Report on the key comparison

CCPR-K2.b

of
spectral responsivity measurements in the wavelength range 300 nm to 1000 nm

Final report

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Foreword

The present report concerns the key comparison CCPR-K2.b, international comparison of spectral responsivity measurements in the wavelength range 300 nm to 1000 nm, piloted by the BIPM.
It is based on the following documents:

- CCPR-K2.b Draft A report, circulated among the participants in April 2002
- Supplement to Draft A, circulated in September 2002
- CCPR-K2.b Working Document no.1, circulated in November 2002
- CCPR-K2.b Working Document no.2, circulated in December 2002
- Recommendation of the CCPR Working Group on Key Comparisons, June 2003
- Minutes of the meeting of the Working group on CCPR-K2.X, June 2003.

- CCPR-K2.b Draft B report, circulated for final approval in August 2004.

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 CCPR-K2.b, international comparison of spectral responsivity measurements in the wavelength range 300 nm to 1000 nm, piloted by the BIPM.

The technical protocol was drawn up by a small working group comprising the BIPM (convenor), the MSL, the NPL, the NIST, the NRC and the PTB.

The comparison was 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 February 2000 and to the second group in September 2000.

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

1. Participants

Group 1:
NML-CSIRO (Australia), HUT (Finland), IFA-CSIC (Spain), NIM (China, which postponed and finally cancelled its participation), NIST (USA), NPL (United Kingdom), NRC (Canada), OMH (Hungary), PTB (Germany).

Group 2:
BNM-INM (France), CSIR-NML (South Africa), NMIJ (Japan), IEN-GF (Italy), KRISS (Republic of Korea), MSL (New Zealand), NMi-VSL (The Netherlands), SMU (Slovak Republic), VNIIOFI (Russia).

2. Principle of the comparison

The Key Comparison (KC) transfer detectors are compared with a BIPM reference detector at each wavelength, before they are sent to the participating laboratory and after their return to check their stability.
The ratio

$R(\lambda) = I_{\mathrm{T}} / I_{\mathrm{Ref}}$, where I_{T} and I_{Ref} are respectively the currents measured from the transfer detector and the reference detector when irradiated by the same source at the same wavelength, is also equal to the ratio of the responsivities of the transfer detector and the reference detector.

If $C_i(\lambda)$ is the responsivity of the same transfer detector as calibrated by the *i*-th laboratory, then

$X_i(\lambda) = C_i(\lambda) / R(\lambda)$ where $X_i(\lambda)$ is the calibration result in A / W of the reference detector, obtained by transfer from the *i-th* laboratory.
The stability of the reference detector is checked as described in section 2.4.1.

From the N calibrations of the same reference detector, derived from the N laboratories' results, it is possible to calculate a reference value, with which each participant's result is compared. A separate reference value is calculated for each wavelength.

2.1. BIPM experimental set-up

2.1.1. General description

The monochromator used was a Jobin & Yvon HR2, double-grating type with a focal length of 600 mm. The holographic gratings are optimized for 330 nm, with a wavelength range of 240 nm to 1200 nm.
The source was a 400 W QTH lamp whose filament was imaged with unit magnification onto the entrance slit by means of a UV-grade lens. The order-sorting filters were placed at the input.
A horizontal slit of 2 mm width was added to the output slit, forming a 2 mm by 2 mm output hole. A slightly inclined spherical mirror imaged the output onto the detectors, again with unit magnification, forming a square spot of the same size.
The bandwidth was 1.4 nm (FBWHM).
A turntable equipped with six detector supports allowed five detectors under test to be compared with one reference detector.
A small part of the output beam was diverted by a quartz beam splitter and imaged onto another trap detector referred to as the monitor. A mechanical shutter, placed at the output, was used for dark-current measurements.

2.2. Preliminary experiments

2.2.1. Transfer detectors

The single-element transfer detectors equipped with windowed photodiodes (Hamamatsu 1337 BQ) were taken from the batch used during the previous comparison of the same type in 1993 and not used since then. Their window was cleaned with pure ethanol and the original connector replaced with a BNC-type.

As an insufficient number of trap detectors were available at the BIPM, it was decided to construct a new series for this comparison.

2.2.1.1. Construction of the trap detectors

Twenty reflection trap detectors were constructed, each comprising three Hamamatsu 1337 windowless photodiodes. The design and the mechanical parts are the same as those used for the 1993 international comparison [1], except that the photodiodes are glued onto their support instead of being clamped with screws.
All the photodiodes are taken from the same batch, purchased in 1997 and kept at the BIPM since that time.

2.2.1.2. Ageing of the trap detectors

It is known that the responsivity of this type of photodiode changes significantly after the first exposure to low-power UV radiation, before reaching a new stable value [2]. To avoid problems arising from accidental exposure of the traps to radiation below 300 nm, they were "aged" by exposure to radiation at 248 nm for 10 minutes. The source was a 200 W Hg arc lamp used with a monochromator. The spot diameter was about 16 mm at the entrance of the trap (overfilled), with a slightly diverging beam. The irradiance was approximately 32 µW/cm^2.

The single-element detectors had already been "aged" during the previous comparison of the same type in 1993.

2.2.2. Polarization effects

When aligned perpendicularly to the beam axis, a single photodiode is not significantly sensitive to the polarization state of the beam. This is not always the case with trap detectors, which sometimes exhibit a residual sensitivity to the polarization state. This sensitivity is due either to small departures of the photodiodes from their ideal position in the trap, or to a slight mismatch in internal quantum efficiency or reflectance between the photodiodes mounted within a trap [3].
After construction at the BIPM, all the trap detectors were tested at 633 nm and 476 nm using a linearly polarized laser beam, at two orthogonal directions of polarization.
The relative changes in responsivity for the two directions were found to be less than 2 parts in 10^4 at 633 nm (typically 1 part in 10^4) and below 3 parts in 10^4 at 476 nm. Some traps were also tested at 351 nm where the effect was not found to be significantly larger.
The test was then performed between 300 nm and 400 nm behind the monochromator for two orthogonal orientations of the trap detectors about the beam axis (the orientation of the reference trap being constant), and no larger effects were found.
The uncertainty associated with polarization effects is discussed in section 2.4.3.

2.2.3. Temperature coefficient measurements

The temperature coefficient as a function of wavelength of the two types of transfer detectors was measured (for a subset of the batches) in the range 20 °C to 30 °C. For this, the detectors were placed in a temperature-controlled copper block. The temperature was set by means of a temperature stabilized water circuit and measured with a sensor placed close to the detector. The source used was a double monochromator with a QTH lamp.
The measurements confirmed previous results showing that the temperature coefficient of the trap detectors is significantly smaller than that of the single elements.
The new measurements also showed that the sign of the temperature coefficient of the single photodiodes changes three times between 275 nm and 400 nm. As trap detectors do not exhibit the same behaviour, this effect seems to be related to the change in reflectance as a function of temperature.

The temperature coefficients of a subset of photodiodes and trap detectors are shown in Figure 1, and the values used for temperature corrections are given in Table 1.

The results of comparisons with the BIPM reference trap detector are always corrected for the differences from the nominal temperature (20.5°C) when testing the single-element photodiodes. The corrections for trap-to-trap comparisons are assumed to be negligible.

These temperature coefficients are also used for both single elements and trap detectors to correct the calibration results for the temperature differences between the BIPM and the participating laboratories.

