,00594	0,00672
850	0,00503	0,00486	0,00561	0,00535	0,00619
900	0,00815	0,00771	0,00846	-0,00099	0,00932
950	0,01040	0,01103	0,01161	-0,01129	0,01177
1 000	0,00433	0,01414	0,01550	-0,00066	0,01061

Wavelength / nm	UME	CMI	BNM-INM	SP
300	0,00649	0,00308	0,00442	0,00878
320	-0,02916	0,01324	0,01130	0,01915
340	-0,06782	0,00249	0,00348	0,00798
360	0,01679	0,01296	0,00713	0,01676
380	0,00786	0,00184	-0,00149	0,00686
400	0,01374	0,00884	0,00828	0,01386

Wavelength / nm	UME	CMI	BNM-INM	SP
450	0,00896	0,01184	0,00959	0,00944
500	0,00917	0,01136	0,00945	0,00984
550	0,00959	0,01143	0,00934	0,01104
600	0,00762	0,00880	0,00694	0,00873
650	0,00643	0,00738	0,00510	0,00765
700	0,00841	0,00822	0,00635	0,00850
750	0,00982	0,01042	0,00831	0,01041
800	0,00586	0,00665	0,00618	0,00678
850	0,00581	0,00664	0,00518	0,00606
900	0,00983	0,00989	0,00939	0,00890
950	0,00635	0,01293	0,01112	0,01358
1 000	-0,03195	0,01629	0,02258	0,02241

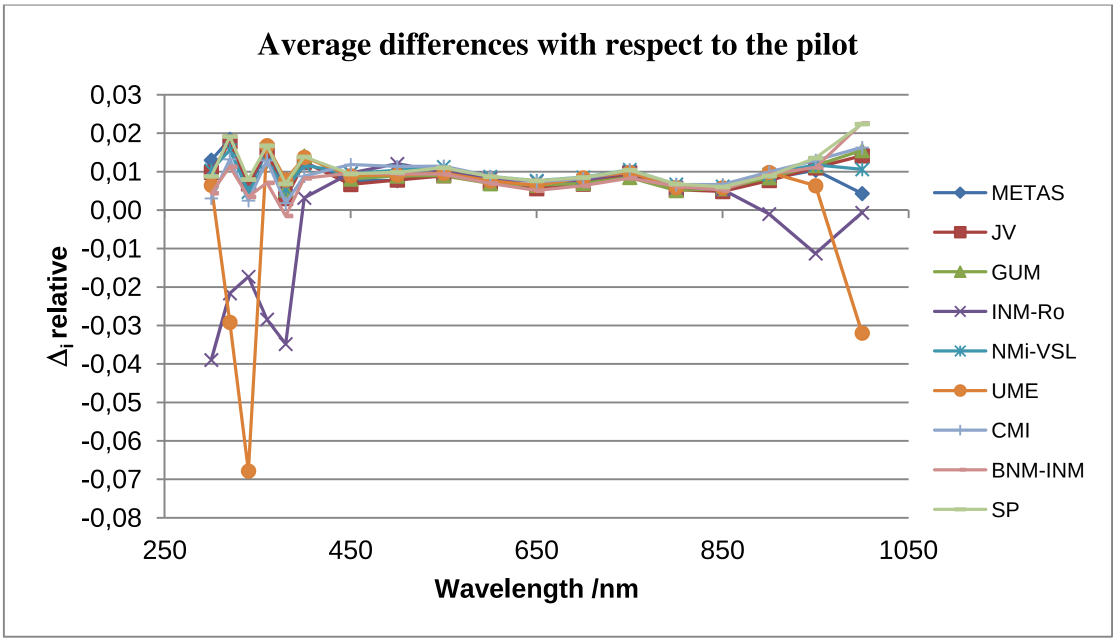


Figure 2. Average relative difference of every laboratory with respect to the pilot.

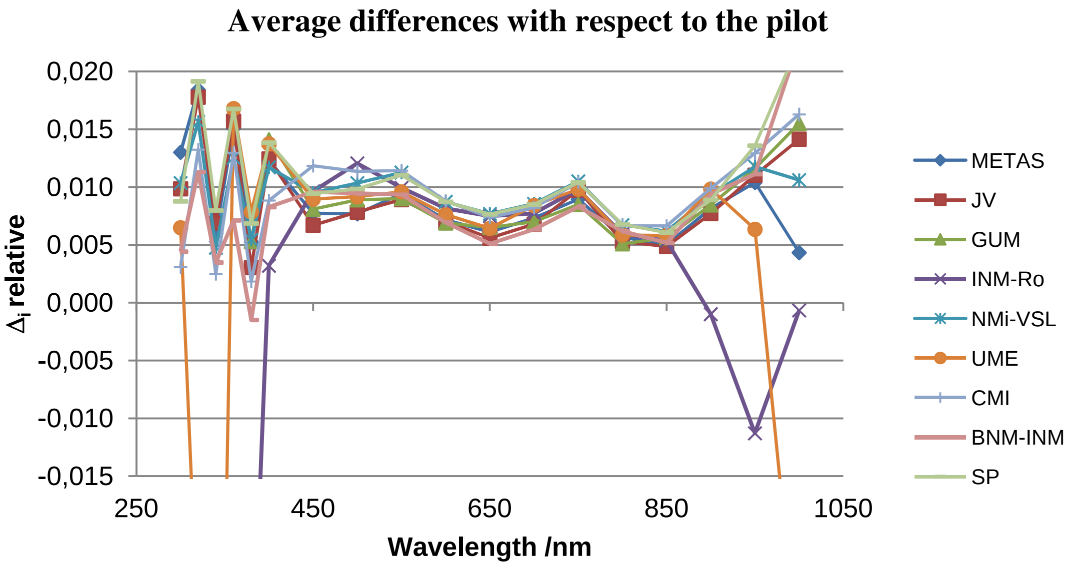


Figure 3. Detail of average relative difference of every laboratory with respect to the pilot.

Table 25. Uncertainty of average relative difference of every participant with respect to the pilot

Wavelength / nm	METAS	JV	GUM	INM-Ro	NMi-VSL
300	0,00555	0,00646		0,02905	0,00557
320	0,00646	0,00659		0,02338	0,00616
340	0,00539	0,00592		0,01932	0,00540
360	0,00659	0,00675		0,01680	0,00593
380	0,00559	0,00594	0,00630	0,01457	0,00561
400	0,00513	0,00543	0,00525	0,00663	0,00492
450	0,00347	0,00405	0,00395	0,00501	0,00277
500	0,00296	0,00333	0,00328	0,00459	0,00271
550	0,00279	0,00300	0,00332	0,00452	0,00263
600	0,00280	0,00337	0,00323	0,00447	0,00266
650	0,00275	0,00307	0,00320	0,00445	0,00264
700	0,00271	0,00293	0,00327	0,00480	0,00264
750	0,00278	0,00310	0,00333	0,00484	0,00263
800	0,00279	0,00295	0,00351	0,00510	0,00262
850	0,00496	0,00512	0,00515	0,00653	0,00494
900	0,00497	0,00525	0,00508	0,00654	0,00498
950	0,00537	0,00530	0,00523	0,00818	0,00509
1 000	0,00538	0,00595	0,00587	0,00904	0,00590

Wavelength / nm	UME	CMI	BNM-INM	SP
300	0,00628	0,00675	0,00653	0,01048
320	0,00659	0,00721	0,00669	0,01082
340	0,00596	0,00660	0,00557	0,01043
360	0,00650	0,00741	0,00628	0,01069
380	0,00590	0,00625	0,00552	0,01052
400	0,00500	0,00594	0,00486	0,01024
450	0,00339	0,00341	0,00321	0,00331
500	0,00318	0,00308	0,00301	0,00327
550	0,00305	0,00305	0,00296	0,00320
600	0,00308	0,00305	0,00305	0,00323
650	0,00315	0,00302	0,00300	0,00321
700	0,00308	0,00303	0,00290	0,00396
750	0,00322	0,00303	0,00295	0,00396
800	0,00332	0,00302	0,00291	0,00395
850	0,00528	0,00515	0,00513	0,00576
900	0,00556	0,00518	0,00511	0,00929
950	0,00583	0,00554	0,00508	0,00935
1 000	0,00596	0,00701	0,00521	0,00961

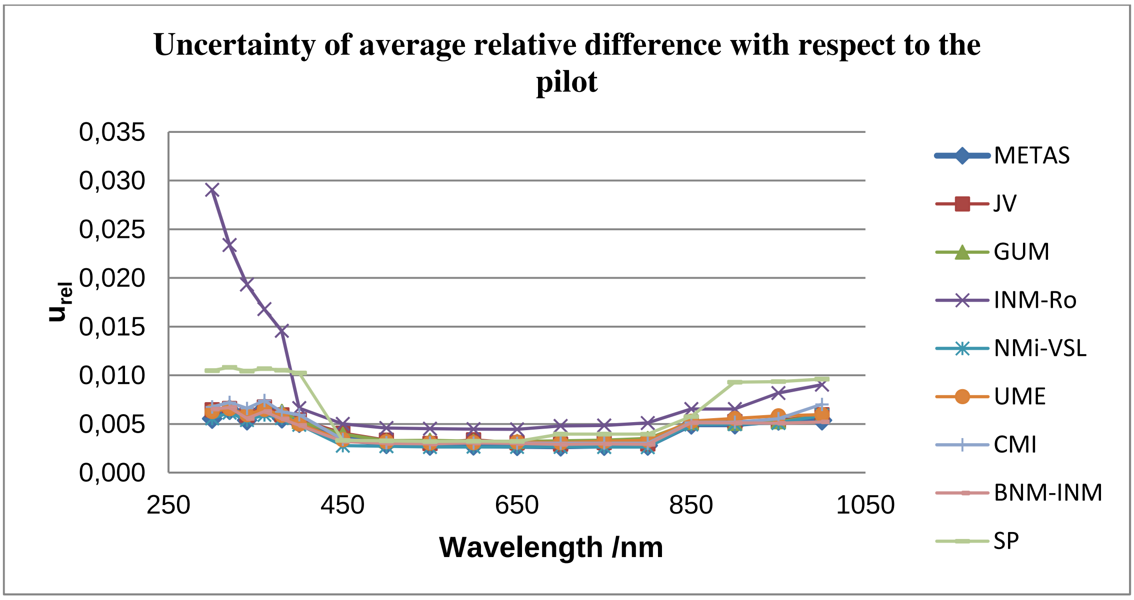


Figure 4. Standard uncertainty of average relative difference of every participant respect to the pilot

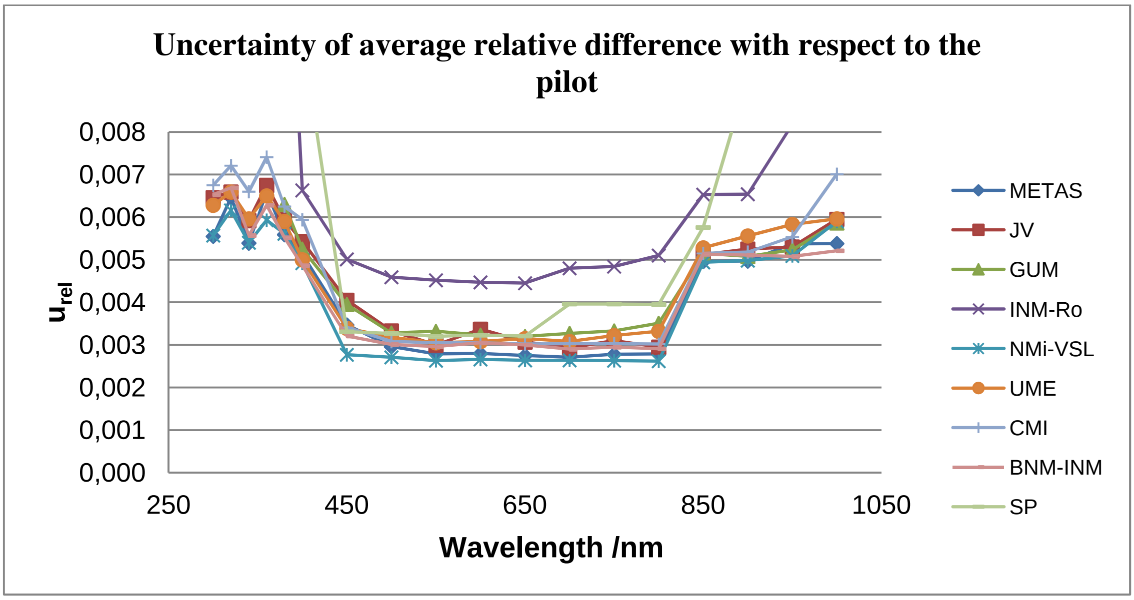


Figure 5. Detail of standard uncertainty of average relative difference of every participant respect to the pilot

c) The relative uncertainty of measurements of NMI i, averaged for all detectors is determined by

$$u_{rel}\left(\bar{R}_i\right) = \frac{1}{4}\sum_{j=1}^{4} u_{rel}\left(R_{i,j}\right) \qquad (9)$$

For convenience of calculation here in after,

$$u_{rel}\left(\bar{R}_0\right) = u_{rel}\left(\bar{R}^{P}\right) \qquad (10)$$

d) The EURAMET-RV is calculated by using weighted mean with cut-off. The cut-off value $u_{cut\text{-}off}$ is calculated by

$$u_{cut-off} = average\left\{u_{rel}\left(\bar{R}_i\right)\right\} \text{ for } u_{rel}\left(\bar{R}_i\right) \le median\left\{u_{rel}\left(\bar{R}_i\right)\right\};\ i=0\ to\ N \qquad (11)$$

The $u_{cut\text{-}off}$ values obtained for every wavelength are shown in Table 25.

Table 26. Uncertainty cut-off

Wavelength /nm	$\mathbf{u_{cut\text{-}off}}$
300	0,00266
320	0,00232
340	0,00204
360	0,00182
380	0,00198
400	0,00138
450	0,00089
500	0,00084
550	0,00084
600	0,00088
650	0,00090
700	0,00085
750	0,00091
800	0,00090
850	0,00091
900	0,00082
950	0,00136
1 000	0,00234

Then, the reported uncertainty $u_{rel}\left(\bar{R}_i\right)$ of each NMI *i* is adjusted by the cut-off as

$$\begin{aligned} u_{rel,adj}\left(\bar{R}_i\right) &= u_{rel}\left(\bar{R}_i\right) \quad for \quad u_{rel}\left(\bar{R}_i\right) \ge cut-off \\ u_{rel,adj}\left(\bar{R}_i\right) &= u_{cut-off} \quad for \quad u_{rel}\left(\bar{R}_i\right) < cut-off \end{aligned} \qquad (12)$$

The values obtained for the adjusted uncertainty after these equations for every laboratory are shown in Table 26.

Table 27. Adjusted relative standard uncertainty for every participant

Wavelength / nm	METAS	JV	GUM	INM-Ro	NMi-VSL	UME	CMI	BNM-INM	SP
300	0,00266	0,00280		0,02850	0,00266	0,00370	0,00455	0,00370	0,00900
320	0,00232	0,00245		0,02250	0,00232	0,00340	0,00450	0,00288	0,00900
340	0,00204	0,00225		0,01850	0,00204	0,00348	0,00450	0,00204	0,00900
360	0,00182	0,00225		0,01550	0,00182	0,00273	0,00450	0,00182	0,00900
380	0,00198	0,00220	0,00323	0,01350	0,00198	0,00308	0,00375	0,00198	0,00900
400	0,00150	0,00220	0,00177	0,00450	0,00138	0,00188	0,00375	0,00138	0,00900
450	0,00089	0,00120	0,00120	0,00350	0,00089	0,00170	0,00200	0,00110	0,00180
500	0,00084	0,00110	0,00119	0,00350	0,00084	0,00138	0,00150	0,00110	0,00180

Wavelength / nm	METAS	JV	GUM	INM-Ro	NMi-VSL	UME	CMI	BNM-INM	SP
550	0,00084	0,00110	0,00135	0,00350	0,00084	0,00123	0,00150	0,00110	0,00180
600	0,00088	0,00110	0,00136	0,00350	0,00088	0,00128	0,00150	0,00125	0,00180
650	0,00090	0,00110	0,00136	0,00350	0,00090	0,00145	0,00150	0,00125	0,00180
700	0,00085	0,00110	0,00150	0,00400	0,00085	0,00135	0,00150	0,00104	0,00295
750	0,00091	0,00110	0,00161	0,00400	0,00091	0,00158	0,00150	0,00118	0,00295
800	0,00090	0,00110	0,00191	0,00425	0,00090	0,00183	0,00150	0,00110	0,00295
850	0,00091	0,00110	0,00134	0,00425	0,00091	0,00175	0,00150	0,00133	0,00295
900	0,00082	0,00110	0,00105	0,00425	0,00082	0,00235	0,00150	0,00118	0,00785
950	0,00214	0,00165	0,00149	0,00650	0,00136	0,00300	0,00250	0,00136	0,00785
1 000	0,00234	0,00325	0,00281	0,00725	0,00234	0,00333	0,00503	0,00234	0,00785

The transfer uncertainty component in $u(\Delta_i)$ is separated by

$$u_T(\Delta_i)=\sqrt{u^2(\Delta_i)-u_{rel}^2\left(\bar{R}_i\right)} \qquad (13)$$

The uncertainty of Δ_i after cut-off is given by

$$u_{adj}(\Delta_i)=\sqrt{u_{rel,adj}^2\left(\bar{R}_i\right)+u_T^2(\Delta_i)} \qquad (14)$$

The weights w_i for every NMI are determined by

$$w_i=\frac{u_{adj}^{-2}(\Delta_i)}{\sum_{i=0}^{N}u_{adj}^{-2}(\Delta_i)} \qquad (15)$$

Weights obtained for every laboratory are shown in Figure 6.

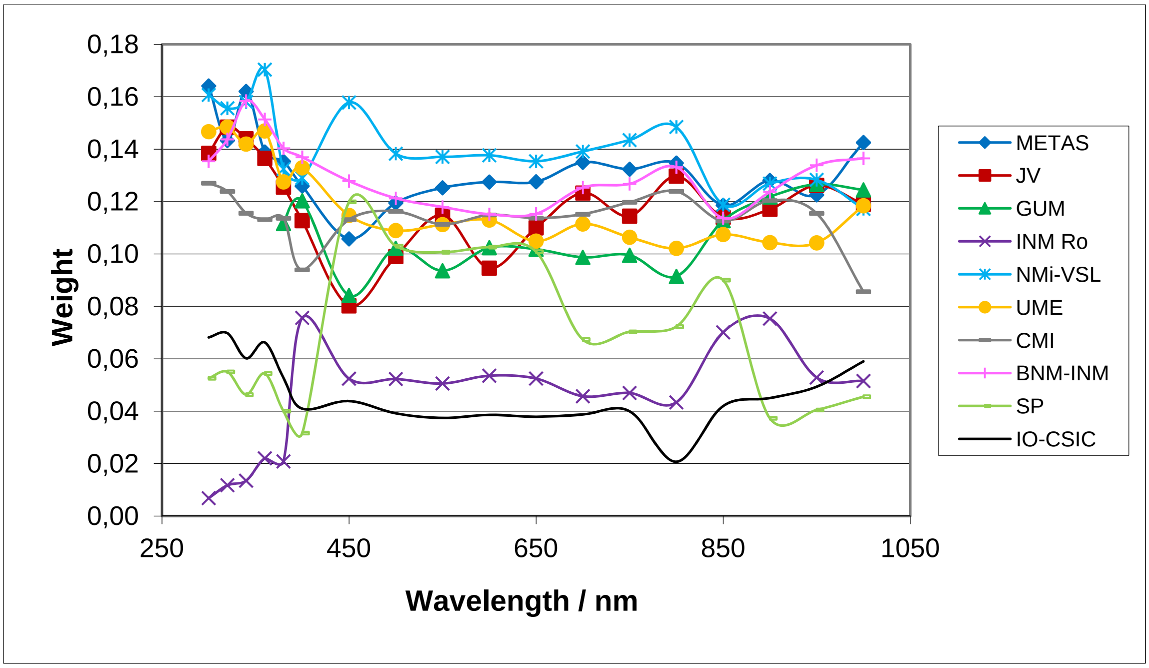


Figure 6. Weight of every laboratory for the calculation of EURAMET-RV

Finally, the EURAMET-RV, $\Delta_{EURAMET\text{-}RV}$, is determined for every wavelength by

$$\Delta_{KCRV}(\lambda) = \sum_{i=0}^{N} w_i(\lambda)\Delta_i(\lambda) \qquad (16)$$

The uncertainty of the EURAMET-RV (weighted mean with cut-off) is given by

$$u(\Delta_{KCRV}(\lambda)) = \frac{\sqrt{\sum_{i=0}^{N} \frac{u^2(\Delta_i(\lambda))}{u_{adj}^4(\Delta_i(\lambda))}}}{\sum_{i=0}^{N} u_{adj}^{-2}(\Delta_i(\lambda))} \qquad (17)$$

Values obtained are shown in Table 27 and Figure 7.

Table 28. EURAMET-RV at every wavelength

Wavelength /nm	$\Delta_{\mathrm{EURAMET\text{-}RV}}$
300	0,0073
320	0,0075
340	-0,0059
360	0,0117
380	0,0030
400	0,0106
450	0,0088
500	0,0091
550	0,0096
600	0,0075
650	0,0064
700	0,0073
750	0,0092
800	0,0059
850	0,0054
900	0,0078
950	0,0093
1 000	0,0071

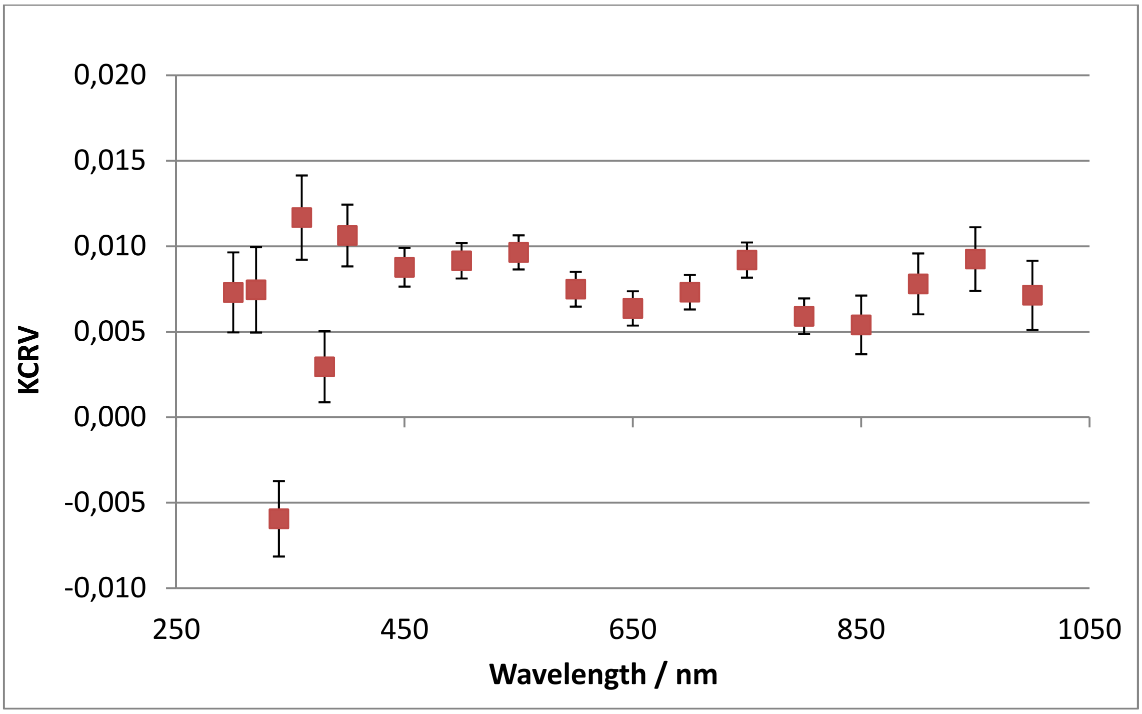


Figure 7. EURAMET-RV versus wavelength. Standard uncertainty is shown as error bars.

7.2 Calculation of degree of equivalence

a) The unilateral degree of equivalence, EURAMET-DoE, of every NMI and its correspondent uncertainty are given by

$$D_i = \Delta_i - \Delta_{KCRV}$$

$$U_i = k\sqrt{u_i^2(\Delta_i) + u^2(\Delta_{KCRV}) - 2\left[\frac{u^2(\Delta_i)}{u_{adj}^2(\Delta_i)} \Big/ \sum_{j=0}^{N} u_{adj}^{-2}(\Delta_j)\right]}\;;\; k = 2 \qquad (18)$$

This takes into account the effect of correlation between Δ_i $\Delta_{\text{EURAMET-RV}}$.

Unilateral EURAMET-DoE and their uncertainties are shown in Figures 8 to 11 and Tables 28 and 29, respectively.

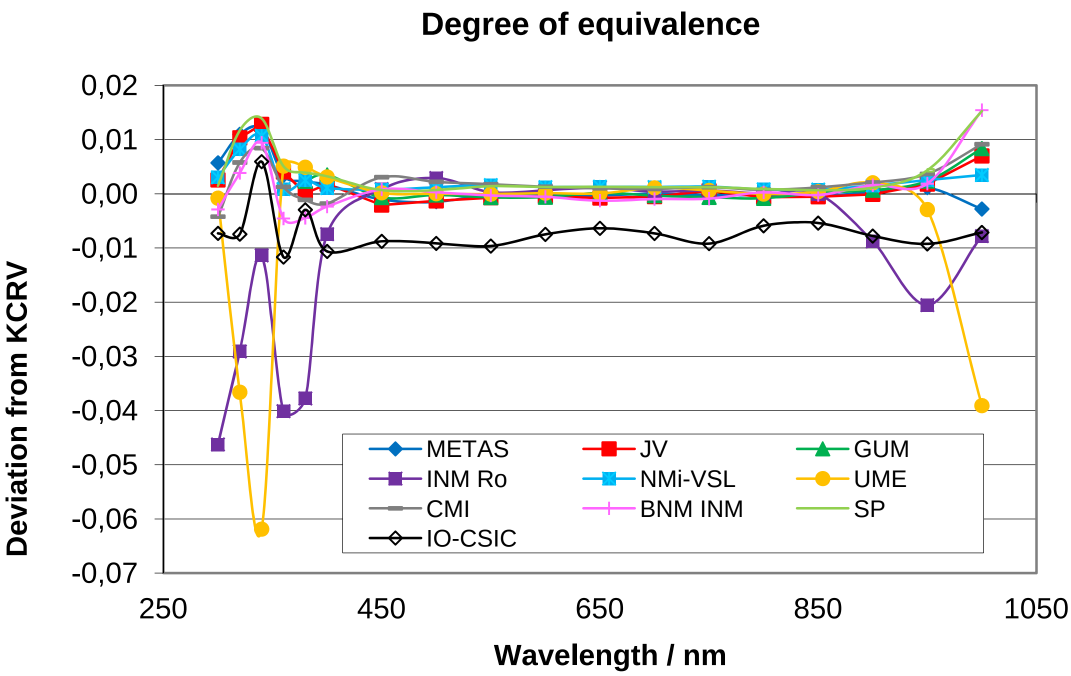


Figure 8. Unilateral deviation of participating laboratories from the EURAMET-RV

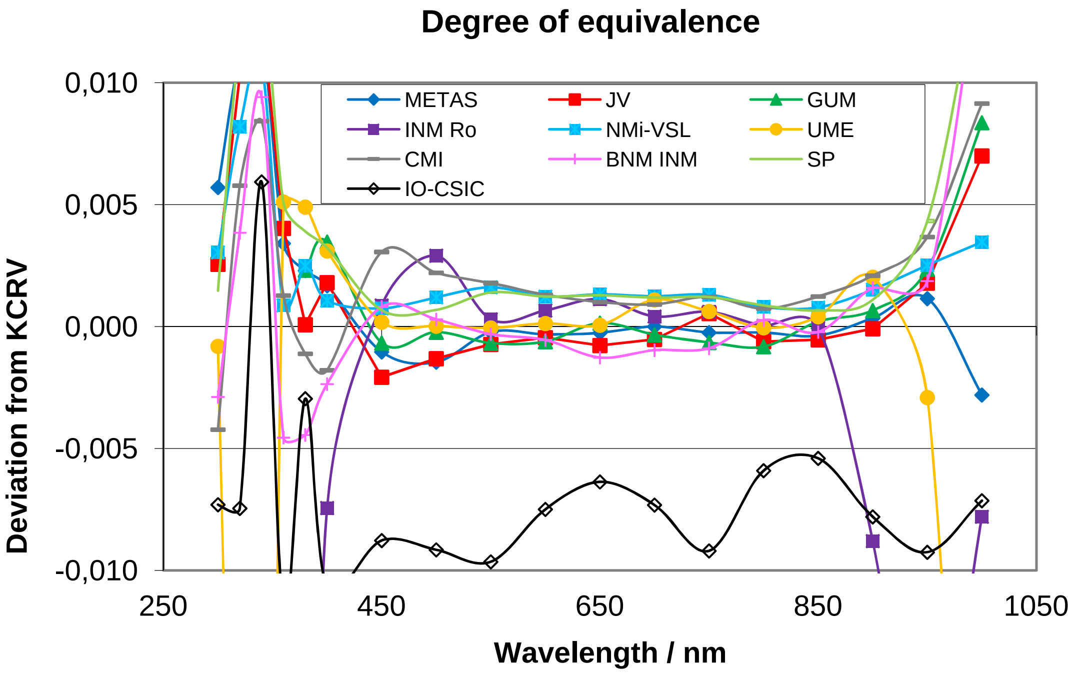


Figure 9. Detail of unilateral deviation of participating laboratories from the EURAMET-RV