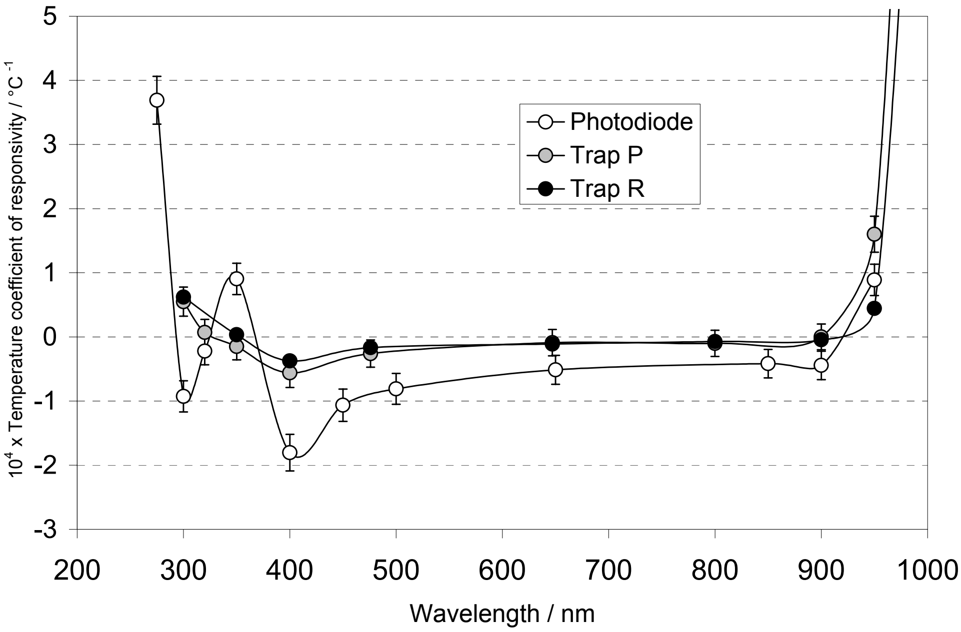


Figure 1 – Measured temperature coefficients of single-element and trap detectors (relative change in responsivity for a temperature change of + 1°C). Trap P was constructed in 1992 and Trap R in 2001 from different batches of photodiodes.

	Temperature coefficient / °C^{-1}	
λ / nm	Photodiode	Trap
300	-9.3E-05	6.2E-05
320	-2.2E-05	4.6E-05
340	5.3E-05	1.5E-05
360	3.6E-05	-4.8E-06
380	-7.2E-05	-2.1E-05
400	-1.8E-04	-3.7E-05
450	-1.1E-04	-2.4E-05
500	-8.1E-05	-1.6E-05
550	-7.1E-05	-1.4E-05
600	-6.1E-05	-1.3E-05
650	-5.1E-05	-1.1E-05
700	-4.9E-05	-9.8E-06
750	-4.6E-05	-8.5E-06
800	-4.4E-05	-7.2E-06
850	-4.2E-05	-5.8E-06
900	-4.4E-05	-4.4E-06
950	8.9E-05	4.4E-05
1000	1.8E-03	1.2E-03

Table 1 – Temperature coefficients of single-element and trap detectors as a function of wavelength: values used for temperature corrections.

2.3. Comparisons with the BIPM reference detector

All the single photodiodes and trap detectors were compared between five and ten times with the BIPM reference detector, using the monochromator-based facility at the wavelengths selected for the comparison.

The comparisons were also repeated for all the trap detectors using laser sources at seven wavelengths in the range 406 nm to 799 nm. This allowed the consistency of the comparisons to be checked: the operation was repeated for a subset of traps at laser line wavelengths, using the monochromator. The average difference between the two series for the two sources was less than 1 part in 10^4.

2.4. Uncertainties associated with the transfer NMI-BIPM

2.4.1. Stability of the BIPM reference

The principle of this comparison relies on the reference detector having a stability over the whole period of the comparison compatible with the uncertainties estimated by the participating laboratories for the calibration of the transfer detectors.

The BIPM reference group comprises a set of four traps and two single-element detectors taken from the BIPM set of detectors, known to be sufficiently "aged" and to exhibit no abnormal drifts with time or irradiation under normal conditions.
However, as it is always possible for a group of detectors to drift globally in a similar way, checks on stability were based on calibrations against the BIPM cryogenic radiometer. As a consequence, all the ratio measurements were performed against one BIPM reference trap detector (referenced BIPM-P4) used to transfer the stability of the cryogenic radiometer. The stability of this reference trap was checked regularly by comparison with the other detectors of the reference group, between the calibrations against the cryogenic radiometer.

Twelve laser lines were used with the cryogenic radiometer: 351.112 nm, 363.789 nm, 406.737 nm, 413.133 nm, 476.243 nm, 487.986 nm, 514.536 nm, 568.188 nm, 632.817 nm, 647.088 nm, 752.546 nm, and 799.322 nm.
The laser lines available at the BIPM do not cover the whole range of the comparison; the stability (here we are not interested directly in the absolute calibration) of the reference detectors was therefore estimated by interpolation within the range 351 nm to 799 nm, and by extrapolation in the ranges 300 nm to 340 nm and 950 nm to 1000 nm.
Interpolation and extrapolation of drifts are based on simple linear models in the UV range and in the Vis-NIR range. Extrapolations based on a pyroelectric detector were used for the BIPM absolute calibrations, but the dispersion of the measurements associated with this type of detector was found to be too large to allow relatively small drifts to be determined.

The group of reference trap detectors was calibrated against the BIPM cryogenic radiometer before Round 1 (referred to as Period A), between the two rounds (Period B) and after Round 2 (Period C).

As expected for this type of detector, the relative changes in spectral responsivity of the reference trap detector were shown to be either very small or negligible (within the uncertainties of the measurements) in the visible and the near infrared, and significantly larger at shorter wavelengths. The black circles in Figure 2 show the changes that occurred during the first round, and the grey circles the sum of the changes that occurred during Round 1 and 2.

All the comparisons of transfer detectors with the reference detector were corrected for these drifts, so the reference is assumed to have been stable, within the estimated uncertainties, over the whole period of the comparison.
The uncertainties associated with these corrections (see Table 2) take into account the uncertainties of absolute calibrations at the laser wavelengths and the uncertainties for extrapolation, which are large at 1000 nm where the detectors are known to be more non-uniform and very temperature-dependent.