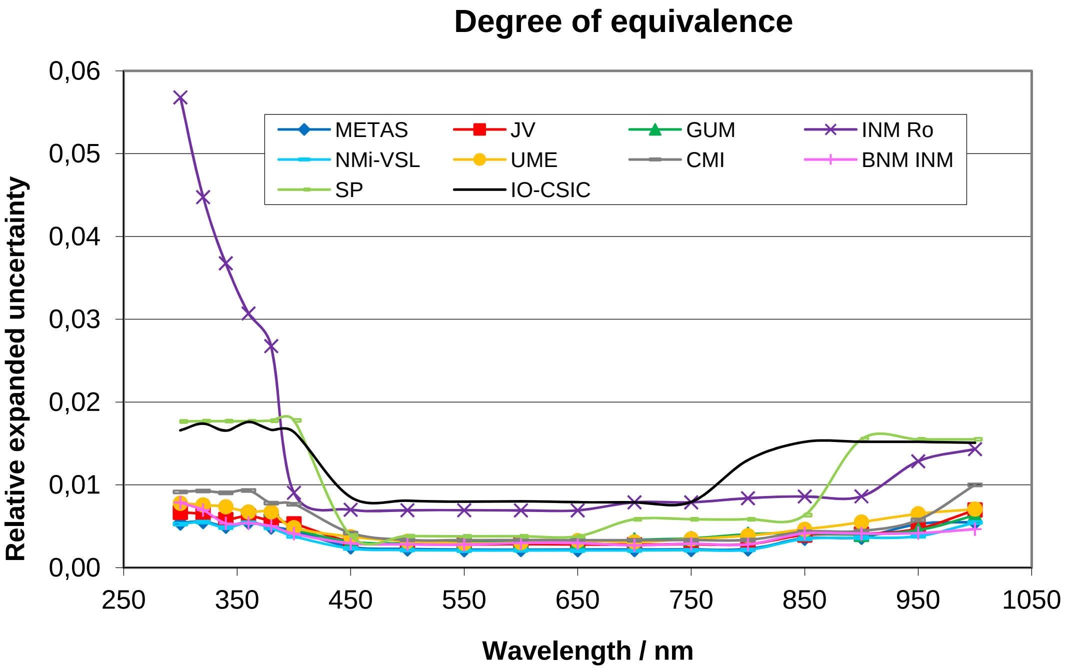


Figure 10. Relative expanded uncertainty of difference from EURAMET-RV for every laboratory

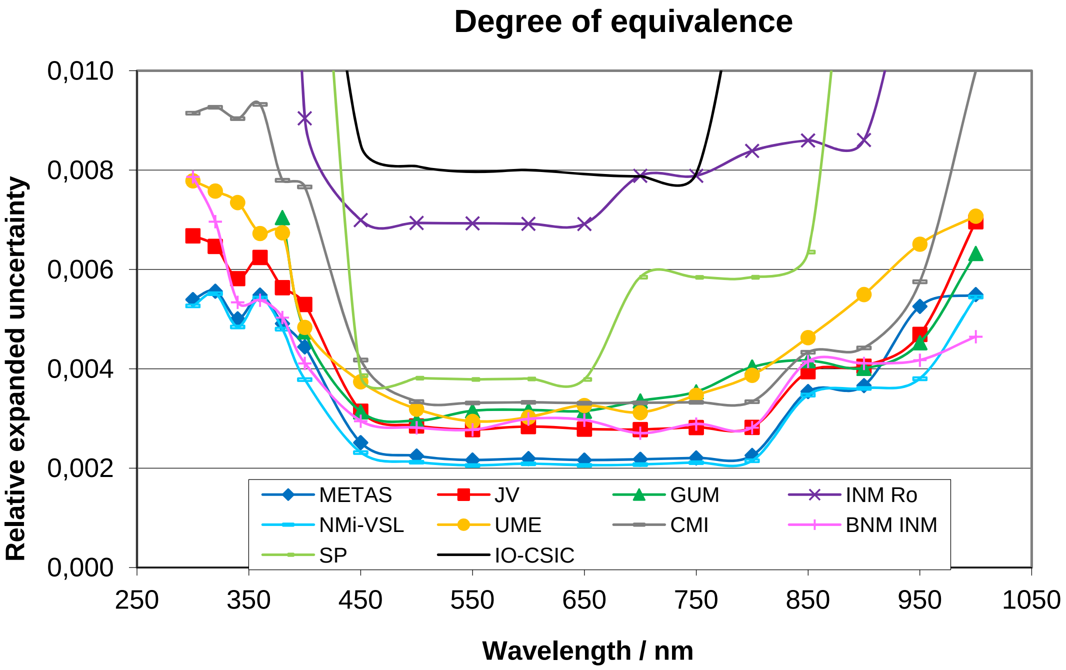


Figure 11. Detail of relative expanded uncertainty of difference from EURAMET-RV for every laboratory

Table 29. Degree of equivalence of participating laboratories with respect to the EURAMET-RV

	UME	GUM	BNM INM	INM Romania	JUSTERVES ENET	METAS	CMI	SP	NMi-VSL	IO-CSIC
Wavelenght (nm)	D_i	D_i	D_i	D_i	D_i	D_i	D_i	D_i	D_i	D_i
300	-0,00081		-0,00288	-0,04625	0,00256	0,00571	-0,00422	0,00148	0,00305	-0,00730
320	-0,03661		0,00385	-0,02909	0,01033	0,01098	0,00578	0,01170	0,00820	-0,00745
340	-0,06188		0,00942	-0,01136	0,01281	0,01194	0,00843	0,01392	0,01070	0,00594
360	0,00511		-0,00455	-0,04011	0,00403	0,00341	0,00128	0,00508	0,00088	-0,01168
380	0,00490	0,00232	-0,00444	-0,03776	0,00008	0,00230	-0,00111	0,00391	0,00249	-0,00295
400	0,00310	0,00347	-0,00236	-0,00744	0,00181	0,00168	-0,00179	0,00323	0,00107	-0,01063
450	0,00019	-0,00067	0,00082	0,00087	-0,00207	-0,00103	0,00307	0,00067	0,00075	-0,00877
500	0,00002	-0,00023	0,00030	0,00291	-0,00131	-0,00146	0,00221	0,00069	0,00120	-0,00915
550	-0,00005	-0,00068	-0,00031	0,00030	-0,00072	-0,00022	0,00179	0,00140	0,00162	-0,00964
600	0,00013	-0,00061	-0,00055	0,00066	-0,00045	-0,00032	0,00131	0,00124	0,00124	-0,00749
650	0,00006	0,00014	-0,00127	0,00113	-0,00077	-0,00025	0,00101	0,00129	0,00133	-0,00637
700	0,00110	-0,00033	-0,00096	0,00042	-0,00052	0,00000	0,00091	0,00119	0,00125	-0,00731
750	0,00062	-0,00065	-0,00089	0,00061	0,00054	-0,00024	0,00122	0,00122	0,00131	-0,00919
800	-0,00004	-0,00082	0,00027	0,00004	-0,00061	-0,00025	0,00074	0,00088	0,00081	-0,00590
850	0,00041	0,00021	-0,00022	-0,00005	-0,00054	-0,00037	0,00124	0,00066	0,00079	-0,00540
900	0,00203	0,00067	0,00159	-0,00879	-0,00008	0,00035	0,00209	0,00110	0,00152	-0,00780
950	-0,00290	0,00236	0,00187	-0,02054	0,00178	0,00115	0,00368	0,00433	0,00252	-0,00925
1000	-0,03909	0,00837	0,01544	-0,00779	0,00700	-0,00280	0,00915	0,01527	0,00347	-0,00714

Table 30. Expanded uncertainty of degree of equivalence

	UME	GUM	BNM INM	INM Romania	JUSTERVESENET	METAS	CMI	SP	NMi-VSL	IO-CSIC
Wavelenght (nm)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)	U_i (k=2)
300	0,00779		0,00787	0,05680	0,00668	0,00540	0,00915	0,01766	0,00527	0,01658
320	0,00758		0,00696	0,04475	0,00647	0,00556	0,00927	0,01770	0,00551	0,01740
340	0,00735		0,00534	0,03676	0,00582	0,00501	0,00904	0,01770	0,00485	0,01654
360	0,00673		0,00538	0,03071	0,00624	0,00549	0,00932	0,01769	0,00543	0,01760
380	0,00673	0,00704	0,00504	0,02675	0,00563	0,00492	0,00779	0,01775	0,00481	0,01664
400	0,00483	0,00475	0,00411	0,00904	0,00529	0,00444	0,00766	0,01779	0,00379	0,01638
450	0,00374	0,00314	0,00295	0,00700	0,00315	0,00252	0,00418	0,00386	0,00232	0,00850
500	0,00319	0,00296	0,00282	0,00694	0,00285	0,00225	0,00334	0,00381	0,00212	0,00808
550	0,00294	0,00315	0,00277	0,00693	0,00278	0,00217	0,00331	0,00379	0,00206	0,00796
600	0,00303	0,00317	0,00299	0,00692	0,00284	0,00219	0,00333	0,00380	0,00209	0,00800
650	0,00326	0,00315	0,00297	0,00692	0,00279	0,00216	0,00331	0,00379	0,00206	0,00792
700	0,00312	0,00336	0,00270	0,00789	0,00278	0,00218	0,00332	0,00585	0,00207	0,00787
750	0,00347	0,00354	0,00289	0,00789	0,00282	0,00221	0,00333	0,00584	0,00211	0,00793
800	0,00387	0,00404	0,00282	0,00839	0,00282	0,00226	0,00334	0,00584	0,00215	0,01300
850	0,00463	0,00417	0,00415	0,00860	0,00394	0,00354	0,00433	0,00635	0,00347	0,01519
900	0,00550	0,00401	0,00411	0,00861	0,00405	0,00366	0,00442	0,01552	0,00361	0,01521
950	0,00651	0,00453	0,00418	0,01285	0,00469	0,00526	0,00575	0,01551	0,00380	0,01520
1000	0,00707	0,00632	0,00465	0,01431	0,00696	0,00550	0,01000	0,01550	0,00545	0,01508

b) Consistency check

The consistency has been checked with a chisquared test. The observed chi-squared value is formed with:

$$\chi^2_{obs} = \sum_{i=1}^{N} \frac{D_i^2}{U_i^2(D_i)} \qquad (19)$$

The consistency check fails if $\Pr\{\chi^2(\nu) > \chi^2_{obs}\} < 0.05$. The degrees of freedom, ν, depend on the number of independent results: $\upsilon = N - 1$. The following table shows the values of the variables involved in this calculation.

Table 31. Chisquared values for the consistency check

Wavelength /nm	χ^2_{obs}	ν	χ^2
300	2,82	8	15,51
320	33,73	8	15,51
340	91,13	8	15,51
360	4,37	8	15,51
380	3,92	9	16,92
400	2,40	9	16,92
450	2,48	9	16,92
500	2,90	9	16,92
550	2,65	9	16,92
600	1,61	9	16,92
650	1,57	9	16,92
700	1,55	9	16,92
750	2,10	9	16,92
800	0,53	9	16,92
850	0,31	9	16,92
900	2,04	9	16,92
950	4,72	9	16,92
1 000	47,29	9	16,92

The consistency check fails at the wavelengths of 320 nm and 340 nm in the UV and 1000 nm in the NIR. At the wavelengths of 320 nm there is a clear outlier. Removing this value, the consistency check does not fail, as can be seen in table 31. At the wavelength of 1 000 nm there is a clear outlier too (not the same laboratory as before), but a second laboratory has to be removed too for the consistency test to pass. The case is different for the wavelength of 340 nm. Three laboratories have to be removed to pass the consistency check. There is a laboratory presenting the maximum deviation (the same as in 320 nm), but removing this lab is not enough to pass the consistency check. The next outliers for this wavelength are a group of three laboratories having a very close deviation, but it is enough not to consider two of them to pass the consistency check.

Table 32. Chisquared values for consistency check without outliers

Wavelength /nm	χ^2_{obs}	ν	χ^2
300	2,82	8	15,51
320	10,40	7	14,07
340	9,67	5	11,07
360	4,37	8	15,51
380	3,92	9	16,92
400	2,40	9	16,92
450	2,48	9	16,92
500	2,90	9	16,92
550	2,65	9	16,92
600	1,61	9	16,92
650	1,57	9	16,92
700	1,55	9	16,92
750	2,10	9	16,92
800	0,53	9	16,92
850	0,31	9	16,92
900	2,04	9	16,92
950	4,72	9	16,92
1 000	5,75	7	14,07

If the outliers were not considered for the EURAMET-RV other results different from those shown before would be obtained for the degree of equivalence. However, since the goal of this comparison is to establish the deviation or degree of equivalence respect to the CCPR KCRV and this is not depending on the the reference value of this comparison, EURAMET RV has been calculated without excluding any point of any laboratory.

c) The bilateral EURAMET-DoE between NMI *i* and NMI *m* and its corresponding uncertainty can be obtained by

$$D_{i,m} = \Delta_i - \Delta_m \qquad (20)$$

$$U_{i,m} = k\sqrt{u^2(\Delta_i) + u^2(\Delta_m)};\; k = 2 \qquad (21)$$

8 Linkage to comparison CCPR-K2.b

The goal of this comparison is to provide a link to the comparison "CCPR-K2.b". According to the comparison's protocol, the linkage is done by calculating a coefficient as found in "Delahaye F. and Witt T. J., 2002 Metrologia 39 (Tech. Suppl.) 01005".

The key comparison reference value derived from CCPR-K2.b is used as the reference value. Results and uncertainties from CCPR-K2.b are unaltered by the linking procedure. The following notation is used here and after:

D_c, is DoE for a linking laboratory in CCPR-k2.b

D'_c is EURAMET-DoE for a linking laboratory in EUROMET PR-K2.b

D'_e is EURAMET-DoE for a participating laboratory in EUROMET PR-K2.b.

The problem consists of calculating a correction d to be applied to D'_e so that the corrected result D_e for every participating laboratory represents the best estimate of what would have been the result from its participation in CCPR-K2.b.

$$D_e = D_e^{'} + d \qquad (22)$$

The quantity $d_c = D_c - D'_c$ calculated for every linking laboratory (BNM-INM/CNAM, IO-CSIC and NMi-VSL) provides an estimate of $d = D_e - D'_e$ because any possible bias in the results of laboratory c are assumed to be reasonable constant over the time period.

Because of wide variations in uncertainty among the three linking laboratories, d is calculated as a weighted mean of d_c of every linking laboratory:

$$d = \sum_{k=1}^{3} w_c \times d_c \qquad (23)$$

Where weights are calculated from

$$w_c = \frac{1 / s_c^2}{\sum_{j=1}^{3} \frac{1}{s_j^2}} \qquad (24)$$

Where s_c is the uncertainty associated with d_c, given by $s_c^2 = t_c^2 + t_c^{'2} + 2r_c^2$. t_c and t'_c are the transfer uncertainty in the comparisons CCPR-k2.b and EUROMET PR-k2.b, respectively, and r_c is the uncertainty associated with the imperfect reproducibility of the results of laboratory c in the time period elapsed between the two comparisons (whence the factor 2). Values for t_c have been taken from the CCPR K2.b final report. Values for t_c' are obtained from Table 4. Values for r_c have been taken equal to the uncertainty declared by linking laboratories in these comparisons (CCPR and EUROMET). Values involved in calculations of d are shown in the following table for every linking laboratory (BNM-INM/CNAM, NMi-VSL and IO-CSIC).

Table 33. BNM values for calculating the link to CCPR K2.b. *t* is the transfer uncertainty of the comparison CCPR, *t'* is the transfer uncertainty of this comparison and *r* is the laboratory standard uncertainty

Wavelength (nm)	t (CCPR)	t' (EUROMET)	r	w_c	D_c	D'_c	d_c
300	0,00075	0,00220	0,00370	0,21737	0,00173	-0,00288	0,00461
320	0,00063	0,00236	0,00288	0,29403	0,00278	0,00385	-0,00107
340	0,00055	0,00207	0,00183	0,38980	0,00324	0,00942	-0,00618
360	0,00045	0,00223	0,00130	0,50260	-0,00033	-0,00455	0,00422
380	0,00045	0,00199	0,00168	0,44009	0,00317	-0,00444	0,00761
400	0,00035	0,00163	0,00110	0,39729	0,00147	-0,00236	0,00383
450	0,00020	0,00156	0,00110	0,33869	0,00233	0,00082	0,00151
500	0,00020	0,00092	0,00110	0,23636	0,00165	0,00030	0,00135
550	0,00020	0,00087	0,00110	0,22417	0,00295	-0,00031	0,00326

Wavelength (nm)	t (CCPR)	t’ (EUROMET)	r	w_c	D_c	D'_c	d_c
600	0,00020	0,00077	0,00125	0,17149	0,00157	-0,00055	0,00212
650	0,00020	0,00080	0,00125	0,17892	-0,00118	-0,00127	0,00009
700	0,00020	0,00076	0,00104	0,21408	-0,00124	-0,00096	-0,00028
750	0,00020	0,00077	0,00118	0,18672	-0,00092	-0,00089	-0,00003
800	0,00020	0,00077	0,00110	0,20629	-0,00022	0,00027	-0,00049
850	0,00020	0,00076	0,00133	0,15925	-0,00134	-0,00022	-0,00112
900	0,00020	0,00083	0,00118	0,20692	-0,00047	-0,00014	-0,00033
950	0,00028	0,00095	0,00110	0,28387	0,00123	0,00033	0,00090
1 000	0,00130	0,00090	0,00135	0,62626	0,01038	0,01691	-0,00653

Table 34. VSL values for calculating the link to CCPR K2.b. *t* is the transfer uncertainty of the comparison CCPR, *t’* is the transfer uncertainty of this comparison and *r* is the laboratory standard uncertainty

Wavelength (nm)	t (CCPR)	t’ (EUROMET)	r	w_c	D_c	D'_c	d_c
300	0,00075	0,00220	0,00147	0,73573	-0,00130	0,00305	-0,00435
320	0,00063	0,00236	0,00141	0,66648	-0,00085	0,00820	-0,00905
340	0,00055	0,00207	0,00122	0,58080	-0,00123	0,01070	-0,01193
360	0,00045	0,00223	0,00140	0,47206	-0,00139	0,00088	-0,00227
380	0,00045	0,00199	0,00140	0,53107	-0,00131	0,00249	-0,00380
400	0,00035	0,00163	0,00065	0,56831	-0,00089	0,00107	-0,00196
450	0,00020	0,00156	0,00032	0,61914	0,00019	0,00075	-0,00056
500	0,00020	0,00092	0,00029	0,74066	0,00024	0,00120	-0,00096
550	0,00020	0,00087	0,00029	0,75395	0,00033	0,00162	-0,00129
600	0,00020	0,00077	0,00029	0,80903	0,00005	0,00124	-0,00119
650	0,00020	0,00080	0,00029	0,80006	0,00024	0,00133	-0,00109
700	0,00020	0,00076	0,00029	0,76734	0,00024	0,00125	-0,00101
750	0,00020	0,00077	0,00029	0,79382	0,00024	0,00131	-0,00107
800	0,00020	0,00077	0,00029	0,78644	0,00022	0,00081	-0,00059
850	0,00020	0,00076	0,00029	0,83528	0,00017	0,00079	-0,00062
900	0,00020	0,00083	0,00031	0,78710	0,00026	-0,00022	0,00048
950	0,00028	0,00095	0,00044	0,70817	0,00015	0,00098	-0,00083
1 000	0,00130	0,00090	0,00209	0,34228	-0,00032	0,00494	-0,00526

Table 35. IO-CSIC values for calculating the link to CCPR K2.b. *t* is the transfer uncertainty of the comparison CCPR, *t’* is the transfer uncertainty of this comparison and *r* is the laboratory standard uncertainty

Wavelength (nm)	t (CCPR)	t’ (EUROMET)	r	w_c	D_c	D'_c	d_c
300	0,00075	0,00220	0,00856	0,04689	-0,00298	-0,00730	0,00432
320	0,00063	0,00236	0,00899	0,03949	-0,00756	-0,00745	-0,00011

Wavelength (nm)	t (CCPR)	t’ (EUROMET)	r	w_c	D_c	D'_c	d_c
340	0,00055	0,00207	0,00850	0,02940	0,00145	0,00594	-0,00449
360	0,00045	0,00223	0,00907	0,02534	-0,00534	-0,01168	0,00634
380	0,00045	0,00199	0,00852	0,02884	0,00510	-0,00295	0,00805
400	0,00035	0,00163	0,00834	0,01514	-0,00676	-0,01063	0,00387
450	0,00020	0,00156	0,00429	0,04217	-0,00201	-0,00877	0,00676
500	0,00020	0,00092	0,00407	0,02298	-0,00345	-0,00915	0,00570
550	0,00020	0,00087	0,00401	0,02188	-0,00266	-0,00964	0,00698
600	0,00020	0,00077	0,00403	0,01947	-0,00156	-0,00749	0,00593
650	0,00020	0,00080	0,00399	0,02102	-0,00223	-0,00637	0,00414
700	0,00020	0,00076	0,00396	0,01858	-0,00388	-0,00731	0,00343
750	0,00020	0,00077	0,00399	0,01946	-0,00548	-0,00919	0,00371
800	0,00020	0,00077	0,00655	0,00728	-0,00253	-0,00590	0,00337
850	0,00020	0,00076	0,00773	0,00547	-0,00313	-0,00540	0,00227
900	0,00020	0,00083	0,00775	0,00598	-0,00627	-0,00954	0,00327
950	0,00028	0,00095	0,00776	0,00795	-0,00615	-0,01079	0,00464
1 000	0,00130	0,00090	0,00774	0,03146	-0,01035	-0,00566	-0,00469

Finally, the correction *d* applied to the EURAMET-DoE of this EUROMET comparison to obtain the DoE respect to the CCPR KCRV is shown in Table 36.

Table 36. Correction to link EURAMET-PR-K2.b to CCPR-k2.b

Wavelength(nm)	Correction for linking
300	-0,00199
320	-0,00635
340	-0,00947
360	0,00121
380	0,00156
400	0,00041
450	0,00045
500	-0,00026
550	-0,00009
600	-0,00048
650	-0,00077
700	-0,00077
750	-0,00078
800	-0,00054
850	-0,00068
900	0,00033
950	-0,00030
1 000	-0,00604

It can be observed that the correction is bigger for those wavelengths at which the consistency was poorer.

9 Degree of equivalence respect to CCPR KCRV

The best estimate of the degree of equivalence that every participating laboratory in this comparison would have obtained from its participation in CCPR-K2.b is shown in the next table, where its expanded uncertainty is also included. Values are shown as $x10^{-2}$ for consistency with CCPR-K2.b.

The degree of equivalence respect to CCPR KCRV and its expanded uncertainty is shown as a function of wavelength in the following figures for every participating laboratory, except for the linking laboratories whose degree of equivalence was established by the comparison CCPR K2.b.

Table 37. Degree of equivalence respect to CCPR-K2.b KCRV

	UME		GUM		INM Romania		JUSTERVESENET		METAS		CMI		SP	
Wavelength							De		De		De		De	
(nm)	D_e	Ui (k=2)	D_e	Ui (k=2)	D_e	Ui (k=2)	D_e	Ui (k=2)	D_e	Ui (k=2)	D_e	Ui (k=2)	D_e	Ui (k=2)
300	-0,28	0,78			-4,8	5,7	0,06	0,67	0,37	0,54	-0,62	0,92	-0,1	1,8
320	-4,30	0,76			-3,5	4,5	0,40	0,65	0,46	0,56	-0,06	0,93	0,5	1,8
340	-7,14	0,74			-2,1	3,7	0,33	0,58	0,25	0,50	-0,10	0,90	0,4	1,8
360	0,63	0,67			-3,9	3,1	0,52	0,62	0,46	0,55	0,25	0,93	0,6	1,8
380	0,65	0,67	0,39	0,70	-3,6	2,7	0,16	0,56	0,39	0,49	0,05	0,78	0,5	1,8
400	0,35	0,48	0,39	0,48	-0,70	0,90	0,22	0,53	0,21	0,44	-0,14	0,77	0,4	1,8
450	0,06	0,37	-0,02	0,31	0,13	0,70	-0,16	0,32	-0,06	0,25	0,35	0,42	0,11	0,39
500	-0,02	0,32	-0,05	0,30	0,27	0,69	-0,16	0,29	-0,17	0,23	0,20	0,33	0,04	0,38
550	-0,01	0,29	-0,08	0,32	0,02	0,69	-0,08	0,28	-0,03	0,22	0,17	0,33	0,13	0,38
600	-0,04	0,30	-0,11	0,32	0,02	0,69	-0,09	0,28	-0,08	0,22	0,08	0,33	0,08	0,38
650	-0,07	0,33	-0,06	0,32	0,04	0,69	-0,15	0,28	-0,10	0,22	0,02	0,33	0,05	0,38
700	0,03	0,31	-0,11	0,34	-0,04	0,79	-0,13	0,28	-0,08	0,22	0,01	0,33	0,04	0,59
750	-0,02	0,35	-0,14	0,35	-0,02	0,79	-0,02	0,28	-0,10	0,22	0,04	0,33	0,04	0,58
800	-0,06	0,39	-0,14	0,40	-0,05	0,84	-0,12	0,28	-0,08	0,23	0,02	0,33	0,03	0,58
850	-0,03	0,46	-0,05	0,42	-0,07	0,86	-0,12	0,39	-0,11	0,35	0,06	0,43	0,00	0,64
900	0,06	0,55	-0,07	0,40	-1,02	0,86	-0,15	0,41	-0,11	0,37	0,07	0,44	-0,03	1,55
950	-0,47	0,65	0,05	0,45	-2,2	1,3	-0,01	0,47	-0,07	0,53	0,18	0,58	0,25	1,55
1 000	-4,37	0,71	0,38	0,63	-1,2	1,4	0,24	0,70	-0,74	0,55	0,5	1,0	1,07	1,55

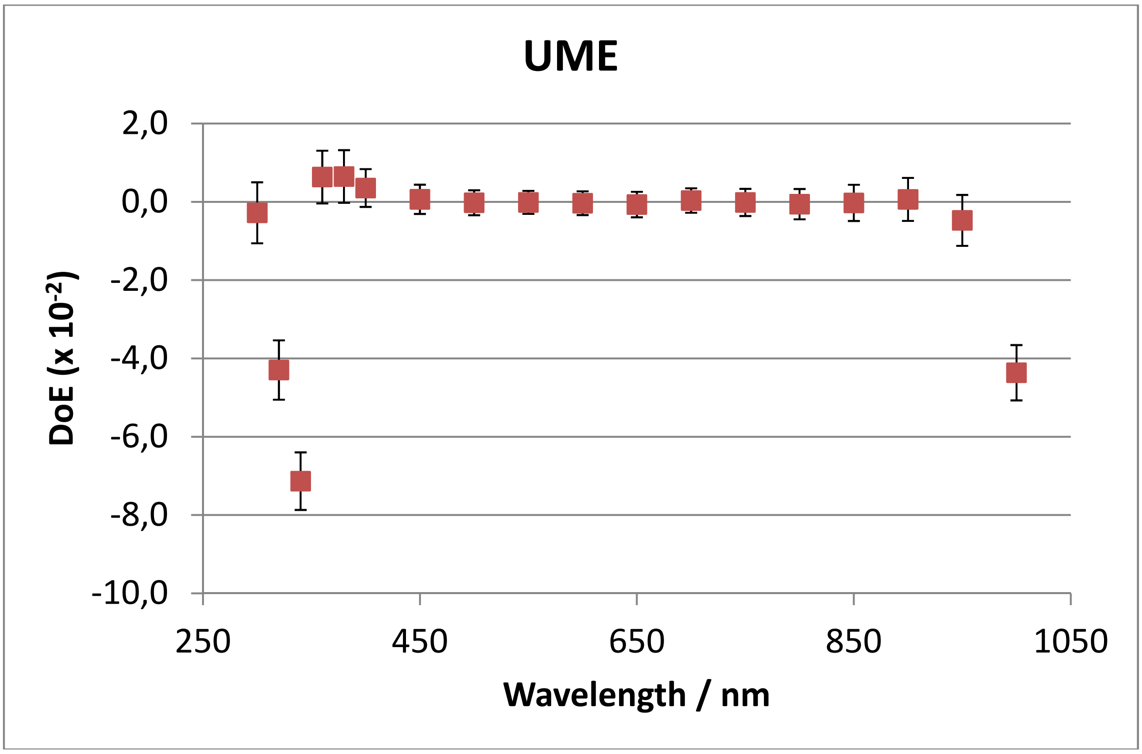


Figure 12. DoE respect to CCPR KCRV and its expanded uncertainty of participant UME

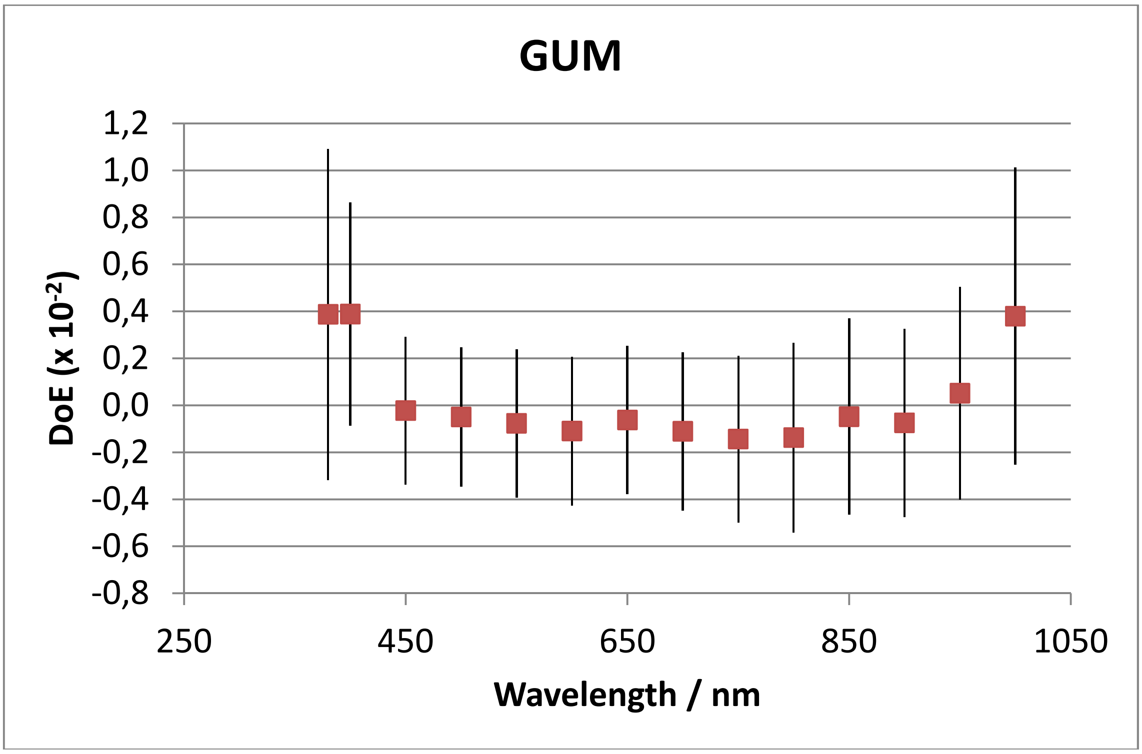


Figure 13. DoE respect to CCPR KCRV and its expanded uncertainty of participant GUM

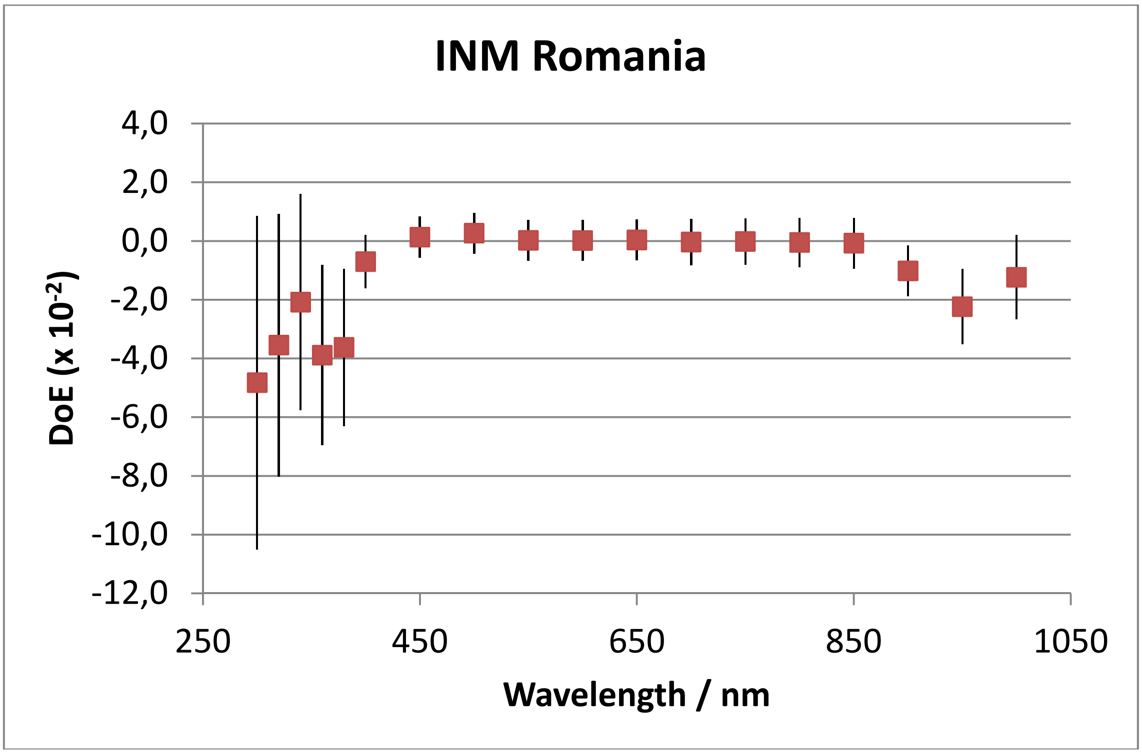


Figure 14. DoE respect to CCPR KCRV and its expanded uncertainty of participant INM Romania

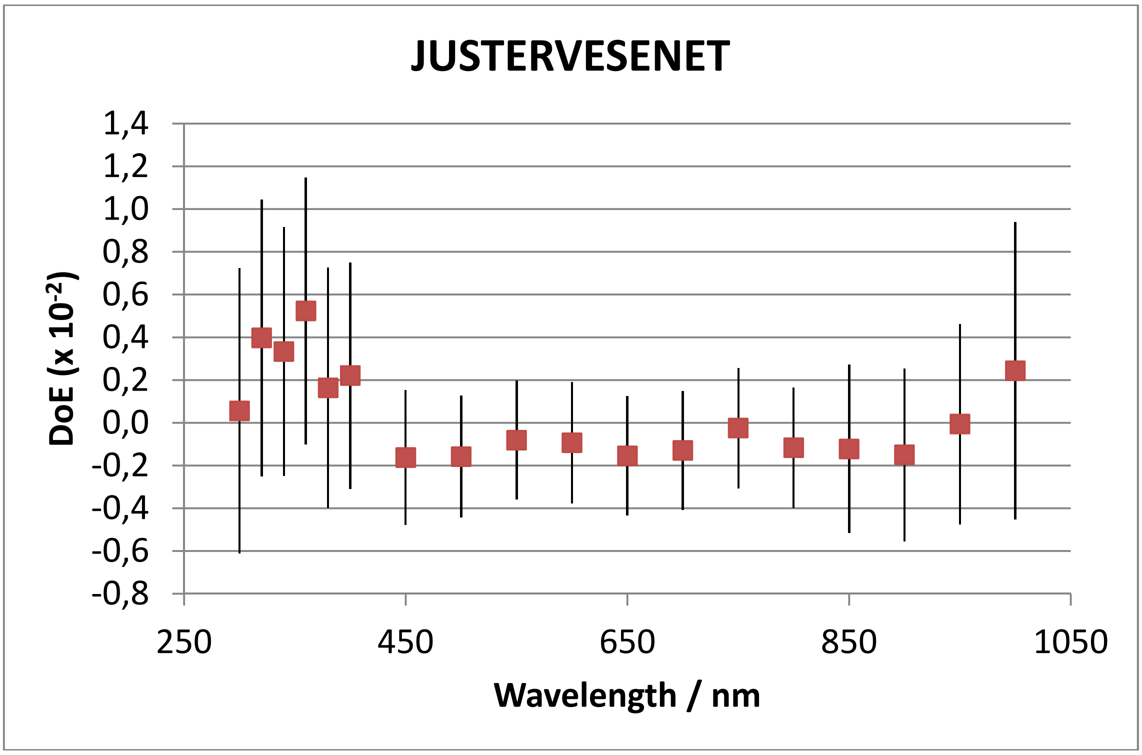


Figure 15. DoE respect to CCPR KCRV and its expanded uncertainty of participant JUSTERVESENET

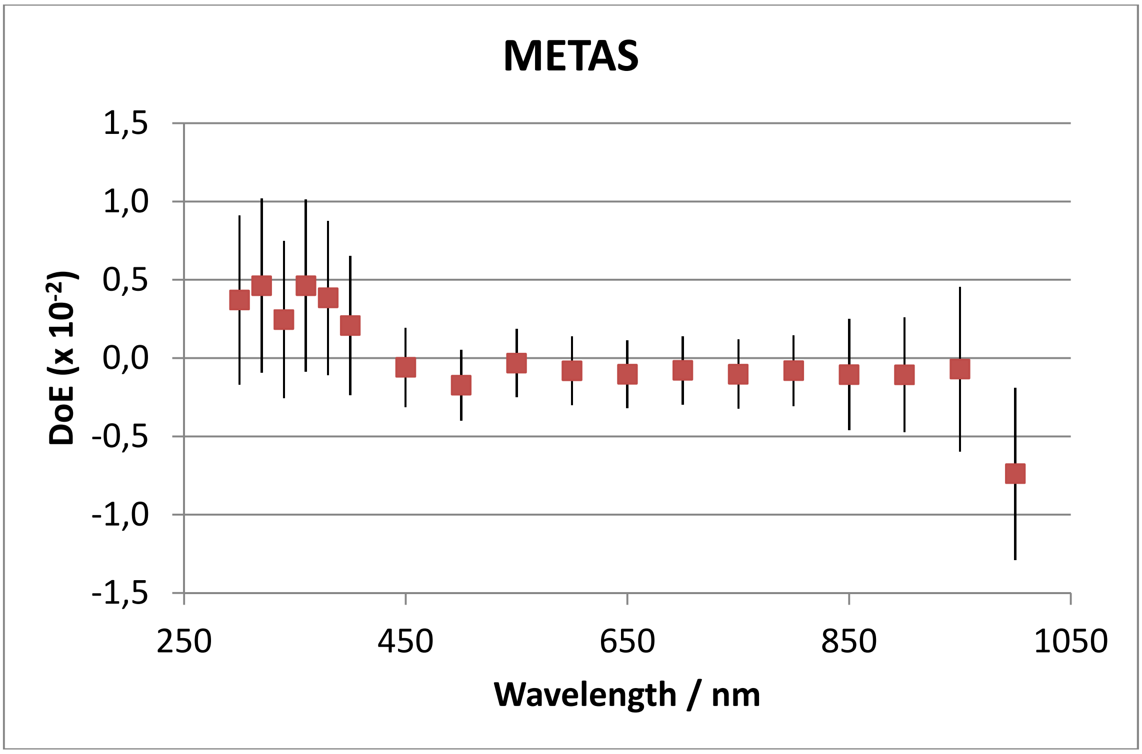


Figure 16. DoE respect to CCPR KCRV and its expanded uncertainty of participant METAS

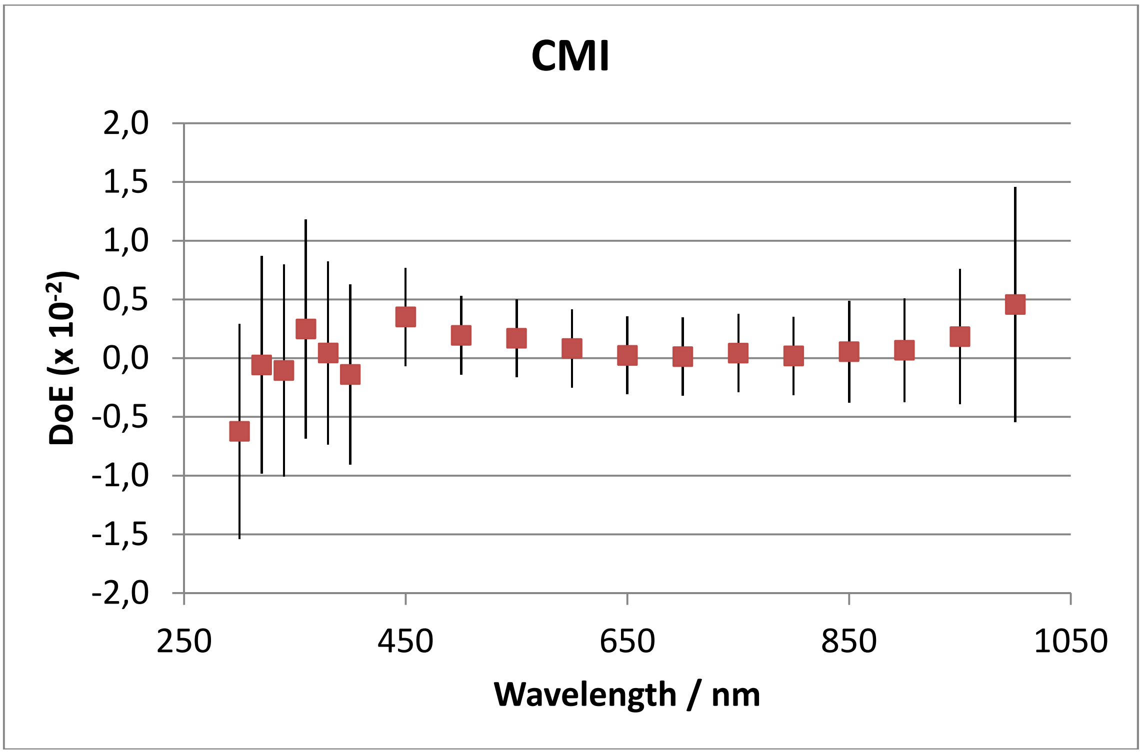


Figure 17. DoE respect to CCPR KCRV and its expanded uncertainty of participant CMI

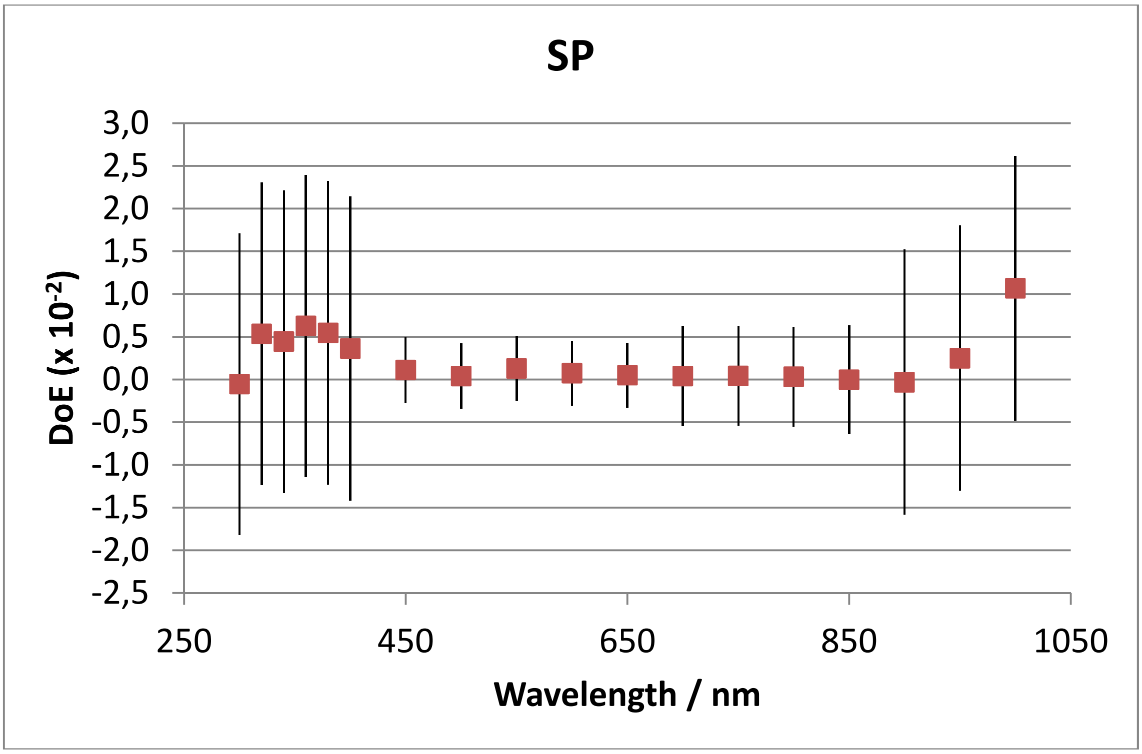


Figure 18. DoE respect to CCPR KCRV and its expanded uncertainty of participant SP

Annexes

CALIBRATION REPORTS OF PARTICIPATING LABORATORIES

Bundesamt für Metrologie und Akkreditierung (METAS)

8.3 Description of the measurement facility and primary reference

Type of primary standard ....

METAS has EUROMET traceable agreement with NPL. The transfer detectors are recalibrated every two years. The last calibration took place between December 3-19, 2002...

Laboratory transfer standards used if any: ....

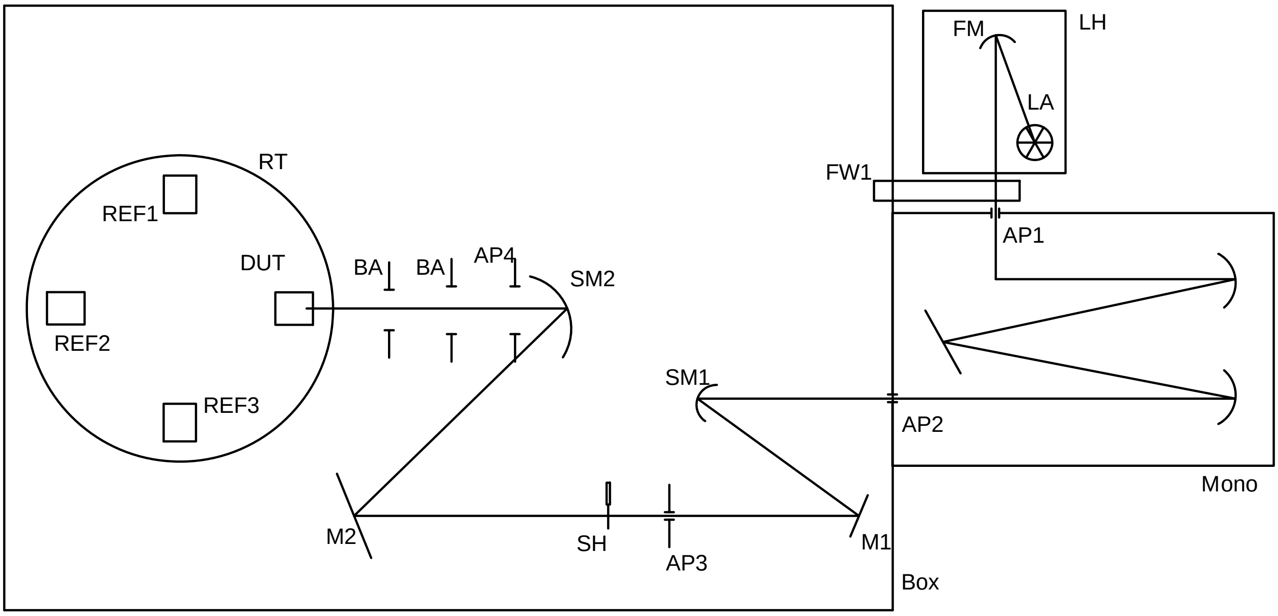
Set of 3 trap detector built by METAS/OFMET. They are of reflection type based on three large area Si-cells (Hamamatsu S3411-02 SPL)..

Monochromator used:: ....

Jobin-Yvan Monochromator Type HR640, with a set of high pass-filter at the entrance port in order to reduce the straylight from higher diffraction orders for wavelength above 400nm and some pass-band filters for wavelength below 400nm.. ....

Primary reference or traceability route of primary reference and breakdown of uncertainty: ....

The geometrical set up is shown in the following figure. The device under test (DUT) and the reference detectors are illuminated by a monochromatic light source. The spot on the third photodiode of the traps had a diameter of 3 mm x 3 mm. The illuminating beam was of f/# 15. The DUT and the three reference detectors are mounted on a computer controlled rotation stage. At each wavelength the photo-current of the DUT with and without illumination is measured (10 times). Then the table rotates to the first reference detector and measures the photo-current with and without illumination. The table rotates to the second reference detector and so on. A complete measure at one wavelength takes about 15 seconds. Each detector has its own picoamperemeter (Vinculum SP-430). Theirs voltage output are connect to a precision voltmeter (Keithley 2001).



legend

LH	:	lamp-house
LA	:	tungsten halogen lamp (6.6 A, 45W)
FM	:	flip-mirror
FW1	:	filter-wheel including 5 bandpass filters, plus one clear aperture
AP1	:	rectangular input aperture (10 mm x 2 mm)
Mono	:	grating monochromator *f*=640mm ($f_{\#}$ = 5.6)
AP2	:	rectangular exit aperture (10 mm x 2 mm)
SM1, SM2	:	spherical mirror
BS	:	beam-splitter (quartz-plate)
M1, M2	:	flat mirror
AP3	:	circular aperture (2mm diameter) to get a circular spot
AP4	:	variable circular aperture (iris) to adjust the f/# of the input beam
DUT	:	device under test
REF1,2,3	:	reference trap detector
RT	:	automated rotation table
BA	:	baffles to reduce straylight
BOX	:	box to remove surrounding lights

……

Data evaluation

The evaluation has been done in two steps: First, a raw reference power has been determined based on three references detectors. In this step a correction of the photo-current measurement has been done for each measured reference value. Second, the spectral responsivity is determined by the ratio of the current of the detector under test and the raw reference power and a correction of the current measurement of the device under test is applied.

reference power

For each of the three reference detector a raw reference power has been determined. To check the consistency of the reference power measurements only type A error has been taken into account.

Model:

$$P_{Ri} = \frac{i_{Ri} - i_{0Ri}}{\varepsilon_{Ri}}(1 - c_{aRi})$$

As an example the uncertainty budget of the determination of the reference power by the reference detector Ref1 (EAM4) at wavelength 300 nm during the first measurement round of the calibration of the Si photodiode F43 is shown:

No	Quantity	Symbol	Value	Standard uncertainty	Type	distr.	Degree of freedom	Sensitivity Coefficient	Uncertainty contribution / µW
1	calibration Ref1	ε_{R1}	0.24386 A/W	0 A/W	B	1	Inf	-7.52E-03 µW / (A/W)	0
2	current Ref1	i_{R1}	4.46E-04 µA	1.18E-07 µA	A	1	9	4.10E+00 1 / (A/W)	4.82E-07
3	dark Ref1	i_{0R1}	-1.39E-06 µA	1.04E-07 µA	A	1	9	-4.10E+00 1 / (A/W)	-4.25E-07
4	amperemeter1	c_{aR1}	0.00055	0	B	1	Inf	-1.84E-03 µW	0.0000E+00

power Ref1 P_{R1} 1.8350E-03 µW ν_{eff} 17.7 $u(P_{R1})$ 6.42557E-07

Quantities:

P_{Ri}	output quantity. Reference power determined by the reference detector i. The value includes corrections of the pico-amperemeters.
ε_{Ri}	spectral responsivity of the reference detector i. The values are given by the calibration certificates of NPL. The uncertainty of the spectral responsivity of the reference detector has been taken into account in the second step.
i_{Ri}	electrical current measurement of the reference detector i , under illumination, average of 10 readings. The readings were taken successively.
i_{0Ri}	electrical current measurement of the reference detector i , dark current, average of 10 readings. The readings were taken successively.
c_{aRi}	correction of the current measurement based of calibration certificates of the pico-amperemeters. The correction is in the order of 4.4e-4 to 8.8e-4. The uncertainty of this correction has been taken into account in the second step.

sensitivity coefficients

The sensitivity coefficients are calculated from the model as partial derivatives with respect to the regarded quantity.

The reference power is the weighted mean of the three individual measurements, the weights given by $1/u^2(P_{Ri})$. Typical values for the reference power are shown in following Table.

wavelength / nm	Power / µW
300	0.001838
320	0.005870
340	0.01181
360	0.2281
380	0.3923
400	1.0155

wavelength / nm	Power / µW
450	0.2416
500	0.3446
550	0.5667
600	0.6318
650	0.6231
700	0.7040

wavelength / nm	Power / µW
750	0.5809
800	0.4374
850	0.4044
900	0.5229
950	0.6094
1000	0.5989

spectral responsivity of the detector under test

Model:

$$\varepsilon_P = \frac{i_P - i_{P0}}{P_R}(1 - c_{\varepsilon R} - c_{aR} - c_{vR} - c_{lin} - c_{uni} - c_{pol} - c_{wl}(\lambda) - c_{stray} - c_T - c_{vP})$$

No	Quantity	Symbol	Value	Standard uncertainty	Type	distr.	Degree of freedom	Sensitivity Coefficient	Uncertainty contribution / (A/W)
1	Power	P_R	1.8361E-03 μW	7.437E-07 μW	A	1	54	-7.14E+01 A/W /μW	-5.31E-05
2	Calibration Ref	$c_{\varepsilon R}$	0	0.0014286	B	1	Inf	-1.31E-01 A/W	-1.87E-04
3	Amperem. Ref	c_{aR}	0	0.0002828	B	1	Inf	-1.31E-01 A/W	-3.71E-05
4	Voltmeter Ref	c_{vR}	0	0.00001	B	1	Inf	-1.31E-01 A/W	-1.31E-06
5	Linearity	c_{lin}	0	0.00005	B	1	Inf	-1.31E-01 A/W	-6.55E-06
6	Uniformity	c_{uni}	0	0.00010	B	1	Inf	-1.31E-01 A/W	-1.31E-05
7	Polarization	c_{pol}	0	0.00001	B	1	Inf	-1.31E-01 A/W	-1.31E-06
8	Wavelength	c_{wl}	0	0.15 nm	B	1	Inf	-2.50E-04 A/W / nm	-3.74E-05
9	Straylight	c_{stray}	0	0.0001	B	1	Inf	-1.31E-01 A/W	-1.31E-05
10	Temperature	c_T	0	1 °C	B	1.73	Inf	-2.62E-06 A/W / °C	-1.51E-06
11	Current DUT	i_P	0.00025085 μA	9.40E-08 μA	A	1	9	5.44E+02 A/W / μA	5.11E-05
12	Dark DUT	i_{0P}	1.004E-05 μA	6.62E-08 μA	A	1	9	-5.44E+02 A/W / μA	-3.60E-05
13	Ampere DUT	c_{aP}	0.0006	0.00013	B	1	Inf	-1.31E-01 A/W	-1.70E-05
14	Voltmeter DUT	c_{vP}	0	1.00E-05	B	1	Inf	-1.31E-01 A/W	-1.31E-06

Responsivity DUT	ε_P	0.13107 A/W	ν_{eff}	Inf	$u(\varepsilon_P)$ 0.00021272
					$u_A(\varepsilon_P)$ 0.00008204
					$u(\varepsilon_P)/\varepsilon_P$ 0.162%

Quantities

ε_P	output quantity, spectral responsivity of the detector under test
R_P	raw reference power, determined by step 1 (see above).
$c_{\varepsilon R}$	pseudo quantity that has been introduced to take into account the calibration uncertainty of the reference detectors. This uncertainty is given by the calibration certificates of NPL. The relative standard uncertainty varies between 0.13% at 300 nm, 0.04% at 500 nm and 0.2% at 1000 nm. The values are shown in Fig. 1.
c_{aR}	pseudo quantity that has been introduced to take into account the uncertainty of the picoampermeter. The quantity itself (thus the correction due to the picoamperemeter) has been used in step 1. The uncertainty of the quantity is in the order of 6e-5 to 1.3 e-4
c_{vR}	The relative standard uncertainty of the voltage reading given by the calibration certificate of the voltage meter is 1e-5. No correction due to this quantity has been made.
c_{lin}	The relative standard uncertainty of non-linearity of the reference detectors has been determined by the super-position principle. For the power level used for this calibration it has been estimated to 5e-5. No correction due to this quantity has been made.
c_{uni}	The relative standard uncertainty of non-uniformity of the reference detectors has been determined by scanning a constant beam. For the spot diameter used for this calibration it has been estimated to 1e-4. No correction due to this quantity has been made.
c_{pol}	The relative standard uncertainty due to polarization has been determined by rotating the polarization axe of a linear polarized beam. For the set-up used for this calibration it has been estimated to 2e-5. No correction due to this quantity has been made.
c_{wl}	The standard uncertainty in respect to wavelength has been measured low-pressure pencil lamps. It has been estimated to 0.15 nm. No correction due to this quantity has been made.

c_{stray} The relative standard uncertainty due to straylight has been estimated to be in the order of 1e-4. No correction due to this quantity has been made.

i_{Pi} electrical current measurement of the detector under test, under illumination, average of 10 readings. The readings were taken successively.

i_{0Pi} electrical current measurement of the detector under test, dark current, average of 10 readings. The readings were taken successively.

sensitivity coefficients

c_8 At each wavelength the electrical current of the reference and of the DUT is measured. The uncertainty contributions of those measurements due to the wavelength uncertainty are therefore fully correlated. The best way to treat this problem is to introduce an auxiliary quantity $r = i_P / i_R = \varepsilon_P / \varepsilon_R$.
The sensitivity coefficient c_8 is then given by

$$c_8 = \frac{\partial \varepsilon_P}{\partial \lambda} = \varepsilon_R \frac{\partial r}{\partial \lambda}$$

Table 1 shows the measured values.

c_{10} A relative sensitivity of -0.00002 / °C has been found in literature (report CCPR-S3).