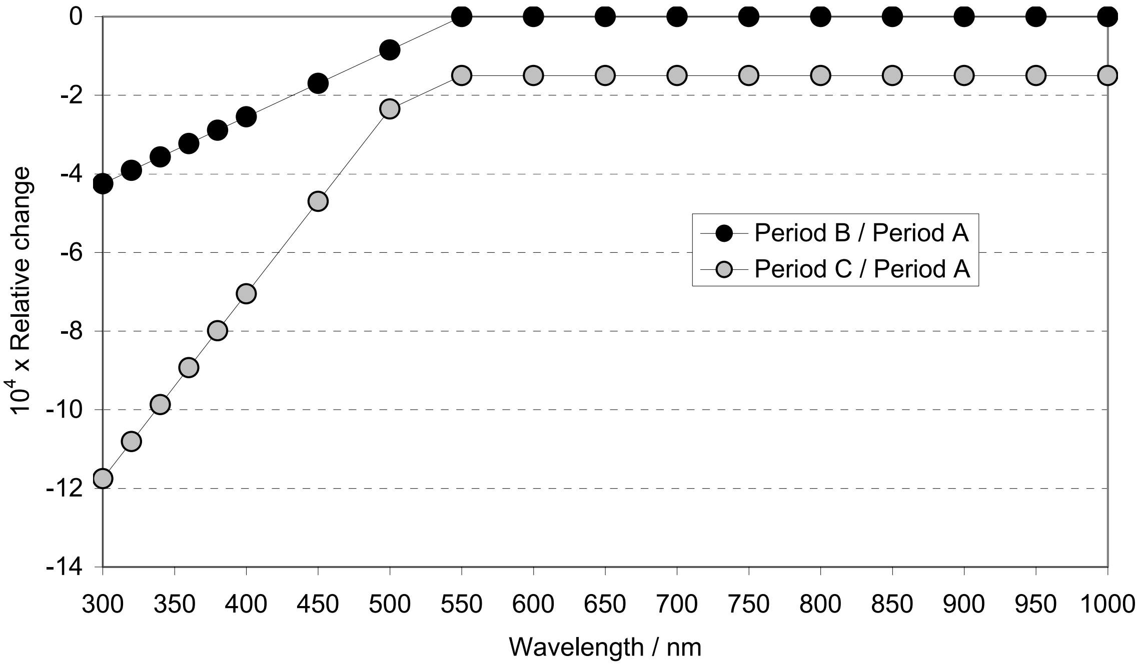


Figure 2 – Relative changes in spectral responsivity of the BIPM reference trap detector, as a function of time, based on measurements against the BIPM cryogenic radiometer (after linear interpolation and extrapolation). Periods A, B and C refer to June 2000, December 2000 and June 2001, respectively. A to B corresponds to Round 1 of the circulation of the transfer detectors, and B to C corresponds to Round 2.

	u_{ref}	
Wavelength / nm	Round 1	Round 2
300	4.0E-04	5.7E-04
320	4.0E-04	5.7E-04
340	4.0E-04	5.7E-04
360	3.2E-04	4.5E-04
380	3.2E-04	4.5E-04
400	2.2E-04	3.1E-04
450	1.4E-04	2.0E-04
500	1.4E-04	2.0E-04
550	1.4E-04	2.0E-04
600	1.4E-04	2.0E-04
650	1.4E-04	2.0E-04
700	1.4E-04	2.0E-04
750	1.4E-04	2.0E-04
800	1.4E-04	2.0E-04
850	1.4E-04	2.0E-04
900	1.4E-04	2.0E-04
950	2.0E-04	2.8E-04
1000	1.0E-03	1.4E-03

Table 2 – Relative standard uncertainty u_{ref} associated with the correction for drifts of the BIPM reference detector. They combine the uncertainties of absolute calibrations at the laser wavelengths and the uncertainties for extrapolation.

2.4.2. Stability of the transfer detectors

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

$$\Delta = \frac{R(\lambda)_{\text{after}} - R(\lambda)_{\text{before}}}{R(\lambda)_{\text{before}}}$$

During each round, the trap detectors were shown to be stable typically within 3 parts in 10^4 in the visible and the near-infrared regions, and about 5 parts in 10^4 in the ultraviolet. Larger changes (up to 1.5 part in 10^3 in the ultraviolet) were detected in a few cases, but no explanation could be found for this behaviour: the detectors had not been exposed to UV radiation below 300 nm, nor to extreme conditions. In some cases, detectors kept at the BIPM and not used during the same period exhibited the same type of decrease in responsivity in the UV region. These specific cases will be discussed in the sections concerning the laboratories results.
The single photodiodes showed similar behaviour, but with a larger amplitude: the average decrease in responsivity at 300 nm was about 1 part in 10^3.

The ratio R associated with each transfer detector was calculated as the average of the values obtained before and after travel.
The uncertainty u_{drift} associated with the possible drifts is estimated to be within $\Delta/2$ with a rectangular probability distribution:

$$u_{\text{drift}} = \frac{\Delta}{2\sqrt{3}}$$

The relative uncertainty associated with a drift as large as 1 x 10^{-3} is of the order 3 x 10^{-4}, which is significantly smaller than the smallest calibration uncertainty stated by any participating laboratory at 300 nm. The results for traps and photodiodes in Rounds 1 and 2 are shown in Figures 3 to 6.

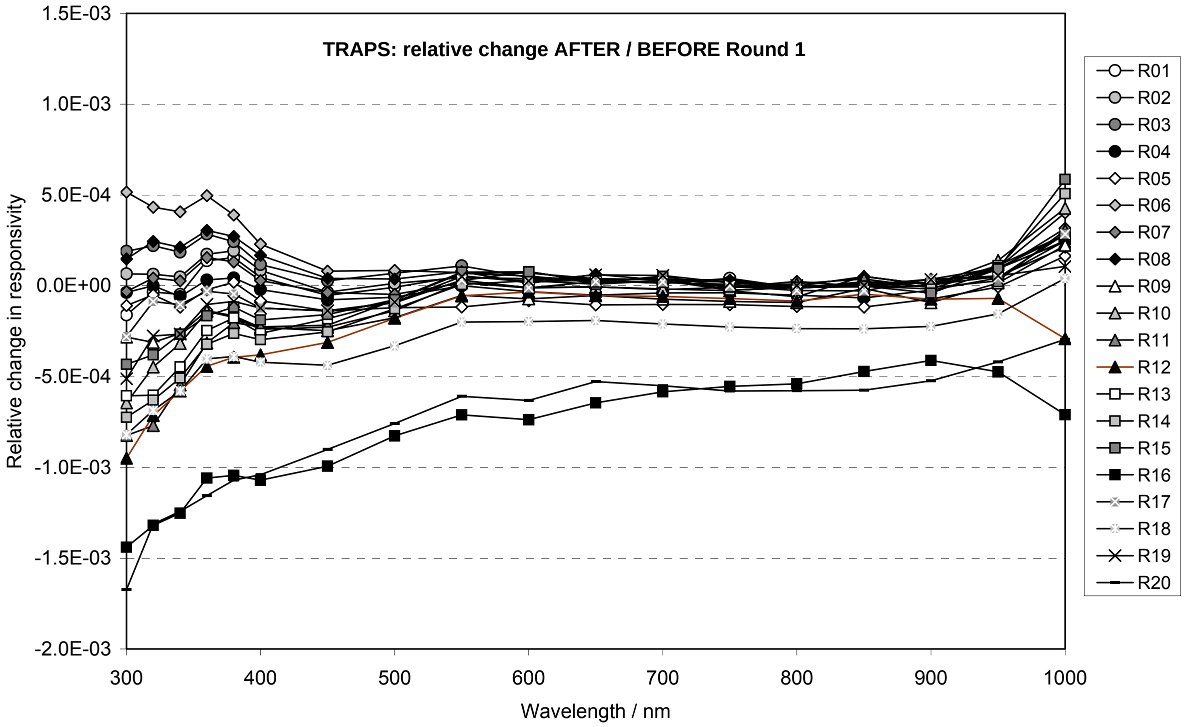


Figure 3 – Trap detectors: relative change in responsivity after / before Round 1.

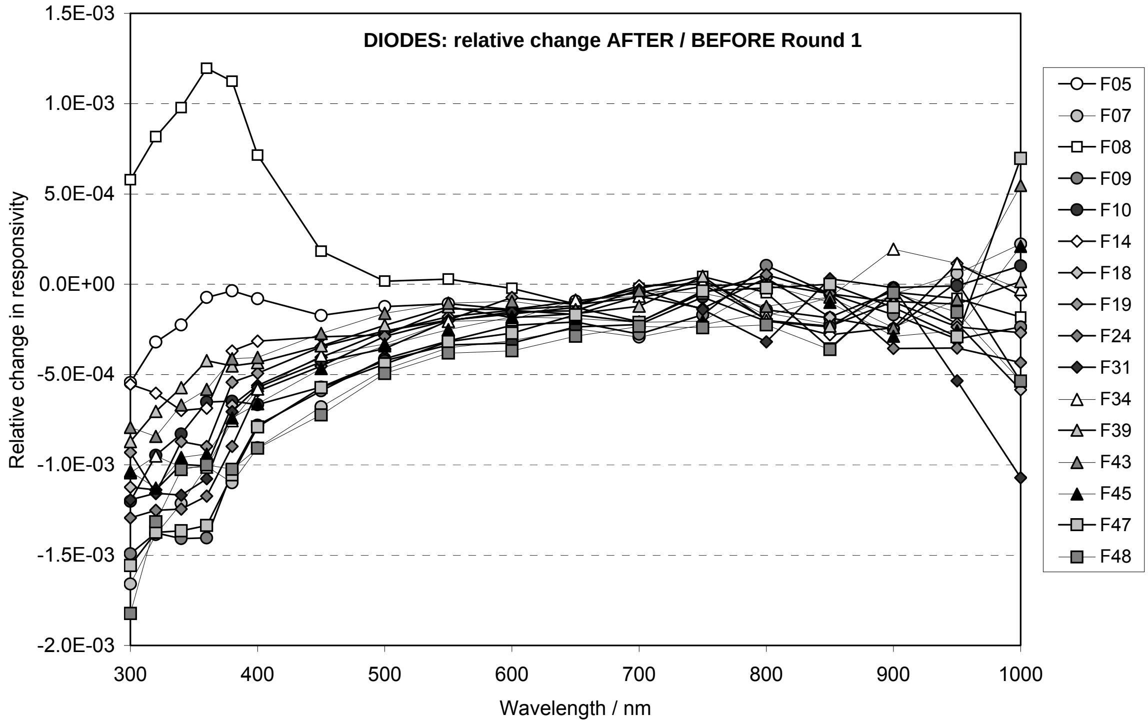


Figure 4 – Single diodes: relative change in responsivity after / before Round 1.

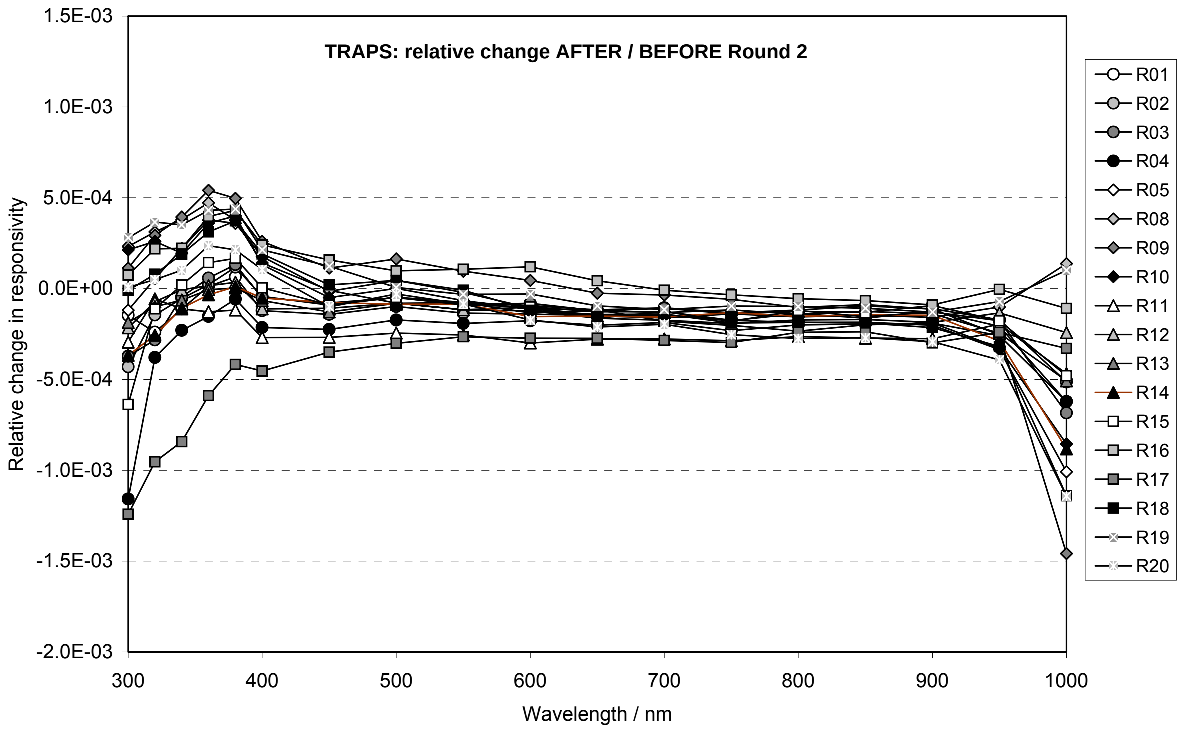


Figure 5 – Trap detectors: relative change in responsivity after / before Round 2.

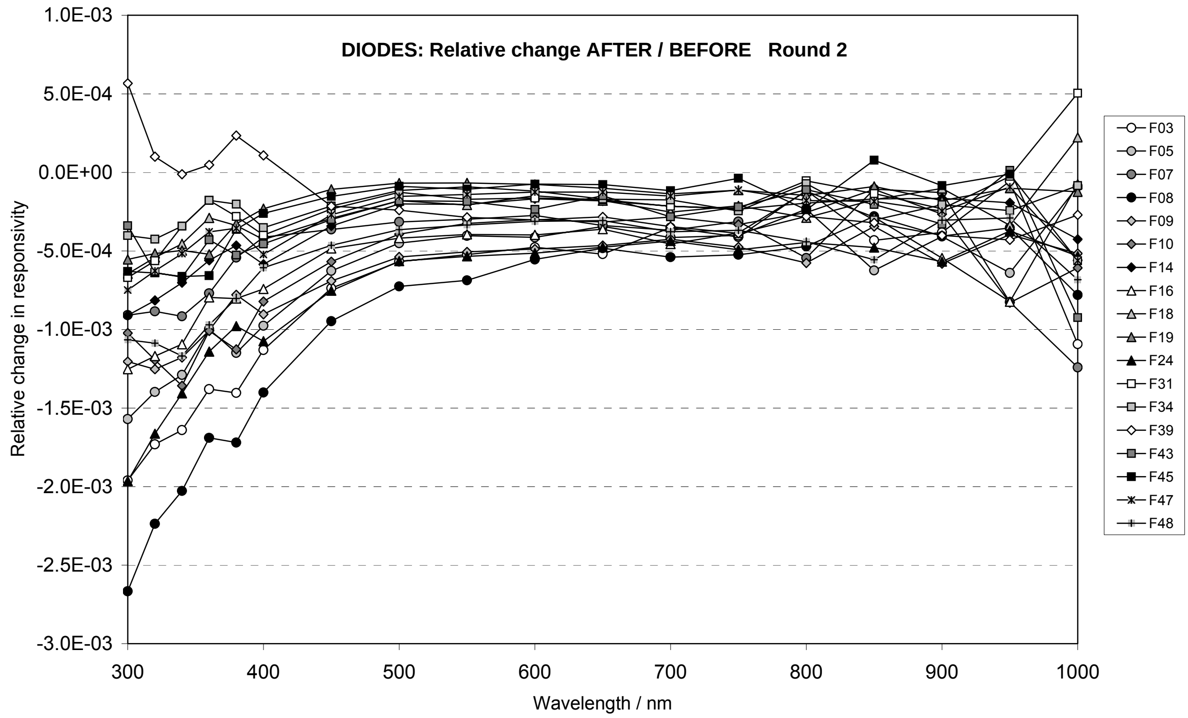


Figure 6 – Single diodes: relative change in responsivity after / before Round 2.