For all the other quantities, the sensitivity coefficients are calculated from the model as partial derivatives with respect to the regarded quantity.

The different uncertainty contribution are visualized for the case of the detector F43 at 300 nm in Fig. 2. The main contribution is due to calibration of the reference detectors.

Each detector has been measured several times (3-4). The reported spectral responsivity is the weighted mean of all the measurements. The reported relative standard deviation is the relative standard deviation of the mean (hence divided by the square root of the number of measurements).

wavelength	sensitivity coefficients c_8	
	Si-cell	Trap
nm	A/W / nm	A/W / nm
300	6.42E-04	-2.50E-04
320	9.02E-05	-1.07E-05
340	-2.10E-04	2.43E-05
360	-5.02E-04	8.96E-06
380	6.76E-04	-4.79E-05
400	4.90E-04	-4.30E-05
450	1.87E-04	-2.10E-05
500	9.99E-05	-1.56E-06
550	6.34E-05	-1.56E-05
600	3.97E-05	-5.62E-06
650	2.58E-05	-5.82E-06
700	2.48E-05	4.24E-06
750	1.92E-05	-6.88E-06
800	1.71E-05	1.85E-06
850	1.44E-05	2.66E-06
900	1.41E-05	-2.24E-05
950	3.58E-04	5.36E-04
1000	1.84E-03	3.28E-03

Table 1 wavelength uncertainty sensitivity coefficients

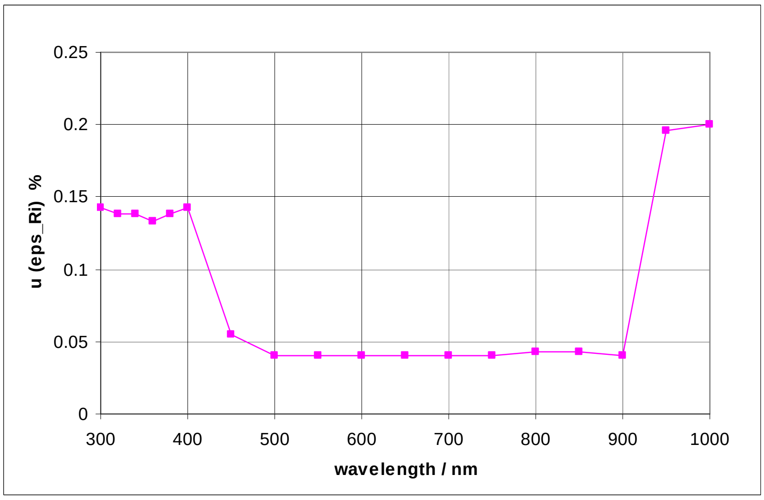


Fig. 1 relative standard uncertainty of the reference detectors given by NPL calibration certificate

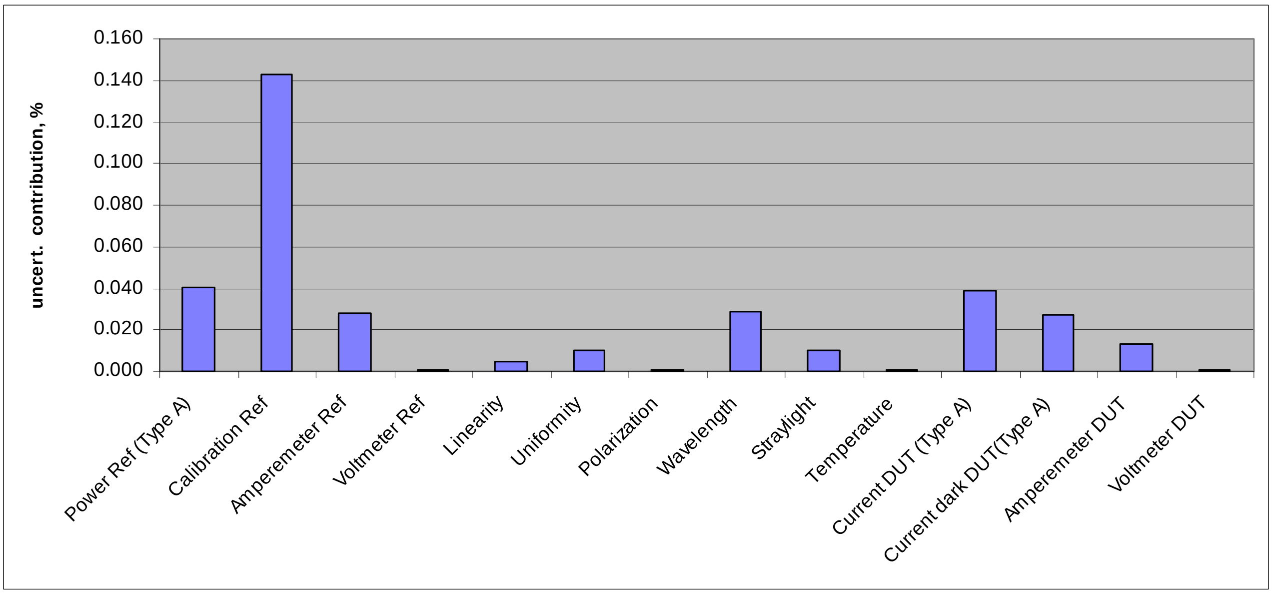


Fig. 2 uncertainty contribution at 300 nm for the photodiode F43.

Description of calibration laboratory conditions: e.g. temperature, humidity etc ....

The calibration laboratory has no air conditioning system however temperature and humidity are monitored permanently by a data logger. The variation of the temperature is typically below 0.5° during one working day. During the summer period 30 June and 30 August the temperature was always 21.3° C and 22.5 °C.

....

Laboratory: ……………………….METAS………………………………………………………………….

Date: ……………………………………………   Signature:

Norwegian Metrology and Accreditation Service (Justervesenet)

Measurement report

EUROMET Key Comparison PR – K2.b
Spectral Responsivity part 2 (300 – 1000 nm)

Norwegian Metrology and Accreditation Service

06.10.2003

Jarle Gran, MSc.

1. Introduction

This report gives the responsivity values of the EUROMET Key Comparison PR-K2.b for the spectral response of silicon photodiodes in the spectral range 300 – 1000 nm given by Norwegian Metrology and Accreditation Service.

2. Measurement conditions

2.1 Measurement set-up

The experimental set-up consists of a McPherson double grating monochromator 2035D, including reflective input optics and order sorting filters.

There were two set of gratings used in the comparison. Between 300 and 400 nm we measured with our UV gratings, with 1200 g/mm blazed at 250 nm. From 400 - 1000 nm we used our visual gratings, with 600 g/mm blazed at 500 nm.

In the 300 – 400 nm spectral range we used a high pressure Xe-lamp and in the extended visible we used a tungsten lamp.

The output optics and detector stage is enclosed in a light tight box.

The measurement set up is fully computer controlled including order sorting filter change.

2.2 Laboratory conditions

The laboratory has climate controlled temperature and humidity. The humidity is set to 45 %RH and the temperature is set to 23 ºC with specified tolerance of ± 0.5 ºC.

The actual temperature was monitored inside the light tight enclosure, close to the detector stage. During the measurements the true temperature was fluctuating within the specified temperature limits.

2.3 Optical specifications

The exit slit of the monochromator was set to 1 mm giving a spectral resolution of 2 nm FWHM in the UV and 4 nm in the extended visible.

The output F/# of the monochromator is f/4.8. This was converted to approximately f/24 with the optics given in figure 1.

The beamsize in focus is approximately circular with Ø 4,2 mm. This is the image of the pinhole. The pinhole is slightly tilted so that reflections from the detectors surface do not retro-reflect onto the detectors via the lower spherical mirror. (Residual reflection misses the lower spherical mirror.) The maximum beamsize on the first detector was calculated to be within 5,3 mm, which is well within the maximum tolerable beamsize of 8,1 mm.

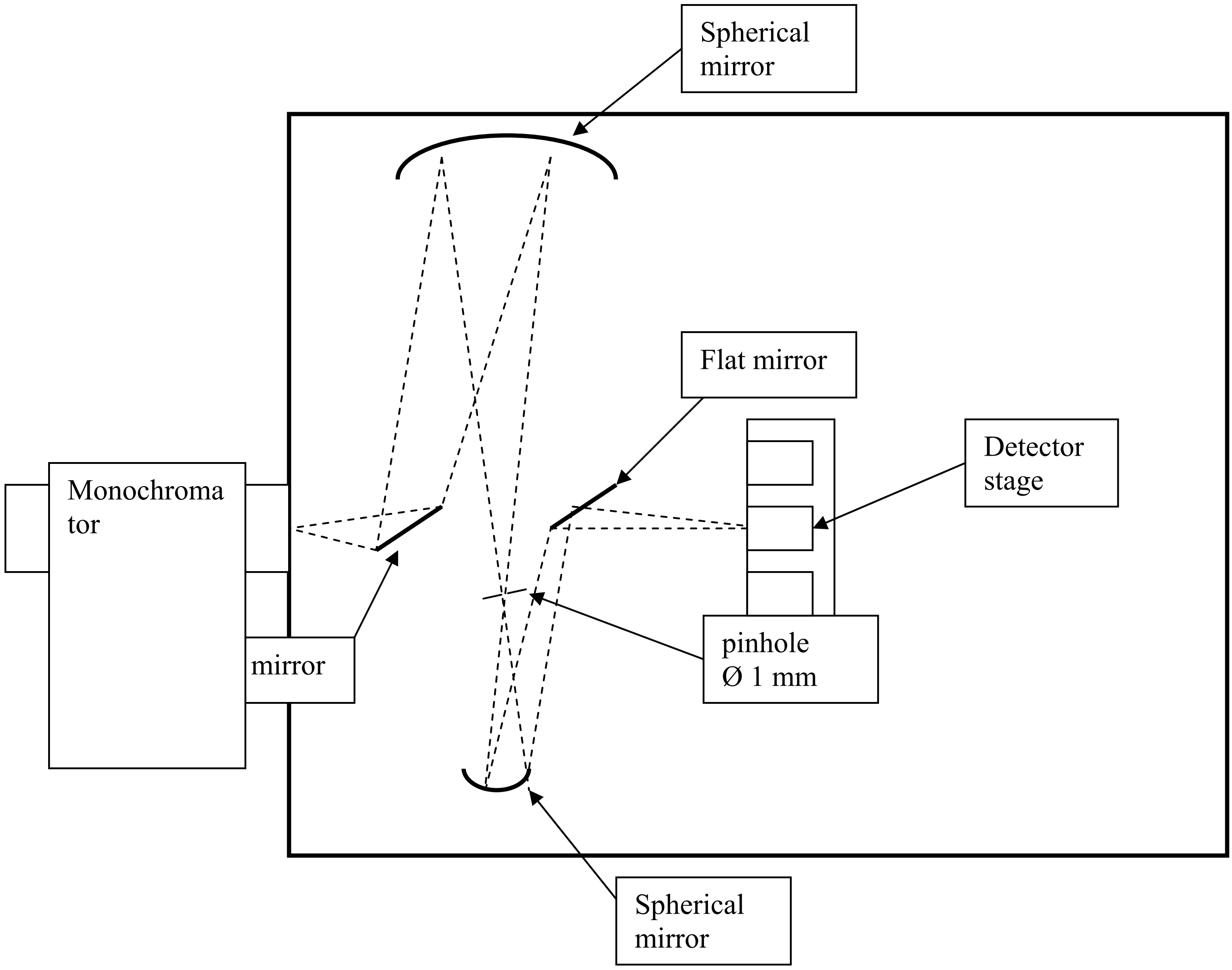


Figure 1. The figure shows a sketch of the output optics from the monochromator, which is converting the f/4.8 to f/24 and imaging the pinhole onto the detector on the detector stage.

3. Traceability

As measurement standard we use Trap detectors supplied and calibrated by NPL, UK in the spectral range 350 – 930 nm traceable to their cryogenic radiometer.

These trap detectors were used as the transfer standard through the whole spectral range. In the spectral range from 300 to 350 and from 930 to 1000 nm these detectors were internally calibrated by ourselves. The calibration was done in two steps. First we measured the relative response between the trap detectors and our spectral invariant cavity pyroelectric detector in the range from 300 to 460 nm with the UV grating and from 800 to 1000 nm with the visual grating. The scaling constant used to convert the relative measurement to an absolute was found by dividing the absolute values with the relative values in the spectral range where we had calibration values. The associated uncertainty was found from the standard deviation in the scaling constant and standard deviation in each point of the relative measurement between the trap divided by pyro measurement in addition to the uncertainty stated from the NPL certificate.

Actually, it was found that the uncertainties with this method gave lower uncertainties in the spectral range from 350 to 400 nm than what was stated by NPL. The relative measurements between our two trap detectors were also more consistent with our new values than the previous ones. Therefore, we used our new values also in the whole spectral range between 300 and 400 nm.

4. Measurement results

Type of Standard Trap detector **Reference Number** BIPM 6

Table 1. Spectral response values of detector BIPM 6.

Wavelength nm	Spectral Responsivity A / W	Bandwidth / nm	Relative Std Dev. / %	Num of measurements	Temperature / °C	Uncertainty / %
300	0,24690	2	0,16	14	23,0 ± 0,5	0,26
320	0,25604	2	0,10	14		0,22
340	0,26894	2	0,09	14		0,20
360	0,28160	2	0,03	14		0,20
380	0,29719	2	0,08	14		0,19
400	0,31665	2/4	0,10	22		0,19
450	0,35960	4	0,05	8		0,10
500	0,40075	4	0,04	8		0,09
550	0,44162	4	0,03	8		0,09
600	0,48212	4	0,02	8		0,09
650	0,52262	4	0,01	8		0,09
700	0,56297	4	0,03	8		0,09
750	0,60346	4	0,02	8		0,09
800	0,64375	4	0,03	8		0,09
850	0,68392	4	0,03	8		0,09
900	0,72430	4	0,04	8		0,09
950	0,76348	4	0,03	8		0,15
1000	0,76271	4	0,11	8		0,32

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Type of Standard Trap detector **Reference Number** BIPM 13

Table 2. Spectral response values of detector BIPM 13.

Wavelength nm	Spectral Responsivity A / W	Bandwidth / nm	Relative Std Dev. / %	Num of measurements	Temperature / °C	Uncertainty / %
300	0,24711	2	0,15	14	23,0 ± 0,5	0,26
320	0,25620	2	0,10	14		0,22
340	0,26914	2	0,10	14		0,20
360	0,28195	2	0,04	14		0,20
380	0,29751	2	0,05	14		0,19
400	0,31687	2/4	0,10	22		0,19
450	0,35974	4	0,01	8		0,10
500	0,40091	4	0,02	8		0,09
550	0,44174	4	0,01	8		0,09
600	0,48223	4	0,01	8		0,09
650	0,52274	4	0,01	8		0,09
700	0,56311	4	0,02	8		0,09
750	0,60356	4	0,01	8		0,09
800	0,64386	4	0,01	8		0,09
850	0,68410	4	0,02	8		0,09
900	0,72443	4	0,02	8		0,09
950	0,76363	4	0,02	8		0,15
1000	0,76297	4	0,11	8		0,32

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Type of Standard single element Silicon detector **Reference Number** F 18

Table 3. Spectral response values of detector F18.

Wavelength nm	Spectral Responsivity A / W	Bandwidth / nm	Relative Std Dev. / %	Num of measurements	Temperature / °C	Uncertainty / %
300	0,13133	2	0,19	14	23,0 ± 0,5	0,30
320	0,14400	2	0,12	14		0,27
340	0,14982	2	0,08	14		0,25
360	0,14682	2	0,08	14		0,25
380	0,15770	2	0,06	14		0,25
400	0,18194	2/4	0,10	22		0,25
450	0,22303	4	0,07	8		0,14
500	0,25587	4	0,02	8		0,13
550	0,28609	4	0,02	8		0,13
600	0,31499	4	0,03	8		0,13
650	0,34327	4	0,03	8		0,13
700	0,37114	4	0,02	8		0,13
750	0,39888	4	0,03	8		0,13
800	0,42638	4	0,03	8		0,13
850	0,45372	4	0,02	8		0,13
900	0,48113	4	0,04	8		0,13
950	0,50583	4	0,04	8		0,18
1000	0,48459	4	0,11	8		0,33

06.10.03

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Type of Standard single element Silicon detector **Reference Number** F 24

Table 4. Spectral response values of detector F 24.

Wavelength nm	Spectral Responsivity A / W	Bandwidth / nm	Relative Std Dev. / %	Num of measurements	Temperature / °C	Uncertainty / %
300	0,13369	2	0,22	14	23,0 ± 0,5	0,30
320	0,14628	2	0,15	14		0,27
340	0,15199	2	0,13	14		0,25
360	0,14885	2	0,14	14		0,25
380	0,15957	2	0,16	14		0,25
400	0,18373	2/4	0,10	22		0,25
450	0,22466	4	0,02	8		0,14
500	0,25732	4	0,02	8		0,13
550	0,28744	4	0,02	8		0,13
600	0,31620	4	0,02	8		0,13
650	0,34437	4	0,02	8		0,13
700	0,37218	4	0,01	8		0,13
750	0,39986	4	0,04	8		0,13
800	0,42726	4	0,02	8		0,13
850	0,45457	4	0,04	8		0,13
900	0,48194	4	0,05	8		0,13
950	0,50661	4	0,04	8		0,18
1000	0,48597	4	0,11	8		0,33

06.10.03

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5. Uncertainty calculation

The uncertainty is calculated by taking into account the different uncertainty components as given in the tables below. The primary realisation is the cryogenic radiometer at NPL. All values are given with 1 σ confidence level.

5.1 Uncertainties in the calibration of JV reference detectors

Spectral invariant uncertainties [%]

Uniformity	0,04
Electrical calibration	0,02
Stray light	0,05
Not ideal pyro	0,05
Long term stability	0,02

Table 5. The table shows different uncertainty components in the calibration of our own standard detector.

Wave-length [nm]	NPL cal of JV detectors [%]	NPL unc. [%]	Unc. Scaling constant [%]	St. Dev pyro meas [%]	Unc. Band-width [%]	Temp-erature [%]	Unc. Wave-length [%]	**Comb. Unc JV ref det. [%]**
300		0,06	0,04	0,20	0,05		0,02	**0,24**
320		0,06	0,04	0,15	0,05		0,02	**0,20**
340		0,06	0,04	0,13	0,05		0,03	**0,18**
360	0,40	0,06	0,04	0,13	0,05		0,02	**0,18**
380	0,40	0,06	0,04	0,11	0,05		0,04	**0,17**
400	0,35	0,06	0,04	0,12	0,05		0,04	**0,17**
450	0,06							**0,06**
500	0,05							**0,05**
550	0,05							**0,05**
600	0,05							**0,05**
650	0,05							**0,05**
700	0,05							**0,05**
750	0,05							**0,05**
800	0,05							**0,05**
850	0,05							**0,05**
900	0,05							**0,05**
950		0,05	0,03	0,07	0,05	0,02	0,01	**0,11**
1000		0,05	0,03	0,18	0,10	0,06	0,14	**0,26**

The first column lists the wavelengths, which the uncertainty components are calculated for. The second column lists the 1 σ uncertainty of NPL calibration values of JV reference detector. The third column shows the uncertainty of the values from the NPL certificate used to scale the relative measurement to absolute values. Column number four shows the uncertainty in the scaling constant given from the ratio between the NPL certificate values and the relative measurement. Calculated at 6 points between 410 and 460 nm and for four points between 900 and 930 nm. The fifth column shows the standard deviation of the pyroelectric detector measurement. The uncertainty caused by the slitwidth is estimated in column 6. Estimated from the graphs of L. - P. Boivin's publication in Appl. Optics Vol. **41**, No. 10, April 2002. The influence of the temperature is estimated in the seventh column. The uncertainty in the responsivity due to the wavelength is shown in column 8. This was calculated from the numerical derivative of the responsivity values with a wavelength uncertainty of 0,4 nm, given by the spec. of the monochromator. The 1 σ combined uncertainty in our reference detectors is given in column 9.

5.2 Uncertainties in the calibration of KC transfer detectors

Spectral invariant uncertainties [%]

Uniformity Trap	0,04
Uniformity Single	0,10
Electrical calibration	0,02
Stray light	0,05
Vignetting error (trap only)	0,04 (300 – 400 nm)

Table 6. The table shows the spectral dependent uncertainty components in the calibration of the key comparison standard detectors. Columns marked with green are related to trap detectors only while columns related to single detectors are yellow.

Wave-length [nm]	Comb. Unc JV ref [%]	Wave-length JV [%]	Wave-length Trap [%]	Wave-length Single [%]	Band-width Trap [%]	Band-width Single [%]	Type A [%]	Temp-erature [%]	Comb unc Trap [%]	Comb unc Single [%]
300	0,24	0,02	0,02	0,03	0,05	0,13	0,02		**0,26**	**0,30**
320	0,20	0,02	0,02	0,03	0,05	0,13	0,02		**0,22**	**0,27**
340	0,18	0,03	0,02	0,01	0,05	0,13	0,02		**0,20**	**0,25**
360	0,18	0,02	0,02	0,01	0,05	0,13	0,02		**0,20**	**0,25**
380	0,17	0,04	0,03	0,02	0,05	0,13	0,02		**0,19**	**0,25**
400	0,17	0,04	0,04	0,05	0,05	0,13	0,02		**0,19**	**0,25**
450	0,06	0,03	0,03	0,03	0,00	0,00	0,00		**0,10**	**0,14**
500	0,05	0,03	0,03	0,03	0,00	0,00	0,00		**0,09**	**0,13**
550	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
600	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
650	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
700	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
750	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
800	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
850	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
900	0,05	0,03	0,02	0,02	0,00	0,00	0,00		**0,09**	**0,13**
950	0,11	0,01	0,02	0,02	0,05	0,05	0,00	0,02	**0,15**	**0,18**
1000	0,26	0,14	0,00	0,02	0,10	0,10	0,01	0,06	**0,32**	**0,33**

The uncertainties in the columns have the same meaning as the previous table. The vignetting errors are considered small due to the f/# used and the low uncertainty in the focal point.

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8.1 Measurement results

Type of Standard: Single photodiode **Reference Number: F 32**

Wavelength nm	Spectral Responsivity A/W	Bandwidth / nm	Relative Std Dev	Num of measurements	Temperature / °C	Uncertainty / %
300						
320						
340						
360						
380	0,15748	4,5	0,001169	11	23	0,287
400	0,18169	4,5	0,001551	11	23	0,167
450	0,22282	4,5	0,001187	11	23	0,127
500	0,25571	4,5	0,001401	11	23	0,146
550	0,28592	4,5	0,001428	11	23	0,150
600	0,31485	4,5	0,001077	11	23	0,114
650	0,34318	4,5	0,001109	11	23	0,116
700	0,37098	4,5	0,001188	11	23	0,126
750	0,39870	4,5	0,001503	11	23	0,155
800	0,42644	4,5	0,001991	11	23	0,202
850	0,45363	4,5	0,001433	11	23	0,148
900	0,48105	4,5	0,001021	11	23	0,109
950	0,50598	4,5	0,001203	11	23	0,131
1000	0,48414	4,5	0,001779	11	23	0,251

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Uncertainty budget of measurements
single photodiode number F 32

Wavelength nm	Uncertainty of reference standard %	Repeatability %	Wavelength calibration %	Short term instability of source %	Stray light %	Combined standard uncertainty (relative) %
380	0,2500	0,1169	0,0769	0,01	0,005	0,287
400	0,0400	0,1551	0,0453	0,01	0,005	0,167
450	0,0305	0,1187	0,0295	0,01	0,005	0,127
500	0,0295	0,1401	0,0236	0,01	0,005	0,146
550	0,0395	0,1428	0,0202	0,01	0,005	0,150
600	0,0305	0,1077	0,0180	0,01	0,005	0,114
650	0,0290	0,1109	0,0162	0,01	0,005	0,116
700	0,0360	0,1188	0,0149	0,01	0,005	0,126
750	0,0320	0,1503	0,0139	0,01	0,005	0,155
800	0,0310	0,1991	0,0128	0,01	0,005	0,202
850	0,0325	0,1433	0,0121	0,01	0,005	0,148
900	0,0335	0,1021	0,0104	0,01	0,005	0,109
950	0,0495	0,1203	0,0086	0,01	0,005	0,131
1000	0,1765	0,1779	0,0090	0,01	0,005	0,251

8.1 Measurement results

Type of Standard: Trap detector **Reference: Number 16**

Wavelength nm	Spectral Responsivity A/W	Bandwidth / nm	Relative Std Dev	Num of measurements	Temperature / °C	Uncertainty / %
300						
320						
340						
360						
380	0,29779	4,5	0,002819	11	23	0,378
400	0,31755	4,5	0,001912	11	23	0,197
450	0,36022	4,5	0,001513	11	23	0,156
500	0,40135	4,5	0,001604	11	23	0,165
550	0,44176	4,5	0,000879	11	23	0,099
600	0,48213	4,5	0,001560	11	23	0,160
650	0,52253	4,5	0,001268	11	23	0,131
700	0,56277	4,5	0,001135	11	23	0,120
750	0,60247	4,5	0,001337	11	23	0,139
800	0,64256	4,5	0,001289	11	23	0,134
850	0,68362	4,5	0,001206	11	23	0,126
900	0,72374	4,5	0,001186	11	23	0,124
950	0,76261	4,5	0,000751	11	23	0,091
1000	0,76065	4,5	0,001498	11	23	0,232

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Uncertainty budget of measurements
trap detector number 16

Wavelength nm	Uncertainty of reference standard %	Repeatability %	Wavelength calibration %	Short term instability of source %	Stray light %	Combined standard uncertainty (relative) %
380	0,2500	0,2819	0,0332	0,01	0,005	0,378
400	0,0400	0,1912	0,0269	0,01	0,005	0,197
450	0,0305	0,1513	0,0228	0,01	0,005	0,156
500	0,0295	0,1604	0,0201	0,01	0,005	0,165
550	0,0395	0,0879	0,0183	0,01	0,005	0,099
600	0,0305	0,1560	0,0168	0,01	0,005	0,160
650	0,0290	0,1268	0,0154	0,01	0,005	0,131
700	0,0360	0,1135	0,0141	0,01	0,005	0,120
750	0,0320	0,1337	0,0133	0,01	0,005	0,139
800	0,0310	0,1289	0,0128	0,01	0,005	0,134
850	0,0325	0,1206	0,0117	0,01	0,005	0,126
900	0,0335	0,1186	0,0107	0,01	0,005	0,124
950	0,0495	0,0751	0,0005	0,01	0,005	0,091
1000	0,1765	0,1498	0,0005	0,01	0,005	0,232

8.1 Measurement results

Type of Standard: Trap detector **Reference Number: 07**

Wavelength nm	Spectral Responsivity A/W	Bandwidth / nm	Relative Std Dev	Num of measurements	Temperature / °C	Uncertainty / %
300						
320						
340						
360						
380	0,29786	4,5	0,004890	11	23	0,550
400	0,31743	4,5	0,002005	11	23	0,207
450	0,36036	4,5	0,000687	11	23	0,079
500	0,40146	4,5	0,000299	11	23	0,048
550	0,44201	4,5	0,001536	11	23	0,160
600	0,48220	4,5	0,001378	11	23	0,143
650	0,52279	4,5	0,002015	11	23	0,204
700	0,56278	4,5	0,002701	11	23	0,273
750	0,60264	4,5	0,002335	11	23	0,236
800	0,64266	4,5	0,002927	11	23	0,295
850	0,68405	4,5	0,000724	11	23	0,081
900	0,72377	4,5	0,000342	11	23	0,050
950	0,76282	4,5	0,002160	11	23	0,222
1000	0,76218	4,5	0,003525	11	23	0,394

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Uncertainty budget of measurements
trap detector number 07

Wavelength nm	Uncertainty of reference standard %	Repeatability %	Wavelength calibration %	Short term instability of source %	Stray light %	Combined standard uncertainty (relative) %
380	0,2500	0,489	0,0329	0,01	0,005	0,550
400	0,0400	0,2005	0,0284	0,01	0,005	0,207
450	0,0305	0,0687	0,0228	0,01	0,005	0,079
500	0,0295	0,0299	0,0202	0,01	0,005	0,048
550	0,0395	0,1536	0,0182	0,01	0,005	0,160
600	0,0305	0,1378	0,0168	0,01	0,005	0,143
650	0,0290	0,2015	0,0153	0,01	0,005	0,204
700	0,0360	0,2701	0,0142	0,01	0,005	0,273
750	0,0320	0,2335	0,0133	0,01	0,005	0,236
800	0,0310	0,2927	0,0129	0,01	0,005	0,295
850	0,0325	0,0724	0,0116	0,01	0,005	0,081
900	0,0335	0,0342	0,0108	0,01	0,005	0,050
950	0,0495	0,216	0,0002	0,01	0,005	0,222
1000	0,1765	0,3525	0,0002	0,01	0,005	0,394

8.1 Measurement results

Type of Standard: Single photodiode **Reference Number: F 09**

Wavelength nm	Spectral Responsivity A/W	Bandwidth / nm	Relative Std Dev	Num of measurements	Temperature / °C	Uncertainty / %
300						
320						
340						
360						
380	0,15936	4,5	0,001628	11	23	0,308
400	0,18357	4,5	0,001212	11	23	0,136
450	0,22473	4,5	0,001074	11	23	0,116
500	0,25750	4,5	0,001093	11	23	0,116
550	0,28745	4,5	0,001247	11	23	0,133
600	0,31622	4,5	0,001238	11	23	0,129
650	0,34443	4,5	0,000863	11	23	0,093
700	0,37220	4,5	0,000686	11	23	0,080
750	0,39976	4,5	0,001080	11	23	0,114
800	0,42742	4,5	0,001284	11	23	0,133
850	0,45481	4,5	0,001762	11	23	0,180
900	0,48217	4,5	0,001331	11	23	0,138
950	0,50693	4,5	0,001421	11	23	0,151
1000	0,48460	4,5	0,001707	11	23	0,246

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Uncertainty budget of measurements
single photodiode number F 09

Wavelength nm	Uncertainty of reference standard %	Repeatability %	Wavelength calibration %	Short term instability of source %	Stray light %	Combined standard uncertainty (relative) %
380	0,2500	0,1628	0,0760	0,01	0,005	0,308
400	0,0400	0,1212	0,0448	0,01	0,005	0,136
450	0,0305	0,1074	0,0292	0,01	0,005	0,116
500	0,0295	0,1093	0,0233	0,01	0,005	0,116
550	0,0395	0,1247	0,0200	0,01	0,005	0,133
600	0,0305	0,1238	0,0178	0,01	0,005	0,129
650	0,0290	0,0863	0,0161	0,01	0,005	0,093
700	0,0360	0,0686	0,0148	0,01	0,005	0,080
750	0,0320	0,108	0,0138	0,01	0,005	0,114
800	0,0310	0,1284	0,0128	0,01	0,005	0,133
850	0,0325	0,1762	0,0120	0,01	0,005	0,180
900	0,0335	0,1331	0,0103	0,01	0,005	0,138
950	0,0495	0,1421	0,0088	0,01	0,005	0,151
1000	0,1765	0,1707	0,0092	0,01	0,005	0,246

Dubrzykowski

Dear Dr Joaquin Campos Acosta, October 14, 2003

Enclosed I send you the final report on the calibrations of single photodiodes and trap detectors (EUROMET PR K2.b) with uncertainty budgets. I would like to apologize you that in provisional results, which I have sent to you in September were errors in printed values (for two different detectors these same values of spectral responsivity). I want to inform you also, that in our measurements the light spot imaged on the detector had dimensions 3 mm x 4 mm.