2.4.3. Polarization effects

Following the study described in section 2.2.2, the uncertainty associated with the residual sensitivity to the polarization state of the beam for trap detectors is shown in Table 3.

Wavelength / nm	$u_{\text{polarization}}$
300	4E-04
320	3E-04
340	2E-04
360	2E-04
380	2E-04
400	2E-04
450	1E-04
500	1E-04
550	1E-04
600	1E-04
650	1E-04
700	1E-04
750	1E-04
800	1E-04
850	1E-04
900	1E-04
950	2E-04
1000	3E-04

Table 3 – Trap detectors: relative standard uncertainty $u_{\text{polarization}}$ associated with the residual sensitivity to the polarization state of the beam.

2.4.4. Linearity

Previous tests have shown that, for a beam size of about 2 mm and an optical power of 20 µW or less, non-linearity effects are negligible compared with the other sources of uncertainty.

2.4.5. Monochromator wavelength calibration

The wavelength selection system of the monochromator was calibrated every day by means of low-pressure spectral lamps. The run-to-run repeatability was better than 0.05 nm and the uncertainty on the absolute calibration over the whole range was estimated to be 0.1 nm.
In a measurement sequence, the monochromator wavelength is set first; then the detectors placed on the turntable are aligned in turn in the beam, in ascending and then in descending order. In this way, any bias in wavelength is the same for all the detectors. Therefore, the uncertainty in the ratio $R(\lambda)$ of the signals, arising from the uncertainty in the wavelength, is a function of the differential rate of change of the signals from the reference trap and the detectors under test.
Based on the measured ratios, the slope of the curve $R(\lambda)$ allowed the relative change of $R(\lambda)$ to be calculated for $\Delta\lambda$ = 0.1 nm.
Assuming a rectangular distribution for the uncertainty in λ, the relative change of $R(\lambda)$ was divided by $\sqrt{3}$ to estimate the contribution to the standard uncertainty on the comparison.
The estimated uncertainty depends on the wavelength and on the type of comparison: trap/trap (low contribution) or diode/trap or trap/pyroelectric detector (see
Table **4**).

Wavelength / nm	u_{wave}	
	Traps	Diodes
300	3.1E-06	9.2E-05
320	2.7E-06	3.8E-05
340	2.4E-06	6.2E-05
360	3.9E-06	4.2E-05
380	1.1E-05	7.1E-05
400	1.2E-05	8.4E-05
450	6.1E-06	3.3E-05
500	2.4E-06	1.4E-05
550	1.1E-06	7.7E-06
600	5.8E-07	4.7E-06
650	3.0E-07	3.1E-06
700	2.2E-07	2.2E-06
750	1.2E-07	1.6E-06
800	5.8E-08	1.3E-06
850	2.3E-08	1.1E-06
900	1.8E-06	5.9E-07
950	2.1E-05	4.6E-06
1000	3.8E-05	9.4E-06

Table 4 – Contribution u_{wave} of the uncertainty in the wavelength to the relative uncertainty on the comparison of the transfer detectors with the reference trap detector.

2.4.6. Stray light

Stray light refers to the out-of-band radiation at the output of the monochromator. During the preliminary experiments, some tests were carried out with the monochromator in single-grating mode. Experimental results showed a significant bias (up to several parts in 10^3) in the ratios of the signals diode/trap due to stray light, especially in the UV where its contribution is larger. They also showed a dependence on the QTH supply current, i.e. on the spectral distribution of the source.
In the double-grating mode 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.

2.4.7. Use of a monitor detector and noise reduction

The monitor trap detector was used to correct results for small drifts of the source at each wavelength. The detector under test and the monitor were connected to two independent amplifiers and two voltmeters triggered simultaneously.
In principle, no significant difference should be found between the average of a large number of measurements before and after correction, the only effect being a reduction of the dispersion. After modification of the initial experimental arrangement (see section 2.4.8), the use of the monitor allowed a reduction of the short-term dispersion by a factor of five to ten, and no detectable bias.

2.4.8. Inter-reflections detector/slits

During the first tests carried out with a combination of horizontal and vertical slits, the signal from the monitor detector allowed inter-reflections between single photodiodes (with high reflectance) and the slits to be detected. The slits have then been blackened, making inter-reflection effects negligible.

2.4.9. Bandwidth effects

With a QTH lamp source used over the whole wavelength range and a bandwidth of 1.4 nm (FBWHM), the bandwidth effects were estimated to be negligible in the comparison of detectors.

2.4.10. Amplifier gain

All the detectors placed on the turntable for comparison were connected to a single current-voltage amplifier via a low-current scanner card. As all the photocurrents were measured using the same voltmeter on the same range, no corrections were applied for amplifier gain.

2.4.11. Uniformity, spot size and alignment

The detectors were aligned in the beam axis to within 0.2 mm. 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 BIPM and the NMIs may introduce some bias in the comparison. Simulations based on previous non-uniformity measurements of the detectors lead to uncertainty contributions given in Table 5.

λ / nm	u_{unif}
300	3.0E-04
320	3.0E-04
340	2.0E-04
360	2.0E-04
380	2.0E-04
400	1.0E-04
450	1.0E-04
500	5.0E-05
550	5.0E-05
600	5.0E-05
650	5.0E-05
700	5.0E-05
750	5.0E-05
800	5.0E-05
850	5.0E-05
900	5.0E-05
950	5.0E-05
1000	3.0E-04

Table 5 – Relative uncertainty u_{unif} associated with non-uniformity of the detectors and spot size.

2.4.12. Beam divergence and vignetting

The output beam divergence was about 6.2° (full angle), with a 2 mm x 2 mm square spot imaged onto the third inner photodiode of the traps, which is clearly within 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.

2.4.13. Temperature

The results of comparisons with the BIPM reference trap detector are always corrected for the small difference from nominal temperature when testing single-element photodiodes. For a 0.2°C difference in temperature between the detectors (assumed to be one standard uncertainty), the uncertainty associated with temperature corrections during comparisons is given in **Table 6**.

λ / nm	u_{Tcorr}
300	3.1E-05
320	1.4E-05
340	7.6E-06
360	8.2E-06
380	1.0E-05
400	2.9E-05
450	1.7E-05
500	1.3E-05
550	1.1E-05
600	9.6E-06

650	8.0E-06
700	7.8E-06
750	7.5E-06
800	7.4E-06
850	7.2E-06
900	7.9E-06
950	9.0E-06
1000	1.2E-04

Table 6 – Relative uncertainty u_{Tcorr} associated with the temperature corrections during diode / trap comparisons at the BIPM.

The results of absolute calibrations from the NMIs have also to be corrected for the temperature difference between the temperature at the participating laboratory and the temperature chosen as the nominal temperature at the BIPM, that is 20.5 °C. In this way, all the calibrations performed at various temperatures can be compared with each other. Temperature corrections were applied to both types of detectors, using the temperature coefficients given in Table 1. The uncertainty associated with this correction was estimated to be 10 % of the magnitude of the correction.

2.4.14. Repeatability

Each transfer detector was compared between three and five times (and even more during the preliminary tests) with the BIPM reference detector (independent comparisons over several days) before and after circulation. The standard deviation of the successive $R(\lambda)$ values within any period was calculated to estimate the repeatability. The average standard deviations for traps and single diodes are given in Table 7; they are used as an estimation of the uncertainty associated with the repeatability.

Wavelength / nm	u_{repeat}	
	Traps	Diodes
300	1.2E-04	4.6E-04
320	1.2E-04	2.1E-04
340	1.1E-04	2.1E-04
360	9.2E-05	2.1E-04
380	7.7E-05	2.1E-04
400	6.3E-05	2.0E-04
450	4.3E-05	1.1E-04
500	3.9E-05	9.0E-05
550	4.1E-05	7.8E-05
600	3.6E-05	7.6E-05
650	3.3E-05	6.7E-05
700	3.3E-05	5.4E-05
750	3.1E-05	6.5E-05
800	3.1E-05	6.3E-05
850	3.5E-05	1.1E-04
900	3.0E-05	1.1E-04
950	7.2E-05	8.9E-05
1000	3.5E-04	4.1E-04

Table 7 – Relative uncertainty associated with the repeatability of the comparison results at the BIPM (three to five independent comparisons over several days).

2.4.15. Combined uncertainty associated with the transfer

The contributions arising from all these parameters (except for the difference in temperature between the BIPM and the NMI, and the drift of the transfer detectors) have been added quadratically. The combined relative standard uncertainties are shown in Table 8. The total relative uncertainty including the contributions from temperature and drift (calculated for each individual detector and added the same way) is given in section 3. The uncertainty for Round 2 is slightly larger because of a larger uncertainty associated with the stability of the reference detector over a longer period.

Wavelength / nm	100 x combined standard uncertainty			
	Round 1		Round 2	
	Traps	Diodes	Traps	Diodes
300	0.07	0.07	0.08	0.08
320	0.06	0.05	0.07	0.07
340	0.05	0.05	0.06	0.06
360	0.04	0.04	0.05	0.05
380	0.04	0.04	0.05	0.05
400	0.03	0.03	0.04	0.04
450	0.02	0.02	0.02	0.02
500	0.02	0.02	0.02	0.02
550	0.02	0.02	0.02	0.02
600	0.02	0.02	0.02	0.02
650	0.02	0.02	0.02	0.02
700	0.02	0.02	0.02	0.02
750	0.02	0.02	0.02	0.02
800	0.02	0.02	0.02	0.02
850	0.02	0.02	0.02	0.02
900	0.02	0.02	0.02	0.02
950	0.03	0.02	0.03	0.03
1000	0.12	0.11	0.15	0.15

Table 8 – Combined relative standard uncertainties associated with the transfers NMI – BIPM, omitting the components for temperature and drift of the transfer detectors, which differ for each participant.

3. Transfer of individual results to a common BIPM reference detector

As explained in section 2, each calibration of a KC detector is used to calibrate the BIPM reference detector, so that four values per laboratory are available: two values are obtained by transfer from the trap detectors, and two from the single photodiodes. In principle, the four results should be approximately equal, i.e. consistent within the uncertainties arising from the repeatability of the measurements and the transfer, and no significant bias should appear for the two types of transfer detectors. The relative standard deviation of the four results was calculated for each laboratory, as an indicator of the consistency of the calibration results (see sections 3.2 to 3.18).

3.1. Uncertainty budgets from the participating laboratories

Many parameters that influence the uncertainty budget are common to the uncertainty budgets sent by all the participants, but the way the various components are presented, grouped or detailed, differs markedly from one laboratory to the other. As it is interesting to compare the influence attributed to the principal parameters by each participant, it was decided to summarize all the budgets, using as uniform a presentation as possible. This task was not easy, because in some cases parameters had to be grouped and in some others split up.

The uncertainties associated with three main procedures have been highlighted:

- the calibration of the NMI's reference detectors against their primary reference;
- the interpolation and the extrapolation to wavelengths not directly available with the primary reference (where appropriate);
- the transfer to KC detectors, including the wavelength calibration of the monochromator, and repeatability.

This corresponds to the most common traceability route in the calibration of detectors by an NMI.
The repeatability gives information on parameters contributing to the variability of the results.
The wavelength calibration is common to all the participants, and is an example of a parameter whose influence is estimated very differently by various participants.

All the original budgets are reproduced in a separate document (CCPR-K2.b Collection of the NMI's calibration reports), already circulated among the participants.
We would like to encourage participants to read these budgets, to compare the various ways the sources of uncertainties are studied and their influences estimated (amplitude, spectral dependence) or neglected.
The reported combined relative uncertainties as a function of wavelength are summarized in Figure 7 for all the participants.

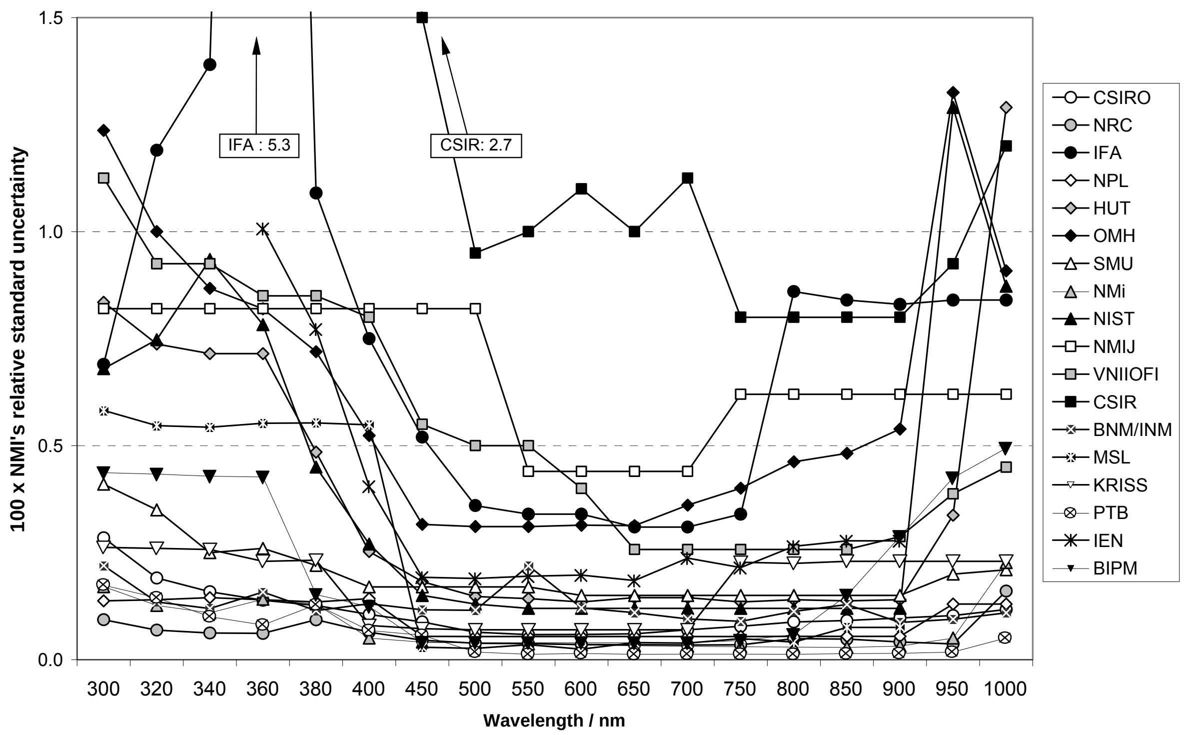


Figure 7 – 100 x NMI's relative standard uncertainty for the calibration of the KC transfer detectors.