Best regards

Jerzy Pietrzykowski

National Institute of Metrology (INM-Romania)

EUROMET Key Comparison: PR-K2.b

INM-Romania final report

Summary

1. Measurement method and installation
2. Reference standard employed and traceability
3. Measurement conditions
4. Calibration results
5. Useful information on the participant

1 Measurement method and installation

The method employed by INM – Romania was the comparison by substitution; the device under calibration and the reference standard were alternatively placed into the measurement beam of the spectro-radiometric comparator.

The signals obtained are corrected for influence factors then their ratio is computed in order to estimate the calibrated device spectral responsivity with respect to the certified value of the reference standard.

1.2 The spectro-radiometric comparator

The installation is a monochromator based comparator (**Fig. 1**).

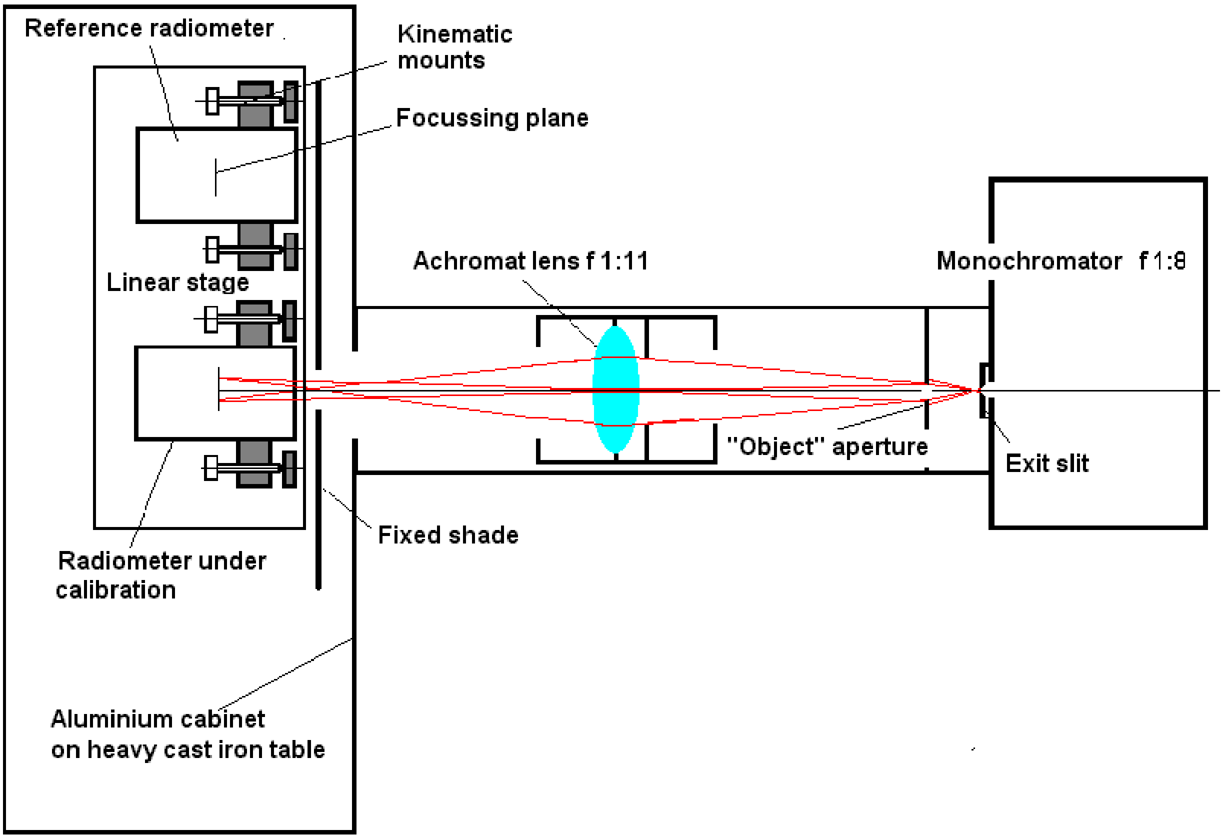

Fig. 1 The INM spectro-radiometric comparator

1.2.1. Power and spectral conditions

A ZEISS, f 1:5,6 Ebert configured monochromator and a set of order sorting filters are used in order to produce the necessary radiant flux.

Due to the low spectral density of the sources employed (halide lamp and a 25W D2 lamp) the “monochromatic” flux obtained was quite small: (5…100) nW in the VIS and IRA and (1…5) nW in the UV range.

A 1,5 nm half-bandwidth was used throughout the VIS-IRA measurements while for UV measurements a 3 nm half bandwidth was used.

After calibration against low pressure spectral lamps, the maximum error of the effective wavelength was estimated to be of +/- 0,2 nm.

1.2.2 Measurement beam geometry

An “object” circular aperture of 2 mm dia. was placed after the exit slit of the monochromator so that it was evenly irradiated.

For VIS-IRA measurements, this aperture was projected with 1,5:1 ratio normal to the center of the calibrated device using an achromat lens of f 1:8.

For UV measurements a single fused quartz lens of f 1:11 was used.

The focus plan was at the level of the third photodiode in the trap devices.

A supplementary aperture with a 4,5 mm dia. was placed some 15 mm in front of the device under calibration in order to filter the scattered and the diffracted components in the measurement beam.

1.2.3 Electronics

A transimpedance amplifier with a 50 E6 transimpedance factor was used throughout in order to provide an as low input impedance as possible.

The transimpedance amplifier output was measured with an Agilent 34420 A nano-voltmeter. It`s input was switched alternatively to the reference standard and to the device under calibration so that most of the uncertainties generated by the electronics canceled. Automatic filtering was used throughout.

1.2.4 Measurement sequence

After alignment and the necessary (thermal) relaxation duration, for each selected wavelength, the measurements were performed according to the following sequence:

$$\mathbf{Y_e - Y_x - Y_e - Y_x - Y_e - Y_x - Y_e - Y_{e0} - Y_{x0}}$$

where:

$\mathbf{Y_e}$ is the signal produced by the employed reference standard;

$\mathbf{Y_x}$ is the signal produced by the device under calibration;

$\mathbf{Y_{e0}}$ is the dark signal of the reference standard (including the dark signal and electronic offsets);

$\mathbf{Y_{x0}}$ is the dark signal of the device under calibration (including the dark signal and electronic offset).

1.2.5 Data processing

Three measurement sequences as described above were performed, (by readjusting the wavelength every time) and three mean responsivity values were computed for each detector and each wavelength.

Typical standard deviations were found to be: s = 0,2…0,3 % in the (300…400) nm range and s = 0,05… 0,08 % in the (400…1000) nm range.

2 Reference standard and traceability route

2.1 SI Traceability

For the (488…632,8) nm range, the INM reference standard is a trap detector with three Hamamatsu S 1337 1010 windowless photodiodes (provided by BIPM).
It was calibrated in 1999 by BNM-INM with respect to secondary standards (trap detectors) themselves calibrated against the primary standard of France, the RADIOX cryogenic, electrical substitution radiometer.

A recent study was performed by the same laboratory at selected wavelengths (487,99; 514,53; 543,36; 611,80 and 632,8 nm) using monochromator radiation and resulting in lower values (-0,20%), possibly due to the trap contamination.
The estimated standard uncertainty was also larger than in the case of the first calibration, performed with laser beams: (0,13 % compared to 0,04%). Extrapolation using second order polynomials was used to cover the (400…700) range.

For the (300…400) nm range, theoretical estimation of the spectral responsivity of the same trap was used, resulting in a much larger standard uncertainty: (1…2) % with the wavelength.

For the IRA calibrations, the INM reference standard - a Hamamatsu S 1337 1010 BQ photodiode – is traceable to BNM-INM (standard uncertainty: 0,20%).

2.2 Internal traceability

Using the above mentioned references, a working standard was calibrated at INM throughout the (300…1000) nm range, using the above mentioned spectro-radiometric comparator and technique (substitution).

According to the spectral range, the estimated standard uncertainties for this calibration were: (1…2,5) % in the (300…400) nm range;
0,30 % in the (400…900) nm range and
0,50 % in the (900…1000) nm range.

This detector was used to calibrate the detectors circulated in EUROMET PR K2.b. Corresponding estimated standard uncertainties are stated in tabs. 1…4, chapter 4.

Detailed uncertainty budgets in both cases (single and trap detectors calibrations) are also dealt with in chapter 4.

3 Measurement conditions

The spectro-radiometric comparator is placed within a black box large enough to accommodate two persons. The two radiometers to be compared are accommodated in a smaller cabinet (all metal) that is part of the spectro-radiometric comparator.

An air conditioning installation is used to control the environment temperature in the room where the black box is accommodated.

A separate digital thermometer, recently calibrated by the INM Temperature lab. with an estimated extended uncertainty of 0,20 ºC (k=2) was used to monitor the temperature inside the small cabinet of the spectro-radiometric comparator.

Yet, with all the sources and the calibration personnel inside the black box it took too long to bring down the temperature at 23 ºC at the radiometers level so it was decided to perform all calibrations at T = (24 +/-) ºC, a much more practical temperature. During all measurements the humidity was < 40 %.

4 Calibrations results

a. Spectral responsivities of the circulated radiometers

Tab. 1: Radiometer serial: F19

Wavelenght (nm)	**Spectral responsivity (provisional) (A/W)**	**Spectral FW at HM (nm)**	**Rel. Std. Deviation (%)**	**Nr. of measurements**	**Temp. ºC**	**Combined Standard uncertainty (%)**
300	**0.1287**	3,0+/-0,3	0,30	3	24+/0,5	3,00
320	**0.1413**					2,40
340	**0.1493**					2,00
360	**0.1428**					1,70
380	**0.1536**					1,50
400	**0.1824**	1,5+/-0,2	0,10			0,50
450	**0.2254**					0,40
500	**0.2580**					0,40
550	**0.2877**					0,40
600	**0.3167**					0,40
650	**0.3449**					0,40
700	**0.3727**					0,40
750	**0.4004**					0,40
800	**0.4278**					0,45
850	**0.4549**					0,45
900	**0.4778**					0,45
950	**0.4956**	1,5+/-0,2	0,10			0,70
1000	**0.4773**					0,75

Tab. 2: Radiometer serial: F45

Wavelength (nm)	Spectral responsivity (provisional) (A/W)	Spectral FW at HM (nm)	Rel. Std. Deviation (%)	Nr. of measurements	Temp. ºC	Standard uncertainty (%)
300	**0.1249**	3,0+/-0,3	0,30	3	24+/0,5	3,00
320	**0.1378**					2,40
340	**0.1458**					2,00
360	**0.1401**					1,70
380	**0.1506**					1,50
400	**0.1793**	1,5+/-0,2	0,10			0,50
450	**0.2227**					0,40
500	**0.2555**					0,40
550	**0.2853**					0,40
600	**0.3143**					0,40
650	**0.3428**					0,40
700	**0.3703**					0,40
750	**0.3979**					0,40
800	**0.4252**					0,45
850	**0.4523**					0,45
900	**0.4753**					0,45
950	**0.4929**	1,5+/-0,2	0,10			0,70
1000	**0.4751**					0,75

Tab. 3: Radiometer serial: BIPM-REF 10

Wavelength (nm)	Spectral responsivity (provisional) (A/W)	Spectral FW at HM (nm)	Rel. Std. Deviation (%)	Nr. of measurements	Temp. ºC	Standard uncertainty (%)
300	**0,2346**	3,0+/-0,3	0,30	3	24+/ 0,5	2,70
320	**0,2453**					2,10
340	**0,2618**					1,70
360	**0,2685**					1,40
380	**0,2856**					1,20
400	**0,3143**	1,5+/-0,2	0,10			0,40
450	**0,3611**					0,30
500	**0,4020**					0,30
550	**0,4422**					0,30
600	**0,4830**					0,30
650	**0,5234**					0,30
700	**0,5631**					0,40
750	**0,6031**					0,40
800	**0,6432**					0,40
850	**0,6830**					0,40
900	**0,7163**					0,40
950	**0,7448**	1,5+/-0,2	0,10			0,60
1000	**0,7488**					0,70

Tab. 4: Radiometer serial: BIPM-REF 12

Wavelength (nm)	Spectral responsivity (provisional) (A/W)	Spectral FW at HM (nm)	Rel. Std. Deviation (%)	Nr. of measurements	Temp. ºC	Standard uncertainty (%)
300	**0,2304**	3,0+/-0,3	0,30	3	24+/ 0,5	2,70
320	**0,2455**					2,10
340	**0,2613**					1,70
360	**0,2678**					1,40
380	**0,2856**					1,20
400	**0,3144**	1,5+/-0,2	0,10			0,40
450	**0,3609**					0,30
500	**0,4019**					0,30
550	**0,4419**					0,30
600	**0,4825**					0,30
650	**0,5231**					0,30
700	**0,5628**					0,40
750	**0,6033**					0,40
800	**0,6430**					0,40
850	**0,6829**					0,40
900	**0,7163**					0,40
950	**0,7449**	1,5+/-0,2	0,10			0,60
1000	**0,7498**					0,70

b. Uncertainties estimation

The measurand value estimation is described with the formula:

$$s_x(\lambda) = s_e(\lambda) * s`_x(\lambda) * C_1 * C_2 * C_3 * C_4 * C_5 * C_6 * C_7$$

where:

$s_x(\lambda)$ is the spectral responsivity of the calibrated detector;

$s_e(\lambda)$ is the spectral responsivity of the standard detector;

$$s`_x(\lambda) = \frac{\bar{Y}_x(\lambda) - \bar{Y}_{x0}(\lambda)}{\bar{Y}_e(\lambda) - \bar{Y}_{e0}(\lambda)}$$

with:

$\bar{Y}_x(\lambda)$ being the mean value of the spectral response of the calibrated detector;

$\bar{Y}_e(\lambda)$ being the mean value of the spectral response of the standard detector;

$\bar{Y}_{x0}(\lambda)$ and $\bar{Y}_{e0}(\lambda)$ being the mean values of the "zero" signals of the device under calibration and of the standard;

C_1 - the correction coefficient for the calibrated detector spatial uniformity;
C_2 - the correction coefficient for the polarizing effects;
C_3 - the correcting coefficient for vignetting effects;
C_4 - the correction coefficient for temperature effects;
C_5 - the correction coefficient for effective wavelength value;
C_6 - the correction coefficient for the effective spectral bandwidth;
C_7 - the correction coefficient for the stary light in the measurement beam.

Accordingly, the following uncertainties budgets resulted:

Calibration of single detectors in the 300…380 nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	≈ 0,25A/W	(0.0063…0.0030) A/W; λ= (300…380)nm	$s`_x(\lambda)$	0.0038…0.0018
$s`_x(\lambda)$	≈ 0,6 (one)	Std. dev. of $s`_x(\lambda)$ s = 0.0018 (one)	$s_e(\lambda)$	0.00045
C_1	1,001 (one)	0.0005 (one)	$s_x(\lambda) \approx$ $\approx 0,15 A/W$	0.00008
C_2	1 (one)	0.0010 (one)	$s_x(\lambda)$	0.00015
C_3	1 (one)	0.0010 (one)	$s_x(\lambda)$	0.00015
C_4	1+α*ΔT ≈ 1,001 (one)	0,0010 $(\Delta T \cong 1,5^0 C)$	$s_x(\lambda)$	0.00015
C_5	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx 0,0009$	$s_x(\lambda)$	0.00013
C_6	1 (one)	0.0020 (one)	$s_x(\lambda)$	0.00030
$s_x(\lambda)$	**(0,128…154) A/W**	**(0,0039…0,0019) A/W or (3…1,2) %**		**0,0039…0,0019**

Calibration of single detectors in the (400…900) nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	(0,31...0,72) A/W	(0.00093…0.00216) (A/W) λ= (400…900) nm	$s`_x(\lambda)$	0.00060…0.00140
$s`_x(\lambda)$	≈ 0,65 (one)	Stdt. dev. of $s`_x(\lambda)$ s = 0.0005 (one)	$s_e(\lambda)$	0.00016…0.00037
C_1	1,0005 (one)	0.0005 (one)	$s_x(\lambda) \approx$ (0,18...0,5) (A/W)	0.00009…0.00025
C_2	1 (one)	0.0005 (one)	$s_x(\lambda)$	0.00009…0.00025
C_3	1 (one)	0.0005 (one)	$s_x(\lambda)$	0.00009…0.00025
C_4	1 + α*ΔT ≈ 1,0010 (one)	0,0005 $(\Delta T \cong 1,5^0 C)$	$s_x(\lambda)$	0.00009…0.00025
C_5	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx 0,0009$ (one)	$s_x(\lambda)$	0.00015…0.00043
C_6	1 (one)	0.0010 (one)	$s_x(\lambda)$	0.00018….0.00050
$s_x(\lambda)$	**(0,18…0,50) (A/W)**	**(0.00069…0.00167) A/W ≈ 0,40%**		**0.00069…0.00167 (0,38…0,33)%**

Calibration of single detectors in the (950…1000) nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	$\approx 0{,}72 A/W$	≈ 0.0036 (A/W); λ= (950…1000)nm	$s^{\backprime}_x(\lambda)$	0.0025
$s^{\backprime}_x(\lambda)$	≈ 0,7 (one)	Stdt. dev. of $s^{\backprime}_x(\lambda)$ s = 0.0008 (one)	$s_e(\lambda)$	0.00058
C₁	1 (one)	0.0005 (one)	$s_x(\lambda)$	0.00025
C₂	1 (one)	0.0010 (one)	$s_x(\lambda)$	0.00050
C₃	1 (one)	0.0005 (one)	$s_x(\lambda)$	0.00025
C₄	1+α*ΔT ≈ 1,0015 (one)	0,0010 $(\Delta T \cong 1{,}5^0 C)$	$s_x(\lambda)$	0.00050
C₅	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx$ 0,0017...0.003	$s_x(\lambda)$	0.00085…0.0017
C₆	1 (one)	0.0010 (one)	$s_x(\lambda)$	.0.00050
$s_x(\lambda)$	**(0,4…0,5) (A/W)**	**(0,0029…0,0034) A/W** **≈ (0,60…0,70) %**		**≈ 0,0029…0,0034**

Calibration of trap detectors in the 300…380 nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	$\approx 0{,}25 A/W$	(0.0063…0.0032) A/W; λ= (300…380)nm	$s^{\backprime}_x(\lambda)$	0.0069…0.0035
$s^{\backprime}_x(\lambda)$	≈ 1,1 (one)	Stdt. dev. of $s^{\backprime}_x(\lambda)$ s = 0.003 (one)	$\approx s_e(\lambda)$	0.00081
C₁	1,0005 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00014
C₂	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00014
C₃	1 (one)	0.0010 (one)	$\approx s_x(\lambda)$	0.00027
C₄	1+α*ΔT ≈ 1,0010 (one)	0,0005 $(\Delta T \cong 1{,}5^0 C)$	$\approx s_x(\lambda)$	0.00014
C₅	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx 0{,}0010$	$\approx s_x(\lambda)$	0.00027
C₆	1 (one)	0.0020 (one)	$\approx s_x(\lambda)$	0.00054
$s_x(\lambda)$	**≈ 0,27 (A/W)**	**(0,0070…0,0037) A/W** **(2,6…1,2) %**		**0,0070…0,0037** **(2,6…1,2) %**

Calibration of trap detectors in the (400…900) nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	≈ (0,30...0,70) (A/W)	0,3% = (0.0009…0.0021) A/W; λ= (400…900)nm	$\approx s`_x(\lambda)$	0.0009…0.00210
$s`_x(\lambda)$	≈ 1 (one)	Stdt. dev. of $s`_x(\lambda)$ s = 0.0008 (one)	$\approx s_e(\lambda)$	0.00024…0,00056
C₁	1,0005 (one)	0.0002 (one)	$\approx s_x(\lambda)$	0.00006…0.00015
C₂	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00015…0.00038
C₃	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00015…0.00038
C₄	1+α∗ΔT ≈ 1 (one)	neglected $(\Delta T \cong 1{,}5^0 C)$	$\approx s_x(\lambda)$	neglected
C₅	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx 0{,}0004$ (one)	$\approx s_x(\lambda)$	0.00012…0.00030
C₆	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00015…0.00038
$s_x(\lambda)$	**(0,32…0,75) (A/W)**	**≈ (0,0010…0,0023) A/W** **≈ 0,31 %**		**≈ 0,0010…0,0023**

Calibration of trap detectors in the (950…1000) nm range

Quantity	Value	Associated uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty (A/W)
$s_e(\lambda)$	$\approx 0{,}70(A/W)$	0,5% = 0.0035 (A/W); λ= (950…1000)nm	$\approx s`_x(\lambda)$ ≈ 1	0.0035
$s`_x(\lambda)$	≈ 1 (one)	Stdt. dev. of $s`_x(\lambda)$ s = 0.0008 (one)	$\approx s_e(\lambda)$	0.00056
C₁	1,0005 (one)	0.0002 (one)	$\approx s_x(\lambda)$	0.00015
C₂	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00038
C₃	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00038
C₄	1+α∗ΔT ≈ 1,0005 (one)	0,0005 $(\Delta T \cong 1{,}5^0 C)$	$\approx s_x(\lambda)$	0.00038
C₅	1 (one)	$u_{\lambda ef} * \frac{\partial s_x}{\partial \lambda} \approx 0{,}0010$ (one)	$\approx s_x(\lambda)$	0.00075
C₆	1 (one)	0.0005 (one)	$\approx s_x(\lambda)$	0.00038
$s_x(\lambda)$	**≈ 0,75 (A/W)**	**≈ 0,0037 (A/W)** **≈ 0,5 %**		**≈ 0,0037**

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Euromet PR-K2.b Key Comparison
Spectral Responsivity part 2 (300 nm to 1000 nm)

NMi VSL contribution

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Contents

Introduction

This report describes the contribution of NMi VSL regarding the Euromet-K2.b Key Comparison Spetral Responsivity part 2 (300 nm to 1000 nm), coordinated by IFA (Spain). Within this comparison the spectral responsivity, in A/W, of four detectors (KC transfer detectors) where measured over the wavelength range of 300 nm to 400 nm in steps of 20 nm and from 400 nm to 1000 nm in steps of 50 nm. The artefacts were two single-element photodiodes; type Hamamatsu 1337-1010BQ (quartz window), and two three-element reflection-trap detectors containing Hamamatsu 1337-1010N (windowless) photodiodes. The measurements were preformed on the ACR spectral calibration facility at NMi VSL consisting of a monochromator-based cryogenic radiometer and three Si-element reflection-trap detectors as transfer standards. The four artefacts are calibrated against the NMi VSL transfer detectors denoted VT1, UVT1 and VT3.

Measurement setup

The layout of the spectral calibration facility is shown in Figure 1. The figure shows three radiation sources were each is used for a specific wavelength range between 0.19 μm and 20 μm. A 150 W Xe-arc lamp covers the wavelength range from 250 nm to 400 nm. The output is stabilized within a few parts in 10^{-4} by means of an optical feedback circuit. For the spectral range between 400 nm and 2500 nm a 100 W quartz-tungsten-halogen lamp (QTH) is used. The current through the filament is stabilized within 10^{-5}. For the wavelength range above 2500 nm and below 250 nm a 8 kW Ar maxi-arc is employed. The radiation sources are dispersed by a monochromator, which is, used either in double-subtractive mode for the UV, visual and near-infrared spectral region or in single mode for the infrared part of the spectrum (above 2.5 μm). When the facility is operated below the latter wavelength range the radiation from the QTH-lamp or Xe-arc is imaged onto the slit of the double-grating monochromator by means of a quartz lens. For measurements above 2.5 μm and below 250 nm the AR maxi-arc radiation is imaged onto the second and first slit (single or double mode) of the monochromator, respectively, using a set of off-axis parabolic mirrors. Note that working in the infrared region the use of a single grating is sufficient for proper out-of-band suppression.

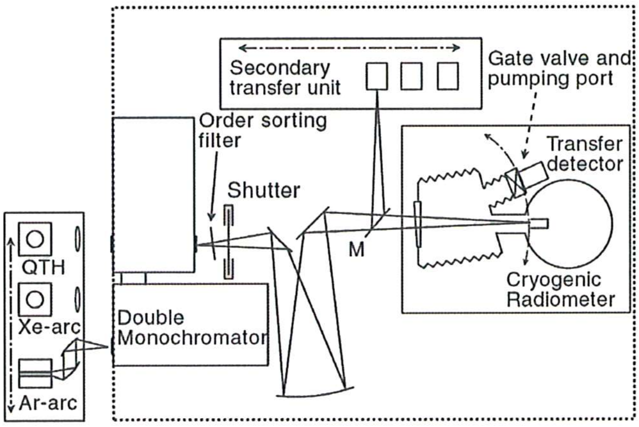

Figure 1: layout of the ACR spectral calibration facility.

The radiation emerging from the monochromator first passes an order-sorting filter and is then imaged onto the transfer detector or the cryogenic radiometer (CR) by a set of two spherical mirrors and one folding mirror. The set of spherical mirrors consists of a convex and a concave mirror. The radii, angles of incidence, and the distances are chosen such that spherical aberrations are minimized. Residual astigmatism is small as the circular output aperture of the monochromator yields a sharp, slightly oval, image in the focal plane with a diameter of about 4.5 mm. The optical system consisting of the two spherical mirrors is also used to match the f-number of the monochromator, about f/4.8, on the one hand, and the f-number, f/8, of the cryogenic radiometer (type Cryorad II, Cambridge Research and Instrumentation). A folding mirror can be placed in the optical path, in Figure 1 denoted with capital M, to redirect the beam to a secondary transfer unit. On this unit calibrations against transfer detectors can be performed. All mirrors are coated with Al and MgF_2 as a protective coating. The complete facility, except for the light-source unit, is enclosed in a light-tight box that minimizes convection and temperature fluctuations from the environment.

The CR and the transfer detector are part of a vacuum system, which allows positioning of either the cavity of the CR or the aperture of the transfer detector in the focal plane of the optical beam. All transfer detectors are equipped with a 6 mm aperture, which matches the aperture of the CR. The 10 mm thick entrance window to the vacuum system is slightly wedged and tilted to prevent multiple-reflections from influencing the calibration results. The cavity sensitivity is about 1.65 K/mW; the cavity absorption at 632.8 nm is 0.99982 as measured by the manufacturer (typically the uncertainty is 1×10^{-5}). The time constant of the cavity is 2.5 s. The relative uncertainty in the power measurement of the CR is 9×10^{-5}. The current from the transfer standards is measured with a home-built transimpedance amplifier and a HP3458A digital voltmeter. The relative uncertainty in the current measurement is 5×10^{-5}.

The wavelength calibration of the monochromator below 2.5 µm is performed by measurement of spectral emission lines of several elements in a low-pressure discharge lamp. The lowest spectral line used for the calibration emanates from a high power Ar-ion laser producing an emission line at 248 nm. The wavelength uncertainty based on the monochromator is presented in Table 1.

Table 1: Uncertainty due to wavelength calibration of monochromator.

Wavelength / nm	250 - 400	400 - 1000
Uncertainty / %	0.08	0.01

Measurement procedure

The calibration of the four KC transfer detectors have been carried out in five steps.