3.2. HUT

Primary reference: cryogenic radiometer at 488 nm, 514 nm and 633 nm
HUT reference detectors: three trap detectors and one InGaAs photodiode (used at 1000 nm)

Experimental set-up:

Single-grating monochromator, order-sorting filters placed at the input, off-axis parabolic mirror at the output in conjunction with a limiting aperture to set the spot size;
Bandwidth: 1 nm in the range 300 nm to 950 nm, and 2 nm at 1000 nm;
Spot size: 3 mm in diameter collimated beam;
Optical power: 20 nW to 10 µW.

Interpolation / extrapolation:

Reflectance and IQE models in the range 400 nm to 950 nm;
Pyroelectric detector in the range 300 nm to 380 nm and at 1000 nm.

The calibration of the HUT reference detectors is directly traceable to the primary reference.
The KC detectors are calibrated by comparison to these reference detectors.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors, and the corresponding uncertainties are given in Table 9.

HUT	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R08	R19	F19	F45	Rel Std Dev	R08	R19	F19	F45
300	0.242715	0.242661	0.242598	0.242664	2.0E-04	0.833	0.833	0.843	0.843
320	0.251541	0.251521	0.251076	0.250894	1.3E-03	0.733	0.743	0.743	0.743
340	0.264368	0.264353	0.263833	0.263748	1.3E-03	0.712	0.712	0.722	0.722
360	0.277325	0.277299	0.276672	0.276433	1.6E-03	0.711	0.711	0.722	0.722
380	0.293620	0.293667	0.293526	0.293274	6.0E-04	0.482	0.482	0.492	0.492
400	0.313262	0.313267	0.313146	0.313003	4.0E-04	0.252	0.242	0.272	0.253
450	0.357850	0.358024	0.358050	0.357722	4.3E-04	0.181	0.171	0.211	0.172
500	0.399947	0.399884	0.400096	0.399855	2.7E-04	0.151	0.141	0.161	0.141
550	0.440775	0.440710	0.441251	0.440948	5.5E-04	0.141	0.131	0.161	0.141
600	0.481198	0.481238	0.481720	0.481532	5.2E-04	0.131	0.121	0.151	0.141
650	0.521654	0.521591	0.522044	0.521862	4.0E-04	0.131	0.141	0.161	0.151
700	0.561837	0.561685	0.562339	0.561995	5.0E-04	0.141	0.131	0.171	0.141
750	0.601402	0.601936	0.602332	0.602426	7.7E-04	0.131	0.121	0.151	0.141
800	0.641727	0.641582	0.642457	0.641997	6.0E-04	0.131	0.141	0.151	0.141
850	0.681845	0.681768	0.682154	0.682691	6.1E-04	0.131	0.131	0.151	0.141
900	0.721279	0.721324	0.720926	0.722188	7.4E-04	0.121	0.131	0.151	0.161
950	0.758490	0.758643	0.761285	0.761127	2.0E-03	0.331	0.341	0.341	0.341
1000	0.731587	0.735022	0.733206	0.732495	2.0E-03	1.295	1.295	1.295	1.295

Table 9 – HUT: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including HUT's uncertainty and transfer.

Cryogenic radiometer	laser lines / nm		
	488	514	633
standard uncertainty	0.024	0.024	0.024

Wavelength / nm	**300**	**320**	**350**	**380**	**400**	**450**	**500 - 900**	**950**	**1000**
Primary reference : Cryogenic radiometer					0.024	0.024	0.024	0.024	
Interpolation / extrapolation									
using IQE and reflectance **models**					0.20	0.12	0.06	0.31	
using a **pyroelectric** detector: spectral flatness, non-uniformity, correction factor for different ranges, AC-DC conversion	0.78	0.67	0.67	0.44					1.17
Wavelength uncertainty	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.1
Calibration of HUT reference detectors (including uniformity, linearity, polarization dependence, wavelength, electrical calibrations, stray light…)	0.25	0.25	0.20	0.16	0.09	0.07	0.07	0.08	0.45
Transfer to KC detectors: repeatability (typical)	0.06	0.09	0.05	0.08	0.09	0.09	0.08	0.08	0.08
Transfer to KC trap detectors (including repeatability, temperature, electrical calibrations, …)	0.15	0.17	0.13	0.10	0.11	0.10	0.09	0.10	0.27
Combined standard uncertainty for KC traps	**0.83**	**0.74**	**0.71**	**0.48**	**0.25**	**0.17**	**0.13**	**0.33**	**1.29**
Transfer to KC single diodes (including repeatability, temperature, electrical calibrations, …)	0.19	0.19	0.18	0.14	0.13	0.12	0.11	0.11	0.27
Combined standard uncertainty for KC diodes	**0.84**	**0.74**	**0.72**	**0.49**	**0.26**	**0.19**	**0.15**	**0.34**	**1.29**

Table 10 - Summary of the HUT uncertainty budget. Uncertainties are expressed as 100 x relative standard uncertainty.

3.3. IFA-CSIC

Primary reference: cryogenic radiometer at eight laser lines (327 nm to 647 nm)

IFA reference detectors: QED100 and trap detectors.
Working standards: one trap detector (300 nm to 400 nm range) and photodiodes (400 nm to 1000 nm range).

Experimental set-up:

Two single-grating monochromators: one for the UV range (300 nm to 400 nm) with a Xe-Hg source and one for the Vis-IR range with a QTH source.
Bandwidth: 3.2 nm in the UV and 5 nm in the Vis-IR
Spot size: 3 mm x 3 mm, 2.17° half angle (UV range)
4 mm x 4 mm, 2.95° half angle (Vis-IR)
Optical power: 0.5 µW to 7 µW.

Interpolation / extrapolation:

IQE and reflectance models in the range 400 nm to 800 nm
ECPR used as a spectrally flat detector in the UV and in the 800 nm to 1000 nm range.

The KC detectors are calibrated by comparison with the IFA working standards.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 11.