1. Primary realization of the spectral responsivity scale between 300 nm to 1050 nm.
2. Calibration of the monochromator with a He and Cs lamp for the spectral range between 400 nm to 1000 nm.
3. Calibration of the KC transfer detectors between 400 nm to 1000 nm.
4. Calibration of the monochromator with a He and Na lamp for the spectral range between 300 nm to 500 nm.
5. Calibration of the KC transfer detectors between 300 nm to 400 nm.

The measurements are performed with a monochromator grating with 1200 grooves/mm and four order-sorting filters, WG280, KV389, OG530 and RG780. The selected radiation source in the wavelength range 300 nm to 400 nm was a 150W Xe-arc100 W. Between 400 nm to 1000 nm a quartz-tungsten-halogen lamp (QTH) was used.

The NMi VSL transfer detectors were calibrated in December 2004 to January 2005. The total practical calibration of the KC transfer detectors started in September 2004 to July 2005.

Results

The results of the spectral responsivity measurements for the four KC transfer detectors are presented in table 2 to 4. As a reference surface for the single element KC transfer detectors a 6 mm aperture was positioned in the focal plane of the setup, just in front of the single-element detectors. The relative standard deviation is determined by the standard deviation of the measurements divided by the absolute responsivity value and is presented in terms of percentage.

Table 2: Type of Standard Single photodiode Reference Number F21

Wavelength / nm	Spectral Responsivity / A·W^{-1}	Bandwidth / nm	Relative Std Dev. / %	Number of measurements / -	Temperature / °C	Uncertainty / %
300	0.13143	5	0.051	20	22.0	0.170
320	0.14378	5	0.063	20	22.0	0.143
340	0.14965	5	0.026	20	22.0	0.128
360	0.14670	5	0.038	20	22.0	0.153
380	0.15768	5	0.050	20	22.0	0.147
400	0.18197	5	0.049	20	22.0	0.072
450	0.22342	5	0.005	10	22.0	0.035
500	0.25639	5	0.008	10	22.0	0.033
550	0.28659	5	0.003	10	22.0	0.032
600	0.31548	5	0.007	10	22.0	0.032
650	0.34371	5	0.005	10	22.0	0.032
700	0.37155	5	0.006	10	22.0	0.032
750	0.39920	5	0.010	10	22.0	0.033
800	0.42660	5	0.007	10	22.0	0.033
850	0.45387	5	0.006	10	22.0	0.032
900	0.48111	5	0.006	10	22.0	0.035
950	0.50542	5	0.008	10	22.0	0.053
1000	0.48221	5	0.015	10	22.0	0.218

Table 3: Type of Standard Single photodiode Reference Number F34

Wavelength / nm	Spectral Responsivity / A·W^{-1}	Bandwidth / nm	Relative Std Dev. / %	Number of measurements / -	Temperature / °C	Uncertainty / %
300	0.13129	5	0.037	20	21.8	0.166
320	0.14370	5	0.050	20	21.8	0.138
340	0.14955	5	0.048	20	21.8	0.134
360	0.14665	5	0.039	20	21.8	0.153
380	0.15760	5	0.031	20	21.8	0.142
400	0.18195	5	0.035	20	21.8	0.063
450	0.22334	5	0.008	10	21.8	0.035
500	0.25627	5	0.008	10	21.8	0.033
550	0.28647	5	0.005	10	21.8	0.032
600	0.31533	5	0.007	10	21.8	0.032
650	0.34358	5	0.007	10	21.8	0.032
700	0.37142	5	0.004	10	21.8	0.032
750	0.39905	5	0.004	10	21.8	0.032
800	0.42648	5	0.004	10	21.8	0.032
850	0.45377	5	0.006	10	21.8	0.032
900	0.48104	5	0.005	10	21.8	0.035
950	0.50538	5	0.007	10	21.8	0.053
1000	0.48223	5	0.009	10	21.8	0.218

As a reference surface for the single element KC transfer detectors we positioned a 6 mm aperture in the focal plane of the setup, just in front of the single element detectors.

Table 4: Type of Standard Trap detector Reference Number REF 11

Wavelength / nm	Spectral Responsivity / A·W^{-1}	Bandwidth / nm	Relative Std Dev. / %	Number of measurements / -	Temperature / °C	Uncertainty / %
300	0.24653	5	0.080	20	22.3	0.129
320	0.25523	5	0.065	20	22.3	0.142
340	0.26816	5	0.041	20	22.3	0.112
360	0.28083	5	0.025	20	22.3	0.125
380	0.29690	5	0.055	20	22.3	0.137
400	0.31641	5	0.046	20	22.3	0.065
450	0.35982	5	0.007	10	22.3	0.029
500	0.40126	5	0.008	10	22.3	0.026
550	0.44204	5	0.003	10	22.3	0.025
600	0.48254	5	0.005	10	22.3	0.025
650	0.52297	5	0.007	10	22.3	0.026
700	0.56331	5	0.005	10	22.3	0.025
750	0.60362	5	0.003	10	22.3	0.025
800	0.64386	5	0.006	10	22.3	0.026
850	0.68403	5	0.004	10	22.3	0.026
900	0.72417	5	0.006	10	22.3	0.026
950	0.76296	5	0.004	10	22.3	0.034
1000	0.76072	5	0.006	10	22.3	0.200

Table 5: Type of Standard Trap detector Reference Number REF 14

Wavelength / nm	Spectral Responsivity / A·W^{-1}	Bandwidth / nm	Relative Std Dev. / %	Number of measurements / -	Temperature / °C	Uncertainty / %
300	0.24653	5	0.065	20	22.0	0.121
320	0.25524	5	0.060	20	22.0	0.140
340	0.26829	5	0.044	20	22.0	0.113
360	0.28089	5	0.043	20	22.0	0.130
380	0.29706	5	0.051	20	22.0	0.135
400	0.31647	5	0.041	20	22.0	0.061
450	0.35980	5	0.006	10	22.0	0.028
500	0.40119	5	0.003	10	22.0	0.025
550	0.44196	5	0.005	10	22.0	0.025
600	0.48246	5	0.008	10	22.0	0.026
650	0.52289	5	0.004	10	22.0	0.025
700	0.56323	5	0.005	10	22.0	0.025
750	0.60353	5	0.007	10	22.0	0.026
800	0.64372	5	0.003	10	22.0	0.026
850	0.68390	5	0.005	10	22.0	0.026
900	0.72405	5	0.005	10	22.0	0.026
950	0.76291	5	0.006	10	22.0	0.035
1000	0.76011	5	0.009	10	22.0	0.200

Uncertainty budgets

The presented uncertainty budgets on the following pages are explained as followed:

u(trans)	uncertainty of the NMi VSL transfer detectors
u(drift)	uncertainty due to the drift of the NMi VSL transfer detectors
u(λ)	wavelength uncertainty
u($\Delta\lambda$)	bandwidth uncertainty
u(i)	uncertainty due to current measurement of the KC transfer detector and the NMi VSL standards
u(uni)	uncertainty due to the non-uniformity of the KC transfer detectors
u(stray)	uncertainty due to the stray light
u(angle)	uncertainty due to angular dependence
u(T)	uncertainty due to the temperature
u(lin)	uncertainty due to the linearity of the KC transfer detectors
u(α)	uncertainty due to the angular dependence of the KC transfer detectors

Table 9: Uncertainty budget REF011

Wavelength / nm	u(trans) / %	u(drift) / %	Relative Std Dev. / %	$u(\lambda)$ / %	$u(\Delta\lambda)$ / %	u(i) / %	u(uni) / %	u(stray) / %	u(T) / %	u(lin) / %	u(total) *k=1* / %
300	0.086	0.04	0.080	0.010	-0.019	0.005	0.025	0.003	0.010	0.005	0.129
320	0.100	0.07	0.065	0.010	0.019	0.005	0.025	0.003	0.000	0.005	0.142
340	0.083	0.05	0.041	0.013	-0.008	0.005	0.025	0.003	0.000	0.005	0.112
360	0.109	0.05	0.025	0.014	0.009	0.005	0.025	0.003	0.000	0.005	0.125
380	0.094	0.08	0.055	0.018	0.008	0.005	0.025	0.003	0.000	0.005	0.137
400	0.027	0.03	0.046	0.004	-0.004	0.005	0.010	0.004	-0.002	0.005	0.065
450	0.021	0.01	0.007	0.004	0.000	0.005	0.010	0.004	-0.001	0.005	0.029
500	0.020	0.00	0.008	0.004	0.000	0.005	0.010	0.004	0.000	0.005	0.026
550	0.020	0.00	0.003	0.004	0.000	0.005	0.010	0.004	0.000	0.005	0.025
600	0.020	0.00	0.005	0.005	0.000	0.005	0.010	0.004	0.000	0.005	0.025
650	0.019	0.00	0.007	0.005	0.000	0.005	0.010	0.004	0.000	0.005	0.026
700	0.019	0.00	0.005	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.025
750	0.020	0.00	0.003	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.025
800	0.020	0.00	0.006	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.026
850	0.020	0.00	0.004	0.007	0.000	0.005	0.010	0.004	0.000	0.005	0.026
900	0.020	0.00	0.006	0.008	0.002	0.005	0.010	0.004	0.001	0.005	0.026
950	0.028	0.00	0.004	0.004	-0.007	0.005	0.010	0.004	0.011	0.005	0.034
1000	0.179	0.02	0.006	-0.003	0.000	0.005	0.010	0.004	0.084	0.005	0.200

Table 10: Uncertainty budget REF14

Wavelength / nm	u(trans) / %	u(drift) / %	Relative Std Dev. / %	u(λ) / %	u($\Delta\lambda$) / %	u(i) / %	u(uni) / %	u(stray) / %	u(T) / %	u(lin) / %	u(total) *k=1* / %
300	0.086	0.04	0.065	0.010	-0.021	0.005	0.025	0.003	0.010	0.005	0.121
320	0.100	0.07	0.060	0.010	0.020	0.005	0.025	0.003	0.000	0.005	0.140
340	0.083	0.05	0.044	0.013	-0.009	0.005	0.025	0.003	0.000	0.005	0.113
360	0.109	0.05	0.043	0.014	0.010	0.005	0.025	0.003	0.000	0.005	0.130
380	0.094	0.08	0.051	0.018	0.007	0.005	0.025	0.003	0.000	0.005	0.135
400	0.027	0.03	0.041	0.004	-0.004	0.005	0.010	0.004	-0.002	0.005	0.061
450	0.021	0.01	0.006	0.004	0.000	0.005	0.010	0.004	-0.001	0.005	0.028
500	0.020	0.00	0.003	0.004	0.000	0.005	0.010	0.004	0.000	0.005	0.025
550	0.020	0.00	0.005	0.004	0.000	0.005	0.010	0.004	0.000	0.005	0.025
600	0.020	0.00	0.008	0.005	0.000	0.005	0.010	0.004	0.000	0.005	0.026
650	0.019	0.00	0.004	0.005	0.000	0.005	0.010	0.004	0.000	0.005	0.025
700	0.019	0.00	0.005	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.025
750	0.020	0.00	0.007	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.026
800	0.020	0.00	0.003	0.006	0.000	0.005	0.010	0.004	0.000	0.005	0.026
850	0.020	0.00	0.005	0.007	-0.001	0.005	0.010	0.004	0.000	0.005	0.026
900	0.020	0.00	0.005	0.008	0.002	0.005	0.010	0.004	0.001	0.005	0.026
950	0.028	0.00	0.006	0.004	-0.007	0.005	0.010	0.004	0.011	0.005	0.035
1000	0.179	0.02	0.009	-0.003	0.000	0.005	0.010	0.004	0.084	0.005	0.200

Table 11: Uncertainty budget F21

Wavelength / nm	u(trans) / %	u(drift) / %	Relative Std Dev. / %	u(λ) / %	u($\Delta\lambda$) / %	u(i) / %	u(uni) / %	u(angle) / %	u(stray) / %	u(T) / %	u(lin) / %	u(total) *k=1* / %
300	0.086	0.04	0.051	0.023	-0.125	0.005	0.025	0.014	0.003	0.010	0.005	0.170
320	0.100	0.07	0.063	0.008	0.010	0.005	0.025	0.027	0.003	0.000	0.005	0.143
340	0.083	0.05	0.026	0.000	-0.066	0.005	0.025	0.029	0.003	0.000	0.005	0.128
360	0.109	0.05	0.038	0.001	0.075	0.005	0.025	0.039	0.003	0.000	0.005	0.153
380	0.094	0.08	0.050	0.020	0.055	0.005	0.025	0.021	0.003	0.000	0.005	0.147
400	0.027	0.03	0.049	0.005	-0.026	0.005	0.010	0.009	0.004	-0.002	0.005	0.072
450	0.021	0.01	0.005	0.003	0.001	0.005	0.010	0.020	0.004	-0.001	0.005	0.035
500	0.020	0.00	0.008	0.003	-0.002	0.005	0.010	0.020	0.004	0.000	0.005	0.033
550	0.020	0.00	0.003	0.003	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
600	0.020	0.00	0.007	0.003	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
650	0.019	0.00	0.005	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
700	0.019	0.00	0.006	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
750	0.020	0.00	0.010	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.033
800	0.020	0.00	0.007	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.033
850	0.020	0.00	0.006	0.004	-0.001	0.005	0.010	0.020	0.004	0.000	0.005	0.032
900	0.020	0.00	0.006	0.006	0.003	0.005	0.010	0.024	0.004	0.001	0.005	0.035
950	0.028	0.00	0.008	0.000	-0.012	0.005	0.010	0.039	0.004	0.011	0.005	0.053
1000	0.179	0.02	0.015	-0.007	0.000	0.005	0.010	0.086	0.004	0.084	0.005	0.218

Table 12: Uncertainty budget F34

Wavelength / nm	u(trans) / %	u(drift) / %	Relative Std Dev. / %	u(λ) / %	u($\Delta\lambda$) / %	u(i) / %	u(uni) / %	u(angle) / %	u(stray) / %	u(T) / %	u(lin) / %	u(total) $k=1$ / %
300	0.086	0.04	0.037	0.023	-0.124	0.005	0.025	0.014	0.003	0.010	0.005	0.166
320	0.100	0.07	0.050	0.008	0.009	0.005	0.025	0.027	0.003	0.000	0.005	0.138
340	0.083	0.05	0.048	0.000	-0.065	0.005	0.025	0.029	0.003	0.000	0.005	0.134
360	0.109	0.05	0.039	0.001	0.074	0.005	0.025	0.039	0.003	0.000	0.005	0.153
380	0.094	0.08	0.031	0.020	0.056	0.005	0.025	0.021	0.003	0.000	0.005	0.142
400	0.027	0.03	0.035	0.005	-0.026	0.005	0.010	0.009	0.004	-0.002	0.005	0.063
450	0.021	0.01	0.008	0.003	0.001	0.005	0.010	0.020	0.004	-0.001	0.005	0.035
500	0.020	0.00	0.008	0.003	-0.002	0.005	0.010	0.020	0.004	0.000	0.005	0.033
550	0.020	0.00	0.005	0.003	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
600	0.020	0.00	0.007	0.003	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
650	0.019	0.00	0.007	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
700	0.019	0.00	0.004	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
750	0.020	0.00	0.004	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
800	0.020	0.00	0.004	0.004	0.000	0.005	0.010	0.020	0.004	0.000	0.005	0.032
850	0.020	0.00	0.006	0.004	-0.001	0.005	0.010	0.020	0.004	0.000	0.005	0.032
900	0.020	0.00	0.005	0.006	0.003	0.005	0.010	0.024	0.004	0.001	0.005	0.035
950	0.028	0.00	0.007	0.000	-0.012	0.005	0.010	0.039	0.004	0.011	0.005	0.053
1000	0.179	0.02	0.009	-0.007	0.000	0.005	0.010	0.086	0.004	0.084	0.005	0.218

Optics Laboratory of TUBITAK-UME (UME)

8.1. Measurement results

Type of Standard: Trap Detector **Reference Number:** 07

Wavelength **nm**	**Spectral Responsivity** **A / W**	**Bandwidth** **/ nm**	**Relative Std Dev.**	**Num of measurements**	**Temperature** **/ °C**	**Uncertainty** **/ %**
300	0,2480	8,1	3,8E-04	5	23	0,38
320	0,2577	8,1	4,0E-04	5	23	0,38
340	0,2701	8,1	3,4E-04	5	23	0,33
360	0,2825	8,1	2,7E-04	5	23	0,29
380	0,2983	8,1	3,6E-04	5	23	0,33
400	0,3178	8,1	2,1E-04	5	23	0,17
450	0,3603	8,1	2,8E-04	5	23	0,18
500	0,4012	8,1	2,5E-04	5	23	0,16
550	0,4421	8,1	1,0E-04	5	23	0,11
600	0,4829	8,1	1,8E-04	5	23	0,12
650	0,5229	8,1	3,3E-04	5	23	0,16
700	0,5644	8,1	3,0E-04	5	23	0,15
750	0,6031	8,1	3,0E-04	5	23	0,14
800	0,6433	8,1	4,4E-04	5	23	0,17
850	0,6839	8,1	4,0E-04	5	23	0,15
900	0,7252	8,1	4,5E-04	5	23	0,25
950	0,7549	8,1	5,5E-04	5	23	0,27
1000	0,6786	8,1	7,3E-04	5	23	0,31

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Date: 13.01.2004 Signature: ………………………………..

Type of Standard: Trap Detector **Reference Number:** 16

Wavelength **nm**	**Spectral Responsivity** **A / W**	**Bandwidth** **/ nm**	**Relative Std Dev.**	**Num of measurements**	**Temperature** **/ °C**	**Uncertainty** **/ %**
300	0,2476	8,1	3,5E-04	5	23	0,36
320	0,2567	8,1	3,3E-04	5	23	0,34
340	0,2690	8,1	3,6E-04	5	23	0,35
360	0,2812	8,1	2,5E-04	5	23	0,28
380	0,2969	8,1	3,6E-04	5	23	0,33
400	0,3167	8,1	5,4E-05	5	23	0,22
450	0,3598	8,1	2,8E-04	5	23	0,19
500	0,4009	8,1	1,7E-04	5	23	0,13
550	0,4418	8,1	9,3E-05	5	23	0,11
600	0,4825	8,1	1,7E-04	5	23	0,12
650	0,5228	8,1	3,2E-04	5	23	0,16
700	0,5634	8,1	2,3E-04	5	23	0,13
750	0,6033	8,1	3,9E-04	5	23	0,16
800	0,6437	8,1	4,7E-04	5	23	0,18
850	0,6840	8,1	5,1E-04	5	23	0,18
900	0,7245	8,1	3,8E-04	5	23	0,25
950	0,7545	8,1	4,8E-04	5	23	0,26
1000	0,6751	8,1	6,9E-04	5	23	0,30

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Date: 13.01.2004 Signature: ………………………………..

Type of Standard: Silicon Detector **Reference Number:** F09

Wavelength **nm**	**Spectral Responsivity** **A / W**	**Bandwidth** **/ nm**	**Relative Std Dev.**	**Num of measurements**	**Temperature** **/ °C**	**Uncertainty** **/ %**
300	0,1316	8,1	2,3E-04	5	23	0,41
320	0,1318	8,1	2,1E-04	5	23	0,39
340	0,1289	8,1	1,6E-04	5	23	0,34
360	0,1491	8,1	6,8E-05	5	23	0,24
380	0,1600	8,1	8,3E-05	5	23	0,25
400	0,1840	8,1	1,2E-04	5	23	0,26
450	0,2227	8,1	1,1E-04	5	23	0,14
500	0,2557	8,1	1,0E-04	5	23	0,13
550	0,2857	8,1	1,1E-04	5	23	0,13
600	0,3147	8,1	1,3E-04	5	23	0,13
650	0,3429	8,1	1,5E-04	5	23	0,13
700	0,3713	8,1	1,8E-04	5	23	0,14
750	0,3988	8,1	2,3E-04	5	23	0,15
800	0,4260	8,1	2,7E-04	5	23	0,16
850	0,4535	8,1	3,5E-04	5	23	0,18
900	0,4812	8,1	5,1E-04	5	23	0,31
950	0,5056	8,1	6,9E-04	5	23	0,35
1000	0,4922	8,1	7,8E-04	5	23	0,39

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Date: 13.01.2004 Signature: ………………………………..

Type of Standard: Silicon Detector **Reference Number:** F32

Wavelength **nm**	**Spectral Responsivity** **A / W**	**Bandwidth** **/ nm**	**Relative Std Dev.**	**Num of measurements**	**Temperature** **/ °C**	**Uncertainty** **/ %**
300	0,1314	8,1	2,2E-04	5	23	0,33
320	0,1315	8,1	1,6E-04	5	23	0,25
340	0,1284	8,1	2,4E-04	5	23	0,37
360	0,1486	8,1	2,1E-04	5	23	0,28
380	0,1595	8,1	2,6E-04	5	23	0,32
400	0,1835	8,1	9,4E-05	5	23	0,10
450	0,2222	8,1	1,6E-04	5	23	0,17
500	0,2552	8,1	1,1E-04	5	23	0,13
550	0,2852	8,1	1,4E-04	5	23	0,14
600	0,3143	8,1	1,5E-04	5	23	0,14
650	0,3424	8,1	1,3E-04	5	23	0,13
700	0,3708	8,1	1,3E-04	5	23	0,12
750	0,3985	8,1	3,1E-04	5	23	0,18
800	0,4258	8,1	4,1E-04	5	23	0,22
850	0,4534	8,1	3,8E-04	5	23	0,19
900	0,4809	8,1	3,2E-04	5	23	0,13
950	0,5052	8,1	8,2E-04	5	23	0,32
1000	0,4919	8,1	8,1E-04	5	23	0,33

Laboratory: Ulusal Metroloji Enstitüsü (UME)…………………………………………………

Date: 13.01.2004 Signature: ………………………………..

8.2. Inspection of the transfer standards

Has the detector transportation package been opened during transit ? e.g. Customs… N.

If Yes please give details……………………………………………………………………..…….

Is there any damage to the transportation package?……N.

If Yes please give details……………………………………………………………………………….

Are there any visible signs of damage to the detector or housing?…..N.

If Yes please give details (e.g. scratches, dust, etc)……………………………………….

Do you believe the transfer standard is functioning correctly ?…N.

If not please indicate your concerns…………………………………………………………..…….
………
………

Laboratory: Ulusal Metroloji Enstitüsü (UME)

Date: 13.01.2004 Signature: ………………………………..

8.3. Description of the measurement facility and primary reference

Type of primary standard:

Traceability chain is based on absolute measurement of optical power using Oxford Instruments/RADIOX electrical-substitution cryogenic radiometer system (ESCR) working at liquid helium temperature (4.2 K). UME made transfer detectors are calibrated once a year and the last calibration was done in March 2003.

Laboratory transfer standards used if any:

- UME made reflection type four trap detectors each consists of three single element Hamamatsu S1337-11 photodiodes.
- RS-5900 model Electrically Calibrated Pyroelectric Radiometer (ECPR)

Monochromator used:

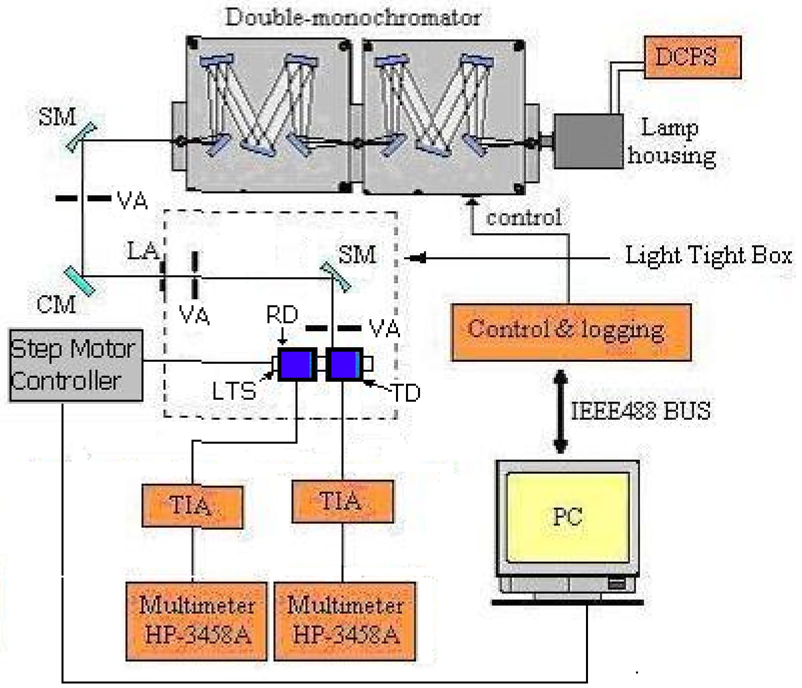
Bentham/DTM 300V model Double-monochromator is used. The monochromator has sorting order filters at 400 nm, 700 nm, 1250 nm, 2000 nm, 3800 nm, 7000 nm and 1200 nm. The diffraction gratings used in this system have 1800 lines/mm@900 nm and 600 lines/mm@2500 nm.

Primary reference or traceability route of primary reference and breakdown of uncertainty:

The absolute responsivities of transfer standards are traceable to optical power measurements performed using improved laser stabilization optics and electrical substitution cryogenic radiometer system at Ar+, He-Ne and Nd:YAG laser wavelengths. The scale was established in two steps. In the first step, UME made reflection type trap detectors was used to measure the absolute responsivity at laser wavelengths. Then using physical models for the trap detector reflectance and internal quantum efficiency the scale was established between 400 nm and 850 nm wavelengths. In the second step, scale, between 250 nm - 400 nm and 800 nm - 1100 nm wavelengths was obtained using spectrally flat ECPR. The wavelength dependence of ECPR was defined by measuring the spectral reflectance of pyroelectric detector.

Measurement procedure

The set up was used for the calibration of detectors is shown in the following figure. The test (TD) and the reference detectors (RD) are placed on the computer controlled linear translation stage. The dimension of the monochromatic light beam incident on the third photodiodes of detectors is 3 mm x 3 mm. Light and dark currents from test and reference detectors were measured 30 times at each wavelengths. The measurements for each TD were repeated five times.



DCPS : Direct Current Power Supply
SM : Spherical Mirror
CM : Cylindrical Mirror
LA : Limiting Aperture
VA : Variable Aperture
RD : Reference Detector
TD : Test Detector
LTS : Linear Translation Stage
TIA : Trans Impedance Amplifier

Evaluation of Uncertainty

Responsivity of test detector is function of various parameters

$$R_{TD} = R_{TD}(V, R_{RD}, NL, H, PS, LS, MM, TI, r, T, WC, Int, r_{rep}, BW, SL) \tag{1}$$

where

V : Measured voltage
R_{RD} : Reference detector
NL : Nonlinearity
H :Homogeneity
PS : Polarization sensivity
LS : Ligth stability
MM : Multimeter
TIA : Transimpedance amplifier
R : Reflectance
PS : Polarization sensivity
WC : Wavelength calibration
Int- : Interpolation
r_{rep} : Repeatability
BW : Bandwidth
SL : Stray Ligth

The combined standard uncertainty U$_c$(R$_{TD}$) is given by the law of propagation of uncertainty as following sum

$$U_c(R_{TD}) == \sqrt{\begin{array}{l} \left(\frac{\partial R_{TD}}{\partial V}u(V)\right)^2 + \left(\frac{\partial R_{TD}}{\partial R_{RD}}u(R_{RD})\right)^2 + \left(\frac{\partial R_{TD}}{\partial NL}u(NL)\right)^2 + \left(\frac{\partial R_{TD}}{\partial H}u(H)\right)^2 \\ + \left(\frac{\partial R_{TD}}{\partial PS}u(PS)\right)^2 + \left(\frac{\partial R_{TD}}{\partial LS}u(LS)\right)^2 + \left(\frac{\partial R_{TD}}{\partial MM}u(MM)\right)^2 + \left(\frac{\partial R_{TD}}{\partial TIA}u(TIA)\right)^2 \\ + \left(\frac{\partial R_{TD}}{\partial r}u(r)\right)^2 + \left(\frac{\partial R_{TD}}{\partial T}u(T)\right)^2 + \left(\frac{\partial R_{TD}}{\partial WC}u(WC)\right)^2 + \left(\frac{\partial R_{TD}}{\partial Int}u(Int)\right)^2 + \\ \left(\frac{\partial R_{TD}}{\partial r_{rep}}u(r_{rep})\right)^2 + \left(\frac{\partial R_{TD}}{\partial BW}u(BW)\right)^2 + \left(\frac{\partial R_{TD}}{\partial SL}u(SL)\right)^2 \end{array}} \qquad (2)$$

where the partial derivatives are the sensitivity coefficients and *u* are the standard uncertainty for each parameters.

The relative combined uncertainty $U_c(R_{TD})/R_{TD}$ is given by

$$U_{c,r}(R_{TD}) = \frac{U_c(R_{TD})}{R_{TD}} = \sqrt{\begin{array}{l} \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial V}u(V)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial R_{RD}}u(R_{RD})\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial NL}u(NL)\right)^2 \\ + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial H}u(H)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial PS}u(PS)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial LS}u(LS)\right)^2 \\ + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial MM}u(MM)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial TIA}u(TIA)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial r}u(r)\right)^2 \\ + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial T}u(T)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial WC}u(WC)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial Int}u(Int)\right)^2 + \\ \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial r_{rep}}u(r_{rep})\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial BW}u(BW)\right)^2 + \left(\frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial SL}u(SL)\right)^2 \end{array}} \qquad (3)$$

Each expression in the square root can be simplified using the following relation

$$\frac{1}{X_i} = \frac{1}{R_{TD}}\frac{\partial R_{TD}}{\partial X_i} \qquad (4)$$

$$U_{c,r} = \frac{U_c(R_{TD})}{R_{TD}} = \sqrt{\begin{array}{l} \left(\frac{u(V)}{V}\right)^2 + \left(\frac{u(R_{RD})}{R_{RD}}\right)^2 + \left(\frac{u(NL)}{NL}\right)^2 + \left(\frac{u(H)}{H}\right)^2 + \left(\frac{u(PS)}{PS}\right)^2 + \left(\frac{u(LS)}{LS}\right)^2 \\ + \left(\frac{u(MM)}{MM}\right)^2 + \left(\frac{u(TIA)}{TIA}\right)^2 + \left(\frac{u(r)}{r}\right)^2 + \left(\frac{u(T)}{T}\right)^2 + \left(\frac{u(WC)}{WC}\right)^2 + \left(\frac{u(Int)}{Int}\right)^2 \\ + \left(\frac{u(r_{ref})}{r_{ref}}\right)^2 + \left(\frac{u(BW)}{BW}\right)^2 + \left(\frac{u(SL)}{SL}\right)^2 \end{array}} \qquad (5)$$

The expanded uncertainty *U* is obtained by multiplying relative combined uncertainty by a coverage factor k.

$$U(R_{TD}) = k.U_{c,r}(R_{TD}) \qquad (6)$$

The relative combined uncertainty and expanded uncertainty corresponding to each parameter was calculated according to equations 5 and 6 and the results were tabulated in Table I

Description of calibration laboratory conditions: e.g. temperature, humidity etc

Temperature : 23.0 ± 0.5 °C

Relative Humidity : % (45.0 ± 5.0)

Laboratory: Ulusal Metroloji Enstitüsü (UME)

Date: 13.01.2004 Signature: ………………………………

Table I. Uncertainty budget.

Source of uncertainty	10^{-4} x standard uncertainty
Primary reference (Laser based CR)	
Window transmittance	0,32
Scattered and diffracted light	0,23
Cavity absorptance	0,05
Non-equivalence electrical / optical power	0,10
Optical Temperature	0,02
Electrical Temperature	0,01
Interpolation and extrapolation	0,10
Spectrally flat detector (ECPR)	
Uniformity	8,50
Laser stability	0,90
Nonlinearity	0,11
Reflectance	5,10
Calibration of reference trap detectors	
Uniformity	0,30
Linearity	0,15
Polarization dependence	1,00
Repeatability	0,10
Electrical calibrations	
Multimeter	0,10
Transimpedance amplifier	0,20
Temperature	2,00
Wavelength calibration	2,00
Bandwidth effects	2,00
Stray light	1,00
Interpolation	1,00
Calibration of KC transfer detectors	
Repeatability	0,10
Wavelength calibration	2,00
Bandwidth effects	2,00
Stray light	1,00
Electrical calibrations	
Multimeter	0,10
Transimpedance amplifier	0,20
Translation stage repeatability	0,02
Combined standard uncertainty (k=2)	**22.2**

Czech Metrology Institute (CMI)

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Description of the measurement facility and primary reference

Type of primary standard:

CMI primary standard absolute cryogenic laser based radiometer.
Laser based facility, for illumination uses Kr-Ion laser, set of four visible lines. For additional radiant power stabilization utilizes the system of external stabilization of laser beam power (parameters see uncertainty budget attached).

For spectral interpolation across the UV, VIS and NIR spectral regions the hemispherical pyroelectric detector is used as a reference standard of relative spectral responsivity.

Laboratory transfer standards used:

Silicon trap detector CMI1337BR1 manufactured at the CMI Radiometry and Photometry laboratory, consisted of three 10 mm x 10 mm Hamamatsu S1337 photodiodes arranged in a light trapping configuration, electrically connected in parallel, and terminated by a three pin socket. The entrance aperture to the detector is a circular hole of diameter 10 mm.

Monochromator used:

McPHERSON 2035D double grating monochromator, subtractive setup.
Detailed description and schematic diagram of the measuring facility see next pages.

Primary reference detector CMI

Set of three single-element silicon detectors CMI-SI-05, 08, 02 consisted of Hamamatsu S1337 1010BQ photodiode with an active area 10 mm x 10 mm mounted in the front of a black cylindrical housing.

Description of calibration laboratory conditions: e.g. temperature, humidity etc

All measurements were made in air conditioned laboratory. The room temperature was maintained at (22,9 ± 0,5) °C during the calibration, air humidity (40 ± 10)%.

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Detailed description and schematic diagram of the measuring facility

At the CMI laboratory the measurements were performed on the CMI reference monochromator based facility developed in CMI optical radiometry laboratory (see fig.1)

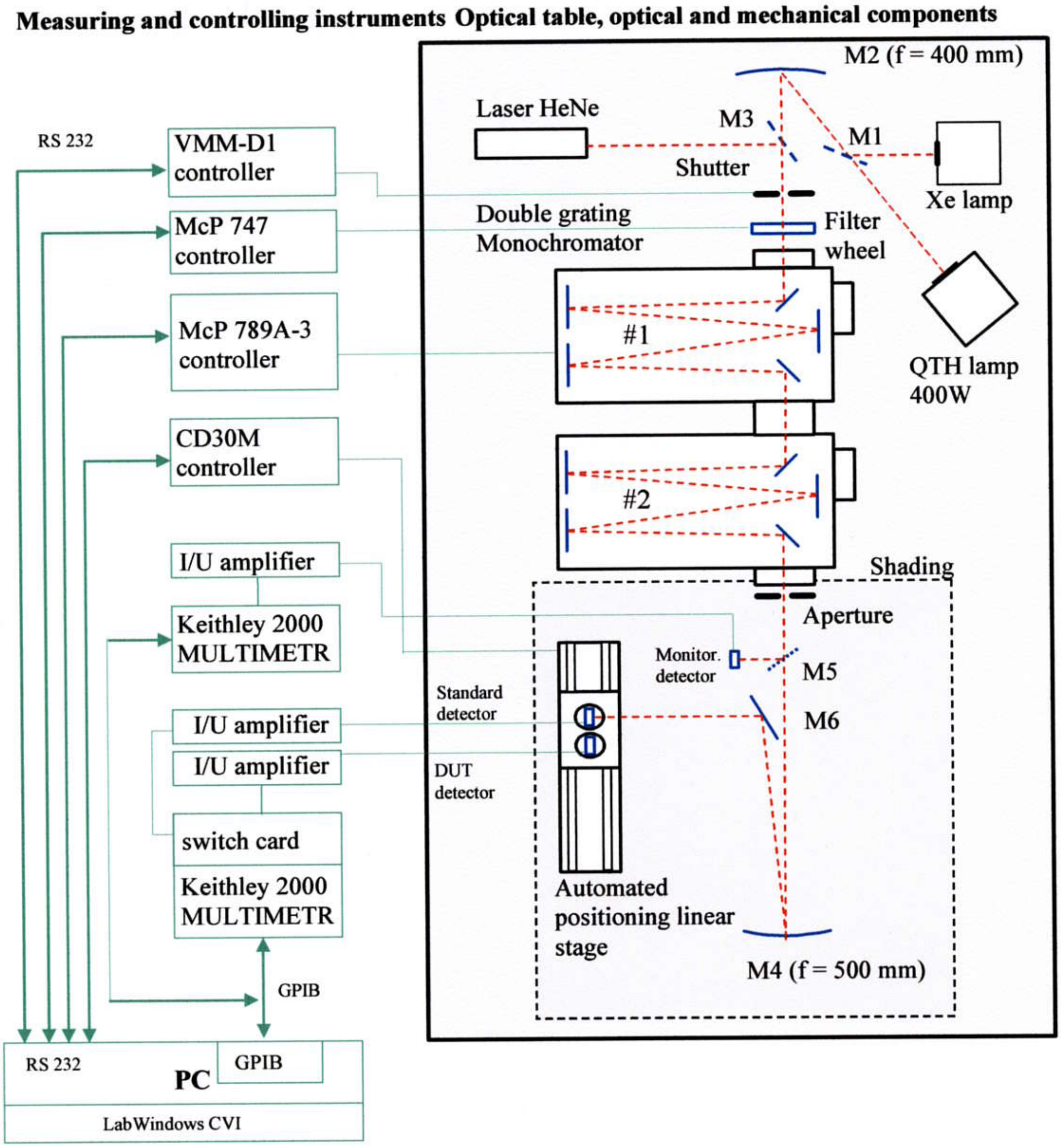


fig.1: Schematic drawing of the CMI reference monochromator based facility. M2, M4 – concave spherical mirrors; M1, M3, M5, M6 – moveable plane mirrors; Filterwheel – filter for stray light suppression and order sorting; HeNe laser used for optical system and measured filter alignment.

CMI monochromator based reference facility for spectral responsivity measurement uses double grating monochromator McPHERSON 2035D with subtractive dispersion, focal length 350 mm.

For alighting of the entrance slit the Xenon lamp 250 W was used for spectral range from 300 nm to 450 nm whilst the Quartz Tungsten Halogen lamp 400 W was used for spectral range from 380 nm to 1000 nm.

For dispersing the beam two couples of ruled gratings 1200 G/mm blazed at 250 nm for the spectral range 300 nm to 380 nm and 600 G/mm blazed at 550 nm for the spectral range 400 nm to 1000 nm were used.

For measurement the spectral bandwidth of 6 nm FWHM was used.

For suppressing of higher orders filter-wheel with set of order sorting filters were utilized at the entrance slit of the monochromator. The optical Shutter is applied at the entrance slit side of the monochromator facility.

At the exit slit side of the facility the reflective optic of f/#: about f/8 for calibrating a single-element detector and f/#: about f/10 for calibrating trap detectors was used for imaging the exit slit, the 4 mm diameter circular spot was imaged on measured detector (single element detectors) or on the third inner photodiode for trap detectors.

The Monitor detector was used to eliminate time fluctuations of radiant flux of measuring beam.

For position exchanging of master and DUT detector was applied motorized linear stage. All measuring procedure was fully automated.

Laboratory: CMI Prague, CZE

Date: 2.12.2004 Signature:

Marek Smid
Head of Radiometry and Photometry department

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Final results

Type of standard: trap **Reference Number: 04**

Wavelength [nm]	Spectral Responsivity [A/W]	Bandwidth [nm]	Relative Std Dev. [%]	Num of measurements	Temperature [°C]	Uncertainty (k=1) [%]
300	0,24617	6	0,105	6	22,9 ± 0,5	0,46
320	0,25626	6	0,029	6	22,9 ± 0,5	0,45
340	0,26937	6	0,027	6	22,9 ± 0,5	0,45
360	0,28261	6	0,040	6	22,9 ± 0,5	0,45
380	0,29696	6	0,008	6	22,9 ± 0,5	0,375
400	0,31657	6	0,012	6	22,9 ± 0,5	0,375
450	0,35972	6	0,013	6	22,9 ± 0,5	0,20
500	0,40111	6	0,012	6	22,9 ± 0,5	0,15
550	0,44177	6	0,019	6	22,9 ± 0,5	0,15
600	0,48227	6	0,019	6	22,9 ± 0,5	0,15
650	0,52242	6	0,021	6	22,9 ± 0,5	0,15
700	0,56287	6	0,023	6	22,9 ± 0,5	0,15
750	0,60332	6	0,020	6	22,9 ± 0,5	0,15
800	0,64360	6	0,018	6	22,9 ± 0,5	0,15
850	0,68403	6	0,016	6	22,9 ± 0,5	0,15
900	0,72426	6	0,018	6	22,9 ± 0,5	0,15
950	0,76334	6	0,018	6	22,9 ± 0,5	0,25
1000	0,76167	6	0,017	6	22,9 ± 0,5	0,50

Laboratory: CMI Prague, CZE

Date: 2.12.2004 Signature

Marek Smid
Head of Radiometry and Photometry department

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Final results

Type of standard: trap **Reference Number: 17**

Wavelength [nm]	Spectral Responsivity [A/W]	Bandwidth [nm]	Relative Std Dev. [%]	Num of measurements	Temperature [°C]	Uncertainty (k=1) [%]
300	0,24629	6	0,038	6	22,9 ± 0,5	0,45
320	0,25633	6	0,031	6	22,9 ± 0,5	0,45
340	0,26948	6	0,015	6	22,9 ± 0,5	0,45
360	0,28273	6	0,005	6	22,9 ± 0,5	0,45
380	0,29714	6	0,017	6	22,9 ± 0,5	0,375
400	0,31670	6	0,008	6	22,9 ± 0,5	0,375
450	0,35995	6	0,006	6	22,9 ± 0,5	0,20
500	0,40138	6	0,005	6	22,9 ± 0,5	0,15
550	0,44221	6	0,003	6	22,9 ± 0,5	0,15
600	0,48271	6	0,002	6	22,9 ± 0,5	0,15
650	0,52294	6	0,002	6	22,9 ± 0,5	0,15
700	0,56342	6	0,002	6	22,9 ± 0,5	0,15
750	0,60393	6	0,002	6	22,9 ± 0,5	0,15
800	0,64423	6	0,003	6	22,9 ± 0,5	0,15
850	0,68465	6	0,002	6	22,9 ± 0,5	0,15
900	0,72490	6	0,006	6	22,9 ± 0,5	0,15
950	0,76400	6	0,003	6	22,9 ± 0,5	0,25
1000	0,76272	6	0,006	6	22,9 ± 0,5	0,50

Laboratory: CMI Prague, CZE

Date: 2.12.2004 Signature:

Marek Smid
Head of Radiometry and Photometry department

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Final results

Type of standard: single **Reference Number: F43**

Wavelength [nm]	Spectral Responsivity [A/W]	Bandwidth [nm]	Relative Std Dev. [%]	Num of measurements	Temperature [°C]	Uncertainty (k=1) [%]
300	0,13068	6	0,060	6	22,9 ± 0,5	0,45
320	0,14357	6	0,028	6	22,9 ± 0,5	0,45
340	0,14940	6	0,036	6	22,9 ± 0,5	0,45
360	0,14647	6	0,029	6	22,9 ± 0,5	0,45
380	0,15764	6	0,017	6	22,9 ± 0,5	0,375
400	0,18186	6	0,012	6	22,9 ± 0,5	0,375
450	0,22316	6	0,010	6	22,9 ± 0,5	0,20
500	0,25608	6	0,006	6	22,9 ± 0,5	0,15
550	0,28631	6	0,006	6	22,9 ± 0,5	0,15
600	0,31525	6	0,004	6	22,9 ± 0,5	0,15
650	0,34333	6	0,002	6	22,9 ± 0,5	0,15
700	0,37131	6	0,005	6	22,9 ± 0,5	0,15
750	0,39906	6	0,002	6	22,9 ± 0,5	0,15
800	0,42655	6	0,001	6	22,9 ± 0,5	0,15
850	0,45405	6	0,008	6	22,9 ± 0,5	0,15
900	0,48141	6	0,003	6	22,9 ± 0,5	0,15
950	0,50563	6	0,003	6	22,9 ± 0,5	0,25
1000	0,48178	6	0,072	6	22,9 ± 0,5	0,51

Laboratory: CMI Prague, CZE

Date: 2.12.2004

Signature:

Marek Smid
Head of Radiometry and Photometry department

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Final results

Type of standard: single **Reference Number: F48**

Wavelength [nm]	Spectral Responsivity [A/W]	Bandwidth [nm]	Relative Std Dev. [%]	Num of measurements	Temperature [°C]	Uncertainty (k=1) [%]
300	0,13245	6	0,070	6	22,9 ± 0,5	0,46
320	0,14538	6	0,036	6	22,9 ± 0,5	0,45
340	0,15111	6	0,030	6	22,9 ± 0,5	0,45
360	0,14804	6	0,028	6	22,9 ± 0,5	0,45
380	0,15902	6	0,021	6	22,9 ± 0,5	0,376
400	0,18319	6	0,015	6	22,9 ± 0,5	0,375
450	0,22435	6	0,011	6	22,9 ± 0,5	0,20
500	0,25715	6	0,008	6	22,9 ± 0,5	0,15
550	0,28726	6	0,007	6	22,9 ± 0,5	0,15
600	0,31612	6	0,005	6	22,9 ± 0,5	0,15
650	0,34411	6	0,003	6	22,9 ± 0,5	0,15
700	0,37202	6	0,005	6	22,9 ± 0,5	0,15
750	0,39970	6	0,004	6	22,9 ± 0,5	0,15
800	0,42713	6	0,002	6	22,9 ± 0,5	0,15
850	0,45456	6	0,009	6	22,9 ± 0,5	0,15
900	0,48184	6	0,002	6	22,9 ± 0,5	0,15
950	0,50627	6	0,003	6	22,9 ± 0,5	0,25
1000	0,48365	6	0,069	6	22,9 ± 0,5	0,50

Laboratory: CMI Prague, CZE

Date: 30.11.2004 Signature:

Marek Smid
Head of Radiometry and Photometry department

EUROMET Key comparison: PR-K2.b

Spectral Responsivity part 2 (300 nm to 1000 nm)

Comprehensive uncertainty budget

Example

Source of uncertainty	Spectral range [nm]	Type	Value	Distribution	Divider (coefficient)	Ci	Ui [%]
Primary reference Laser based CR							
Window transmittance	$\lambda = 476.2$ $\lambda = 530.9$ $\lambda = 568.2$ $\lambda = 647.1$	A	0.005	standard	1	1	0.005
Scattered and diffracted light		B	10	standard	2	0.0001	0.0005
Cavity absorptance		B	0.001	rectangular	1.732	1	0.000577
Electrical power measurements		B	0.002001	standard	2	1	0.001001
Radiometer sensitivity		B	0.001	rectangular	1.732	1	0.000577
Changes in scatter and thermal radiation		B	0.001	rectangular	1.732	1	0.000577
Repeatability of measurement		A	0.001509	standard	1	1	0.001509
Optical power measurement		B	0.010868	standard	2	1	0.005434
calibration of DVM for detectors		B	0.0005	rectangular	1.732	1	0.000289
drift DVM for detectors		B	0.0005	rectangular	1.732	1	0.000289
I/U transducer calibration		B	0.01	rectangular	1.732	1	0.005774
drift of I/U transducer		B	0.001	rectangular	1.732	1	0.000577
Spot diameter influence		B	0.005	rectangular	1.732	1	0.002887
laser stability		B	0.005	rectangular	1.732	1	0.002887
Alignment repeatability		B	0.005	standard	2	1	0.002500
measurement repeatability		A	0.000566	standard	1	1	0.000566
Spectrally flat detector							
residual wavelength dependence	$300 < \lambda < 1000$	B	0.1	rectangular	1.732	1	0.058
uniformity	$300 < \lambda < 1000$	B	0.02	rectangular	1.732	1	0.012
stability	$300 < \lambda < 1000$	B	0.02	rectangular	1.732	1	0.012
repeatibility	$300 < \lambda < 375$	A	0.58	standard	2	1	0.29
	$375 < \lambda < 405$		0.6				0.30
	$405 < \lambda < 450$		0.26				0.13
	$450 < \lambda < 920$		0.18				0.09
	$920 < \lambda < 960$		0.25				0.13
	$960 < \lambda < 1000$		0.5				0.25

EUROMET Key comparison: PR-K2.b Spectral Responsivity part 2 (300 nm to 1000 nm)

Comprehensive uncertainty budget

Example

Source of uncertainty	**Spectral range [nm]**	**Type**	**Value**	**Distribution**	**Divider (coefficient)**	**Ci**	**Ui [%]**
Calibration of NMI reference detectors at monochromator based facility (internal transfer)							
Primary standards Drift	$300 < \lambda < 375$	B	0.02	rectangular	1.732	1	0.01
	$375 < \lambda < 405$		0.02				0.01
	$405 < \lambda < 450$		0.02				0.01
	$450 < \lambda < 920$		0.02				0.01
	$920 < \lambda < 960$		0.02				0.01
	$960 < \lambda < 1000$		0.02				0.01
Uniformity	$300 < \lambda < 375$	B	0.1	rectangular	1.732	1	0.058
	$375 < \lambda < 405$		0.1				0.058
	$405 < \lambda < 450$		0.1				0.058
	$450 < \lambda < 920$		0.1				0.058
	$920 < \lambda < 960$		0.1				0.058
	$960 < \lambda < 1000$		0.1				0.058
Linearity	$300 < \lambda < 1000$	B	0.01	rectangular	1.732	1	0.0058
Polarization dependence	$300 < \lambda < 1000$	B	0.0001	rectangular	1.732	1	0.0001
Vignetting effects	$300 < \lambda < 1000$	B	0.0001	rectangular	1.732	1	0.0001
Temperature	$300 < \lambda < 375$	B	0.0005	rectangular	1.732	1	0.000
	$375 < \lambda < 405$		0.0005				0.000
	$405 < \lambda < 450$		0.0005				0.000
	$450 < \lambda < 920$		0.0005				0.000
	$920 < \lambda < 960$		0.0005				0.000
	$960 < \lambda < 1000$		0.05				0.029
Bandwidth effects	$300 < \lambda < 1000$	B	0.001	rectangular	1.732	1	0.001
Voltmeter linearity	$300 < \lambda < 375$	B	0.005	rectangular	1.732	1	0.003
	$375 < \lambda < 405$		0.005				0.003
	$405 < \lambda < 450$		0.005				0.003
	$450 < \lambda < 920$		0.005				0.003
	$920 < \lambda < 960$		0.005				0.003
	$960 < \lambda < 1000$		0.005				0.003
I/U transducer dut detector	$300 < \lambda < 375$	B	0.01	standard	2	1	0.005
	$375 < \lambda < 405$		0.01				0.005
	$405 < \lambda < 450$		0.01				0.005
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
I/U transducer standard detector	$300 < \lambda < 375$	B	0.01	standard	2	1	0.005
	$375 < \lambda < 405$		0.01				0.005
	$405 < \lambda < 450$		0.01				0.005
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
Stray light	$300 < \lambda < 375$	B	0.02	rectangular	1.732	1	0.012
	$375 < \lambda < 405$		0.01				0.006
	$405 < \lambda < 450$		0.00				0.000
	$450 < \lambda < 920$		0.00				0.000
	$920 < \lambda < 960$		0.00				0.000
	$960 < \lambda < 1000$		0.00				0.000
Wavelength calibration	$300 < \lambda < 375$	B	0.19	standard	2	1	0.095
	$375 < \lambda < 405$		0.03				0.015
	$405 < \lambda < 450$		0.02				0.010
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
Measurement repeatability	$300 < \lambda < 375$	A	0.11	standard	2	1	0.055
	$375 < \lambda < 405$		0.02				0.010
	$405 < \lambda < 450$		0.02				0.010
	$450 < \lambda < 920$		0.02				0.010
	$920 < \lambda < 960$		0.02				0.010
	$960 < \lambda < 1000$		0.02				0.010

EUROMET Key comparison: PR-K2.b

Spectral Responsivity part 2 (300 nm to 1000 nm)

Comprehensive uncertainty budget

Example

Source of uncertainty	Spectral range [nm]	Type	Value	Distribution	Divider (coefficient)	Ci	Ui [%]
Calibration of KC transfer detectors or calibration fo custometr detectors							
Working standards drift	$300 < \lambda < 375$	B	0.5	rectangular	1.732	1	0.289
	$375 < \lambda < 405$		0.34				0.196
	$405 < \lambda < 450$		0.21				0.121
	$450 < \lambda < 920$		0.14				0.081
	$920 < \lambda < 960$		0.35				0.202
	$960 < \lambda < 1000$		0.75				0.433
Temperature	$300 < \lambda < 375$	B	0.0005	rectangular	1.732	1	0.000
	$375 < \lambda < 405$		0.0005				0.000
	$405 < \lambda < 450$		0.0005				0.000
	$450 < \lambda < 920$		0.0005				0.000
	$920 < \lambda < 960$		0.0005				0.000
	$960 < \lambda < 1000$		0.05				0.029
Bandwidth effects	$300 < \lambda < 1000$	B	0.001	rectangular	1.732	1	0.001
Voltemter linearity	$300 < \lambda < 375$	B	0.005	rectangular	1.732	1	0.003
	$375 < \lambda < 405$		0.005				0.003
	$405 < \lambda < 450$		0.005				0.003
	$450 < \lambda < 920$		0.005				0.003
	$920 < \lambda < 960$		0.005				0.003
	$960 < \lambda < 1000$		0.005				0.003
I/U transducer dut detector	$300 < \lambda < 375$	B	0.01	standard	2	1	0.005
	$375 < \lambda < 405$		0.01				0.005
	$405 < \lambda < 450$		0.01				0.005
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
I/U transducer satndard detector	$300 < \lambda < 375$	B	0.01	standard	2	1	0.005
	$375 < \lambda < 405$		0.01				0.005
	$405 < \lambda < 450$		0.01				0.005
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
Stray light	$300 < \lambda < 375$	B	0.02	rectangular	1.732	1	0.012
	$375 < \lambda < 405$		0.01				0.006
	$405 < \lambda < 450$		0				0.000
	$450 < \lambda < 920$		0				0.000
	$920 < \lambda < 960$		0				0.000
	$960 < \lambda < 1000$		0				0.000
Wavelength calibration	$300 < \lambda < 375$	B	0.19	standard	2	1	0.095
	$375 < \lambda < 405$		0.03				0.015
	$405 < \lambda < 450$		0.02				0.010
	$450 < \lambda < 920$		0.01				0.005
	$920 < \lambda < 960$		0.01				0.005
	$960 < \lambda < 1000$		0.01				0.005
Measurement repeatibility	$300 < \lambda < 375$	A	0.21	standard	2	1	0.105
	$375 < \lambda < 405$		0.042				0.021
	$405 < \lambda < 450$		0.026				0.013
	$450 < \lambda < 920$		0.046				0.023
	$920 < \lambda < 960$		0.036				0.018
	$960 < \lambda < 1000$		0.144				0.072
Combined standard uncertainty	**$300 < \lambda < 375$**			**standard**			**0.46**
	$375 < \lambda < 405$						**0.37**
	$405 < \lambda < 450$						**0.20**
	$450 < \lambda < 920$						**0.15**
	$920 < \lambda < 960$						**0.25**
	$960 < \lambda < 1000$						**0.51**

Laboratory: CMI Prague, CZE

Date: 2.12.2004

Signature:

Marek Smid
Head of Radiometry and Photometry department

Bureau National de Metrologie (BNM-INM/CNAM)

EUROMET PR-K2.b :
Spectral responsivity of detectors from 300 nm to 1000 nm

BNM-INM/CNAM Report

Introduction

Under the Mutual Recognition Arrangement (MRA) the metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM working closely with the Regional Metrology Organisations (RMOs).
EUROMET has approved the realisation of this comparison on Spectral Responsivity within the 300 nm to 1000 nm range under the title EUROMET PR K2.b, as project # 587. The object of this comparison is to link participants to the reference value of this quantity derived from comparison CCPR-K2.b.

The present report contains the results of the BNM-INM for this comparison, which was conducted by IFA-CSIC as pilot laboratory. The detectors which have been measured at the BNM-INM had the following references :

- Ref10 and Ref12 for the two trap detectors,
- F19 and F45 for the two single element photodiodes.

The measurements at the BNM-INM were carried out in February and March 2004.

Measurement method at the BNM-INM

The primary absolute measurements of spectral responsivity of detectors are carried out at the BNM-INM with a cryogenic radiometer, but only at a restricted number of laser wavelengths in the visible range [1]. The calibration of silicon detectors over all their spectral range is based on an interpolation and extrapolation method using silicon trap detectors, calibrated directly or indirectly against the cryogenic radiometer.

Measurement principle

The detectors of the EUROMET comparison have been calibrated by comparison to a reference detector of our laboratory (P-99-S). This reference detector is a large-area three-element reflection trap detector with Hamamatsu S3204-09 photodiodes. Its relative spectral responsivity has been determined by comparison to a non-selective thermal detector, and its absolute spectral responsivity has been measured at the laser wavelengths of 488, 514, 543, 612 and 633 nm by comparison to the cryogenic radiometer [2].

Experimental set-up

The experimental set-up used in our laboratory to study the spectral responsivity of the detectors over a large spectral range is schematically drawn in figure 1. Its main part is a double prism-grating monochromator capable of working from 200 nm to 2000 nm using several orders of the grating. All spectral responsivity measurements are carried out by comparison of the test detector to a reference detector. For the measurements reported in this document, the reference detector is the large-area trap detector, P-99-S describes above. A computer controlled translation stage puts alternatively the detectors into the monochromatic beam. The optical arrangement at the exit of the monochromator allows to have a radiant beam with a small numerical aperture. It is set in such a way that the aperture D in front of the light source is imaged with the right size on the detector. By this method, it is possible to have on the detector an irradiance with a rather good uniformity, while having a sufficient level of flux.

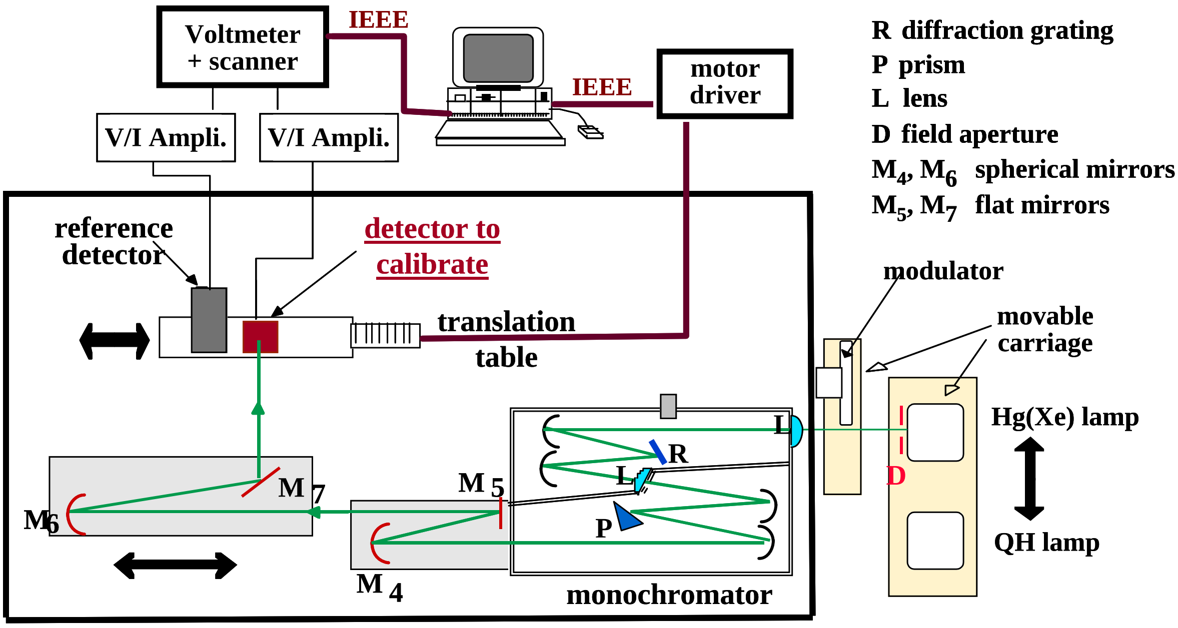


Figure 1 - Experimental set-up for the spectral responsivity measurements at the BNM-INM.

Conditions of measurements for the EUROMET PR-K2b comparison

The light sources used for these measurements were a Xenon arc lamp for the spectral range below 650 nm and a quartz halogen lamp for the spectral range from 650 to 1000 nm. The characteristics of the mirrors M4 to M7 and their position were chosen for having a spot size of the order of 5 mm on the active area of the detectors (the position of the traps detectors has been adjusted in the beam so that the 5 mm spot size was situated on the third photodiode in the traps, for avoiding vignetting effects). Depending on the wavelength, the level of flux was in the range of 2 µW to 15 µW. The temperature in the room was approximately 22,5°C.

The spectral bandwidth of the monochromator, defined as the full width at half the maximum, was set at 3,1 nm.

Measurements of the spectral responsivity of the detectors for the comparison

Comparison of the detectors to the large-area trap detector

The measurements of the spectral responsivity of the detectors are carried out by comparing the detectors to the reference detector, P-99-S, which is constitute by the large-area trap detector.

The photocurrent of each detector was measured using current to voltage converters. In order to avoid the precise calibration of the conversion coefficients of the current to voltage converters the following procedure of measurement was used. In a first step a set of measurement is carried out with the reference detector connected to one of the current to voltage converter and the test detector connected to the second one. After that a second set of measurement is carried out with the reference detector connected to the second current to voltage converter and the test detector connected to the first current to voltage converter. The responsivity of the test detector is given by :

$$s_t = s_r \sqrt{V_t * V_t')/(V_r * V_r')}$$

with :

s_t responsivity of the test detector,

s_r responsivity of the reference detector,

V_t and V_t' voltages measured for the test detector,

V_e and V_e' voltages measured for the reference detector.

For the spectral range from 300 nm to 600 nm three sets of measurements have been used for each detector of the comparison. In each set of measurements the detector was compared four times to the reference detector. Between each set of measurements, the detectors have being put again and realigned in the measurement facility. The final value for the spectral responsivity is calculated by the mean value of these measurements.

For the spectral range from 650 to 1000 nm only two set of measurements identical to the previous one have been carried out for each detector of the comparison because the quartz halogen lamp used for this part of the spectral range is much more stable than the xenon arc.

Uncertainty budget

Due to the method of measurement used, the uncertainty budget has been split in three parts : the first is the realisation of the reference for radiometric measurement with the cryogenic radiometer at a restricted number of wavelengths, the second is the calibration of the transfer detector (large area trap detector P-99-S) used for interpolation and extrapolation of measurements and the third is the calibration of the detectors of the comparison against the large-area trap detector.

Uncertainty on the reference for radiometric measurements

The primary reference for radiometric measurements in the laboratory is a cryogenic radiometer. The correction factors and standard uncertainties of this devices are listed in table 1.

Table 1 – Correction factors and uncertainties of the cryogenic radiometer primary reference of the BNM-INM laboratory.

Quantity	Correction factor	Relative uncertainty (1σ)
Cavity absorptance	0.99988	1.0 10^{-5}
Window transmittance	0.99974	3.0 10^{-5}
Heating non-equivalence	1.00000	1.0 10^{-5}
Scattered light	1.00000	2.0 10^{-5}
Electrical power measurement	1.00000	3.0 10^{-5}
Total	0.99960	5.0 10^{-5}

The correction factors and standard uncertainties listed in table 1 are only for laser wavelengths in the visible range. The wavelengths usually used are : 488, 514, 543, 612 and 633 nm.

For carrying out measurements at other wavelengths the large area trap detector used as reference in this comparison is calibrated in a two step method. First it is calibrated by comparison to the cryogenic radiometer at the laser wavelengths. After its relative spectral responsivity is determined by comparison to a thermal non selective detector using the experimental set-up previously described. In combining the two sets of measurement it is possible to get the absolute calibration of the trap detector. The relative spectral responsivity of the trap detector has been measured at the wavelength used for the EUROMET comparison, also it was not necessary to use an interpolation method for doing these measurements.

Uncertainty on the transfer detector

The uncertainty components related to the calibration of the transfer detector are listed in table 2. The repeatability being wavelength dependant, the limit value given in the table are only for information. For each wavelength the uncertainty has been calculated and is used in the calculation.

Table 2 – Uncertainty budget for the calibration of the reference detector (P-99-S).

Uncertainty component	Relative standard uncertainty (1σ)
Repeatability	1.0 10^{-4} to 3.5 10^{-3} wavelength dependant
Flat detector	2.0 10^{-4}
Uniformity	1.5 10^{-4}
Linearity	1.0 10^{-4}
Polarisation	2.5 10^{-4}
Temperature	0.5 10^{-4}
Wavelength calibration	3.0 10^{-4}
Bandwidth effect	1.0 10^{-4}
Stray light	1.0 10^{-4}
Current to voltage converter calibration	7.0 10^{-4}
Locking amplifier calibration	2.0 10^{-4}
Absolute calibration	2.1 10^{-4}
Internal consistency	2.2 10^{-4}
Total uncertainty (u_{abs})	9.4 10^{-4} to 3.6 10^{-3} wavelength dependant

Uncertainty on the test detectors of the comparison

The uncertainty components taken into account in the case of the calibration of the photodiodes and trap detectors used for the comparison are summarised in the following table 3. The values given in this table are for relative standard uncertainty (k=1).

The values for the components denoted u_A and u_{abs} in table 3 are wavelength dependent : u_A is calculated for each wavelength from all the available series of measurements, and u_{abs} has been calculated at each wavelength of the absolute spectral responsivity measurement for the large-area trap detector (see table 2).

The final standard uncertainty is the combined standard uncertainty u(λ) and is calculated for each wavelength of the comparison.

Table 3 – Uncertainty budget for the calibration of the detectors of the comparison.

Uncertainty component	Relative standard uncertainty
Repeatability	u_A
Temperature	$0.5\ 10^{-4}$
Wavelength calibration (300-900 nm)	$4.8\ 10^{-5}$
Wavelength calibration (950-1000 nm)	$3.8\ 10^{-4}$
Stray light	$1.0\ 10^{-4}$
Bandwidth effect	$1.0\ 10^{-4}$
Reference uncertainty	u_{abs}
Relative combined standard uncertainty	u(λ)

The final standard uncertainty is the combined standard uncertainty u(λ) and is calculated for each wavelength of the comparison.

Results

The results of the comparison are given in the tables 4 and 5 for the two trap detectors, and in tables 6 and 7 for the two photodiodes measured by the BNM-INM for the comparison.

In each table are reported in the first column the assigned central wavelength of the measured spectral responsivity, and in the second column, the value of the absolute spectral responsivity of the detector. The third column indicates the spectral bandwidth of the monochromator used for the comparison at the BNM-INM, it is defined as the full width at half the maximum. In the fourth and fifth columns are reported respectively the standard deviation of measurements made to obtain the assigned spectral responsivity (noticed u_A in tables 3), and the number of independent measurements made to obtain the specified standard deviation. In the sixth column is indicated the temperature in the measurement set-up during calibration of the detectors. Finally, in the last column is reported the total relative uncertainty of the measurement of the spectral responsivity, for a coverage factor of k=1.

Remark

In inspecting the trap detector Ref 10 during the measurement, a small dust on the first photodiode was discovered. It was removed by blowing it away with a soft air flow.

References

[1] Jeanne-Marie COUTIN, Oualid TOUAYAR, Jean BASTIE, The using conditions of the BNM-INM cryogenic radiometer as the basis for the French optical radiation measurement scales, Proceedings of the 24th Session of the CIE, Warsaw, Poland, 24-30 June 1999, Pages 222-224.

[2] Jeanne-Marie COUTIN, Fatima TAYEB, Jean BASTIE, Development of large area trap detectors for improving spectral responsivity measurement of detectors at the BNM-INM, Proceedings of the 25th Session of the CIE, San Diego, California, USA, 23 June – 3 July 2003, Pages D2-50 to D2-53

Table 4 – Results for the trap detector Ref 10

Type of standard : **trap** Reference Number : **ref 10**

Wavelength nm	**Spectral Responsivity A/W**	Bandwidth / nm	Relative Std Dev. %	Number of Measurements	Temperature /°C	**Uncertainty / %**
300	**0.24646**	3.1	0.14%	6	22.7 ± 0.4	**0.37%**
320	**0.25541**	3.1	0.03%	6	22.7 ± 0.4	**0.26%**
340	**0.26919**	3.1	0.07%	6	22.7 ± 0.4	**0.12%**
360	**0.28030**	3.1	0.05%	6	22.7 ± 0.4	**0.13%**
380	**0.29637**	3.1	0.01%	6	22.7 ± 0.4	**0.18%**
400	**0.31613**	3.1	0.10%	6	22.7 ± 0.4	**0.11%**
450	**0.35918**	3.1	0.01%	6	22.7 ± 0.4	**0.11%**
500	**0.40053**	3.1	0.04%	6	22.7 ± 0.4	**0.11%**
550	**0.44135**	3.1	0.07%	6	22.7 ± 0.4	**0.11%**
600	**0.48177**	3.1	0.12%	6	22.7 ± 0.4	**0.13%**
650	**0.52168**	3.1	0.01%	4	22.7 ± 0.4	**0.13%**
700	**0.56232**	3.1	0.01%	4	22.7 ± 0.4	**0.11%**
750	**0.60272**	3.1	0.01%	4	22.7 ± 0.4	**0.12%**
800	**0.64338**	3.1	0.01%	4	22.7 ± 0.4	**0.11%**
850	**0.68332**	3.1	0.01%	4	22.7 ± 0.4	**0.14%**
900	**0.72414**	3.1	0.01%	4	22.7 ± 0.4	**0.12%**
950	**0.76229**	3.1	0.01%	4	22.7 ± 0.4	**0.11%**
1000	**0.76656**	3.1	0.02%	4	22.7 ± 0.4	**0.15%**

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Table 5 – Results for the trap detector Ref 12

Type of standard : **trap** Reference Number : **ref 12**

Wavelength nm	**Spectral Responsivity A/W**	Bandwidth / nm	Relative Std Dev. %	Number of Measurements	Temperature /°C	**Uncertainty / %**
300	**0.24666**	3.1	0.13%	6	22.9±0.4	**0.37%**
320	**0.25557**	3.1	0.08%	6	22.9±0.4	**0.26%**
340	**0.26926**	3.1	0.07%	6	22.9±0.4	**0.12%**
360	**0.28048**	3.1	0.13%	6	22.9±0.4	**0.13%**
380	**0.29644**	3.1	0.10%	6	22.9±0.4	**0.18%**
400	**0.31621**	3.1	0.07%	6	22.9±0.4	**0.11%**
450	**0.35898**	3.1	0.11%	6	22.9±0.4	**0.11%**
500	**0.40052**	3.1	0.04%	6	22.9±0.4	**0.11%**
550	**0.44081**	3.1	0.07%	6	22.9±0.4	**0.11%**
600	**0.48153**	3.1	0.04%	6	22.9±0.4	**0.13%**
650	**0.52154**	3.1	0.01%	4	22.9±0.4	**0.13%**
700	**0.56219**	3.1	0.01%	4	22.9±0.4	**0.11%**
750	**0.60254**	3.1	0.01%	4	22.9±0.4	**0.12%**
800	**0.64320**	3.1	0.01%	4	22.9±0.4	**0.11%**
850	**0.68313**	3.1	0.01%	4	22.9±0.4	**0.14%**
900	**0.72388**	3.1	0.01%	4	22.9±0.4	**0.12%**
950	**0.76211**	3.1	0.01%	4	22.9±0.4	**0.11%**
1000	**0.76706**	3.1	0.03%	4	22.9±0.4	**0.15%**

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Table 6 – Results for the single element photodiode F 19

Type of standard : **photodiode** Reference Number : **F19**

Wavelength nm	**Spectral Responsivity A/W**	Bandwidth / nm	Relative Std Dev. %	Number of Measurements	Temperature /°C	**Uncertainty / %**
300	**0.13285**	3.1	0.11%	6	22.5±0.4	**0.37%**
320	**0.14563**	3.1	0.06%	6	22.5±0.4	**0.26%**
340	**0.15165**	3.1	0.03%	6	22.5±0.4	**0.12%**
360	**0.14801**	3.1	0.11%	6	22.5±0.4	**0.13%**
380	**0.15863**	3.1	0.13%	6	22.5±0.4	**0.18%**
400	**0.18347**	3.1	0.07%	6	22.5±0.4	**0.11%**
450	**0.22441**	3.1	0.10%	6	22.5±0.4	**0.11%**
500	**0.25709**	3.1	0.03%	6	22.5±0.4	**0.11%**
550	**0.28719**	3.1	0.03%	6	22.5±0.4	**0.11%**
600	**0.31598**	3.1	0.02%	6	22.5±0.4	**0.13%**
650	**0.34374**	3.1	0.02%	4	22.5±0.4	**0.13%**
700	**0.37176**	3.1	0.01%	4	22.5±0.4	**0.11%**
750	**0.39940**	3.1	0.02%	4	22.5±0.4	**0.12%**
800	**0.42707**	3.1	0.01%	4	22.5±0.4	**0.11%**
850	**0.45423**	3.1	0.02%	4	22.5±0.4	**0.14%**
900	**0.48189**	3.1	0.02%	4	22.5±0.4	**0.12%**
950	**0.50582**	3.1	0.02%	4	22.5±0.4	**0.11%**
1000	**0.48672**	3.1	0.03%	4	22.5±0.4	**0.14%**

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Table 7 – Results for the single element photodiode F 45

Type of standard : **photodiode** Reference Number : **F45**

Wavelength nm	**Spectral Responsivity A/W**	Bandwidth / nm	Relative Std Dev. %	Number of Measurements	Temperature /°C	**Uncertainty / %**
300	**0.12945**	3.1	0.11%	6	22.7±0.4	**0.37%**
320	**0.14225**	3.1	0.06%	6	22.7±0.4	**0.26%**
340	**0.14846**	3.1	0.06%	6	22.7±0.4	**0.12%**
360	**0.14502**	3.1	0.03%	6	22.7±0.4	**0.13%**
380	**0.15589**	3.1	0.04%	6	22.7±0.4	**0.18%**
400	**0.18074**	3.1	0.02%	6	22.7±0.4	**0.11%**
450	**0.22186**	3.1	0.01%	6	22.7±0.4	**0.11%**
500	**0.25490**	3.1	0.05%	6	22.7±0.4	**0.11%**
550	**0.28504**	3.1	0.03%	6	22.7±0.4	**0.11%**
600	**0.31398**	3.1	0.03%	6	22.7±0.4	**0.13%**
650	**0.34191**	3.1	0.01%	6	22.7±0.4	**0.13%**
700	**0.37008**	3.1	0.01%	6	22.7±0.4	**0.11%**
750	**0.39771**	3.1	0.01%	6	22.7±0.4	**0.12%**
800	**0.42559**	3.1	0.01%	6	22.7±0.4	**0.11%**
850	**0.45278**	3.1	0.01%	6	22.7±0.4	**0.14%**
900	**0.48068**	3.1	0.01%	6	22.7±0.4	**0.12%**
950	**0.50468**	3.1	0.01%	6	22.7±0.4	**0.11%**
1000	**0.48642**	3.1	0.03%	6	22.7±0.4	**0.14%**

Paris, October 08th, 2004

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Comentario [SK1]: Detta är ett bokmärke som refereras till i sidhuvudet på sida 2. Om du ändrar detta, spara första och sista tecknet till sist!

Measurement report

Comparison on spectral responsivity, EUROMET PR-K2.b

Measured detectors: Silicon trap No. 11
Silicon trap No. 14
Silicon diode No. F21
Silicon diode No. F34

Measurement facility and method

The main measurements where performed in monochromator Zeiss MM12, fitted with motors for automatic wavelength and bandwidth setting. A ∅4 mm converging (8°) output beam was used for the detectors F21 and F34, while a ∅4 mm (close to) parallel beam was used for trap 11 and 14. As working standard a Hamamatsu 1337 silicon diode was used. The monochromator can be equipped with different prisms and lamps. For this comparison glass prisms and a tungsten halogen lamp was used for wavelengths from 400 nm and up, while quartz prisms and a xenon lamp was used below 400 nm. The monochromator's basic wavelength calibration is made using a deuterium lamp. Typically a bandwidth of 5 nm has been used, although smaller at lower wavelengths.

In the range 450-850 nm the two trap detectors were calibrated against SP:s reference trap detectors using discrete laser wavelengths (vacuum) at 458,1 nm (Ar), 545,5 and 633,0 nm (HeNe). These results were then inter- and extrapolated to the requested wavelengths (450, 500 etc.).

Basic traceablility chain

Working standards for spectral responsivity are calibrated directly or indirectly to a cryogenic electrical substitution radiometer at SP, using discrete laser wavelengths. At intermediate and other wavelengths, the non-selective properties of gold black absorber in another electrical substitution radiometer, ECPR, is used. In the VIS range a large area silicon trap detector is used in first place.

In principle the calibration scheme looks like this:

Cryoradiometer → laser power → trap detector → laser power → ECPR →
→ monochromator power → silicon (or germanium detector).

For this particular comparison, the ECPR is providing traceability in the the range 300 – 400 nm and 900-1000 nm, and CR (traps) in the range 450-850 nm. For practical means when measuring the detectors F21 and F34, a working standard of similar type was used for the whole range. The same working standard was used for the traps (no. 11 and 14) in UV/IR. This standard is calibrated by the ECPR in the ranges 300-400 nm and 900-1000 nm. In the UV, discreet lines from discharge lamps are used together with interpolation.

Results

	Detector responsivity (A/W)			
Wavelength (nm)	F21	F34	Trap 11	Trap 14
300	0,1311	0,1311	0,2462	0,2463
320	0,1442	0,1444	0,2559	0,2561
340	0,1500	0,1502	0,2690	0,2691
360	0,1473	0,1474	0,2818	0,2820
380	0,1580	0,1582	0,2969	0,2970
400	0,1824	0,1826	0,3167	0,3170
450	0,2235	0,2237	0,3594	0,3594
500	0,2564	0,2566	0,4005	0,4006
550	0,2866	0,2868	0,4415	0,4416
600	0,3156	0,3158	0,4820	0,4821
650	0,3438	0,3442	0,5223	0,5224
700	0,3717	0,3720	0,5626	0,5627
750	0,3996	0,3994	0,6028	0,6030
800	0,4272	0,4271	0,6428	0,6431
850	0,4543	0,4544	0,6828	0,6832
900	0,4812	0,4817	0,7227	0,7232
950	0,5074	0,5078	0,7620	0,7627
1000	0,4900	0,4902	0,7652	0,7663

Measurement uncertainty

Depending on the wavelength and the detector type, the traceability-chain is different, thus making the uncertainty analysis rather complex. We feel that it is unnecessary to include each uncertainty component going from the cryogenic radiometer (CR) to the working standard, thus we have made some simplifications and used our standard uncertainties for example trap-calibrations using the CR. This uncertainty is motivated by other comparisons and also the ingoing components are often negligible compared to the actual ones later in the chain. If a component is wavelength dependent, the largest possible contribution within a certain wavelength range has typically been used. Also, since the uncertainties are expressed in percent (%), typically the responsivity in the middle of a certain wavelength range has been used. In the table below a summarization of the calculated uncertainties is given.

Combined measurement uncertainty (k=1):

Wavelength range	**Traps 11 and 14**	**Diodes F21 and F34**
300 nm - 400 nm	±0,93	±0,87
450 nm – 650 nm	±0,13	±0,23
700 nm – 850 nm	±0,25	±0,34
900 nm – 1000 nm	±0,79	±0,78

General uncertainty components

Temperature: The laboratory's temperature is 23 ±1 °C. During the measurements, due to shielding and various heat sources, this range is assumed to possibly increase to 23 ±2 °C. Depending on the wavelength this contributes a certain amount to the overall uncertainty (from ±0,05% in UV/VIS up to ±0,2 % at 1000 nm, using the data sheet for a typical silicon diode).

Repeatability: This component has been determined using the pooled standard deviation over a certain wavelength range. Typically the standard deviations are calculated as mean values from five repeated measurements. For the trap measurements at discrete laser wavelengths, this component is very small (around 10^{-5}).

Linearity: At the low power levels and large spot sizes (3-5 mm) used during the comparison, this component is assumed to be negligible in comparison to others.

Electrical measurements: The voltmeters and amplifiers used are calibrated at NMI for electricity. Also, all measurements are comparative, which almost completely will eliminate the small residual error. This component is assumed to be negligible in comparison to others.

Others: Estimates for vingetting effects, reflections, polarizations, stray light, bandwidth effects, and to some extent non-uniformity, are type B estimates which are based on experience regarding the detector types used (single element or trap) and the measurement set-up.

Trap no.11 and 14: Range 450 nm – 850 nm

The uncertainty for extrapolation is based on the excellent quantum efficiency for the used detectors and the general behaviour of silicon traps. The extrapolation has been checked at higher wavelengths (800 nm and 850 nm) using the calibrated working standard. All values are expressed in %.

Source of uncertainty	**Range 450 nm - 650 nm**		**Range 700 nm - 850 nm**	
	Estimate	**Standard uncertainty (k=1)**	**Estimate**	**Standard uncertainty (k=1)**
Calibration of NMI reference detectors SP reference trap, U=0,08%		**0,04**		**0,04**
Drift/contamination etc. since last calibration (1 year ago)	**±0,05**	**0,03**	**±0,05**	**0,03**
Calibration of KC transfer detectors				
Interpolation and / or extrapolation	**±0,15**	**0,09**	**±0,40**	**0,23**
Repeatability (laser stability etc.)	**--**	**Negl.**	**--**	**Negl.**
Temperature 23 ±2 °C	**±0,05**	**0,03**	**±0,10**	**0,06**
Wavelength calibration		**Negl.**		**Negl.**
Stray light	**±0,05**	**0,03**	**±0,05**	**0,03**
Polarization effects		**Negl.**		**Negl.**
Non-uniformity (detector surface)	**±0,05**	**0,03**	**±0,05**	**0,03**
Others (spot size, polarization, etc.)	**±0,08**	**0,05**	**±0,05**	**0,08**
Combined standard uncertainty		**0,13**		**0,25**

Trap no.11 and 14: Range 300 nm – 400 nm

The responsivity for the ECPR is assumed to be wavelength independent. Its responsivity is determined at different power levels against traps at visible laser wavelengths. The transfer to UV (and IR) is estimated using the manufacturer’s specifications and observations made at visible wavelengths. This uncertainty is dominated by the ECPR (going from VIS to UV at low power levels, including zero-drift etc.) together with interpolations from the discrete discharge lamp lines, so other components have been neglected.

Source of uncertainty	Estimate %	Standard uncertainty (k=1)
Calibration of NMI radiometer (ECPR) U=0,5%		**0,25**
Spectrally flat detector (residual wavelength dependence, uniformity, stability, …)	**±0,8**	**0,46**
Calibration of NMI working standard (incl. interpolation to requested wavelengths)	**±1,0**	**0,58**
Calibration of KC transfer detectors		

Repeatability (stability of source, alignment, ..)		**0,40**
Temperature	**±0,05**	**0,03**
Wavelength calibration	**±0,05**	**0,03**
Stray light	**±0,20**	**0,12**
Reflectance, non-uniformity, spot size etc (mainly due to single element contra trap detector)	**±0,50**	**0,29**
Combined standard uncertainty		**0,93**

Trap no.11 and 14: Range 900 nm – 1000 nm

The responsivity for the ECPR is assumed to be wavelength independent. Its responsivity is determined at different power levels against traps at visible laser wavelengths. The transfer to IR (and UV) is estimated using the manufacturer's specifications and observations made at visible wavelengths. This uncertainty is dominated by the ECPR (going from VIS to IR at low power levels, including zero-drift etc.) so other components have been neglected.

Source of uncertainty	Estimate %	Standard uncertainty (k=1)
Calibration of NMI radiometer (ECPR) U=0,5%		**0,25**
Spectrally flat detector (residual wavelength dependence, uniformity, stability, …)	**±0,8**	**0,46**
Calibration of NMI working standard (wavelength, stability etc)		**0,30**
Calibration of KC transfer detectors		
Repeatability (stability of source, alignment, ..)		**0,15**
Temperature	**±0,2**	**0,12**
Wavelength calibration	**±0,1**	**0,06**
Stray light	**±0,1**	**0,06**
Reflectance, non-uniformity, spot size etc (mainly due to single element contra trap detector)	**±0,8**	**0,46**
Combined standard uncertainty		**0,79**

Detector no.F21 and F34: Range 300 nm - 400 nm

Source of uncertainty	Estimate %	Standard uncertainty (k=1)
Calibration of NMI radiometer (ECPR) U=0,5%		**0,25**
Spectrally flat detector (residual wavelength dependence, uniformity, stability, …)	**±0,8**	**0,46**
Calibration of NMI working standard (repeatability, interpolation)		**0,58**
Calibration of KC transfer detectors		
Repeatability (stability of source, alignment, ..)		**0,30**
Temperature	**±0,1**	
Wavelength calibration	**±0,1**	
Stray light	**±0,2**	
Non-uniformity, spot size, bandwidth etc	**±0,3**	**0,17**
Combined standard uncertainty		**0,87**

Detector no.F21 and F34: Range 450 nm - 850 nm

Source of uncertainty	**Range 450 nm - 650 nm**		**Range 700 nm - 850 nm**	
	Estimate	**Standard uncertainty (k=1)**	**Estimate**	**Standard uncertainty (k=1)**
Calibration of NMI reference detectors SP reference trap, U=0,08%		**0,04**		**0,04**
Drift/contamination etc. since last calibration (1 year ago)	**±0,05**	**0,03**	**±0,05**	**0,03**
Interpolation and / or extrapolation	**±0,10**	**0,06**	**±0,25**	**0,14**
Calibration of SP Working standard				
Repeatability		**0,08**		**0,10**
Wavelength calibration	**±0,05**	**0,03**	**±0,10**	**0,06**
Stray light	**±0,10**	**0,06**	**±0,10**	**0,06**
Temperature	**±0,05**	**0,03**	**±0,10**	**0,06**
Reflectance, non-uniformity, spot size etc (mainly due to single element contra trap detector)	**±0,25**	**0,14**	**±0,40**	**0,23**
Calibration of KC transfer detectors				
Repeatability		**0,08**		**0,06**
Temperature 23 ±2 °C	**±0,05**	**0,03**	**±0,10**	**0,06**
Wavelength calibration	**±0,05**	**0,03**	**±0,05**	**0,03**
Stray light	**±0,05**	**0,03**	**±0,05**	**0,03**
Alignment	**±0,05**	**0,03**	**±0,05**	**0,03**
Non-uniformity, spot size, bandwidth etc	**±0,10**	**0,06**	**±0,15**	**0,09**
Combined standard uncertainty		**0,23**		**0,34**

Detector no.F21 and F34: Range 900 nm - 1000 nm

Source of uncertainty	Estimate %	Standard uncertainty (k=1)
Calibration of NMI radiometer (ECPR) U=0,5%		**0,25**
Spectrally flat detector (residual wavelength dependence, uniformity, stability, …)	**±0,8**	**0,46**
Calibration of NMI working standard (wavelength, stability etc)		**0,40**
Calibration of KC transfer detectors		
Repeatability (stability of source, alignment, ..)		**0,15**
Temperature	**±0,2**	**0,12**
Wavelength calibration	**±0,1**	**0,06**
Stray light	**±0,1**	**0,06**
Non-uniformity, spot size, bandwidth etc	**±0,6**	**0,35**
Combined standard uncertainty		**0,78**