IFA	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R04	R15	F18	F43	Rel Std Dev	R04	R15	F18	F43
300	0.240004	0.238342	0.242158	0.241487	7.1E-03	0.693	0.693	0.694	0.694
320	0.248204	0.246634	0.249337	0.248569	4.6E-03	1.192	1.192	1.192	1.191
340	0.263140	0.263658	0.262375	0.263447	2.1E-03	1.391	1.391	1.391	1.391
360	0.274508	0.274545	0.272332	0.274059	3.8E-03	5.310	5.310	5.310	5.310
380	0.294238	0.293589	0.292195	0.293630	2.9E-03	1.091	1.091	1.091	1.091
400	0.311322	0.311071	0.310439	0.309492	2.6E-03	0.751	0.751	0.751	0.751
450	0.357084	0.356183	0.356796	0.356759	1.1E-03	0.520	0.520	0.520	0.520
500	0.398350	0.397900	0.398266	0.398189	4.9E-04	0.360	0.360	0.361	0.360
550	0.439823	0.439117	0.439685	0.439538	7.0E-04	0.340	0.341	0.340	0.340
600	0.480976	0.480507	0.480762	0.480817	4.1E-04	0.340	0.340	0.340	0.340
650	0.520990	0.520588	0.520841	0.520782	3.2E-04	0.311	0.311	0.310	0.310
700	0.560317	0.559954	0.560254	0.560181	2.8E-04	0.311	0.311	0.310	0.310
750	0.599624	0.599052	0.599443	0.599552	4.3E-04	0.340	0.340	0.340	0.340
800	0.640822	0.640859	0.641982	0.641870	9.8E-04	0.860	0.860	0.860	0.860
850	0.680402	0.680450	0.681698	0.681756	1.1E-03	0.840	0.840	0.840	0.840
900	0.717767	0.718059	0.719549	0.719257	1.2E-03	0.830	0.830	0.830	0.830
950	0.754493	0.754677	0.755579	0.755780	8.5E-04	0.840	0.840	0.840	0.840
1000	0.726511	0.726709	0.726224	0.725468	7.5E-04	0.848	0.848	0.848	0.848

Table 11 – IFA: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including IFA's uncertainty and transfer.

Cryogenic radiometer	laser lines / nm							
	327	407	441	488	515	568	647	676
standard uncertainty	0.045	0.015	0.015	0.015	0.015	0.015	0.015	0.015

	Wavelength / nm	**300 - 380**	**400 - 800**	**850 - 1000**
Primary reference : Cryogenic radiometer		0.045	0.015	0.015
Interpolation / extrapolation using models			0.25	
extrapolation using a pyroelectric detector		0.4		0.81
Calibration of IFA reference detectors	Uniformity, linearity, repeatability, etc.	0.088	0.073	0.085
	Wavelength calibration	$(\partial I/\partial \lambda)$ x 0.05 nm		$(\partial I/\partial \lambda)$ x 0.11 nm
Calibration of KC detectors	Repeatability (average values)	0.47 – 0.72	0.05 – 0.9	0.03 – 0.23
	Wavelength calibration	$(\partial I/\partial \lambda)$ x 0.05 nm	$(\partial I/\partial \lambda)$ x 0.11 nm	$(\partial I/\partial \lambda)$ x 0.11 nm
	Bandwidth effects, stray light	0.014		
Combined standard uncertainty for KC detectors		see table below		

wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
100 x combined standard uncertainty for KC detectors	0.69	1.19	1.39	5.31	1.09	0.75	0.52	0.36	0.34	0.34	0.31	0.31	0.34	0.86	0.84	0.83	0.84	0.84

Table 12 – Summary of the IFA-CSIC uncertainty budget. Relative uncertainties are expressed as 100 x standard uncertainty.

3.4. NIST

Primary reference: cryogenic radiometer used at laser lines,
with a relative combined uncertainty of 0.1 %

NIST reference detectors: Four silicon photodiode working standards in the range 200 nm to 350 nm
Four silicon photodiode working standards in the range 355 nm to 1000 nm

Experimental set-up:

UV : Double monochromator using an argon arc, with a circular exit
Bandwidth: 3 nm
Spot diameter: 1.5 mm (≈ f / 5)

VIS-NIR: Double monochromator using a QTH source, with a circular exit
Bandwidth: 4 nm
Spot diameter: 1.1 mm (≈ f / 9)

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 13.

NIST	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R12	R16	F07	F48	Rel Std Dev	R12	R16	F07	F48
300	0.241179	0.241457	0.241964	0.242073	1.7E-03	0.902	0.634	0.606	0.596
320	0.251464	0.251792	0.251980	0.252043	1.0E-03	0.982	0.683	0.673	0.663
340	0.263773	0.264147	0.264161	0.264272	8.2E-04	1.151	0.882	0.852	0.862
360	0.275056	0.275391	0.274910	0.274935	8.0E-04	0.791	0.781	0.782	0.782
380	0.291427	0.291686	0.291621	0.291514	3.9E-04	0.452	0.452	0.453	0.453
400	0.312489	0.312625	0.312363	0.312339	4.2E-04	0.272	0.273	0.273	0.273
450	0.358095	0.358271	0.357907	0.357881	5.1E-04	0.151	0.153	0.153	0.153
500	0.400374	0.400539	0.400209	0.400196	4.0E-04	0.131	0.133	0.132	0.132
550	0.441377	0.441569	0.441282	0.441253	3.2E-04	0.121	0.123	0.122	0.122
600	0.482026	0.482215	0.481977	0.481914	2.7E-04	0.121	0.123	0.122	0.122
650	0.522510	0.522712	0.522496	0.522460	2.2E-04	0.121	0.123	0.121	0.121
700	0.562887	0.563092	0.562913	0.562878	1.8E-04	0.121	0.123	0.121	0.121
750	0.603171	0.603371	0.603248	0.603118	1.8E-04	0.121	0.122	0.121	0.121
800	0.643405	0.643622	0.643543	0.643413	1.6E-04	0.121	0.122	0.121	0.121
850	0.683644	0.683842	0.683983	0.683432	3.5E-04	0.121	0.122	0.122	0.122
900	0.723820	0.724021	0.724114	0.724073	1.8E-04	0.121	0.122	0.121	0.121
950	0.758740	0.758950	0.759008	0.759124	2.1E-04	1.290	1.290	1.290	1.290
1000	0.731822	0.731636	0.731126	0.735887	3.0E-03	0.879	0.879	0.880	0.890

Table 13 – NIST: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NIST's uncertainty and transfer.

In the UV the trap detector R16 showed a relative change in responsivity significantly larger than that usually observed, but very similar to that of one of the traps sent to the NRC at the same period (about -1.0×10^{-3}).

Source of uncertainty	Wavelength / nm																	
(100 x relative standard uncertainty)	UV Working Standards			Visible Working Standards														
Calibration of NIST trap detectors	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Transfer from cryogenic radiometer to NIST trap				0.100	0.100	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075		
Calibration of NIST WS photodiodes																		
Cryogenic radiometer calibration	0.15	0.15																
Pyroelectric relative calibration			0.517															
Transfer from Vis WS (scaling factor)			0.18															
Trap calibration (Near-IR > 920 nm)				0.100	0.100	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.902	0.749
Repeatability and reproducibility	0.43	0.60	0.407	0.150	0.050	0.113	0.041	0.025	0.012	0.013	0.008	0.007	0.007	0.012	0.008	0.010	0.899	0.395
DVM uncertainty			0.008	0.408	0.222	0.120	0.041	0.024	0.018	0.015	0.017	0.019	0.023	0.033	0.040	0.024	0.018	0.012
Trap / Near-IR WS amplifier gain				0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
WS detector amplifier gain				0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wavelength calibration	0.32	0.12	0.018	0.023	0.087	0.050	0.033	0.025	0.021	0.018	0.016	0.015	0.014	0.013	0.012	0.011	0.016	0.025
Stray light	0.10	0.10	0.001	0.005	0.003	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.001
UV & Vis WS long-term stability	0.229	0.222	0.242	0.091	0.065	0.031	0.013	0.010	0.007	0.006	0.006	0.005	0.004	0.006	0.012	0.007	0.011	0.126
Combined std unc. for NIST WS photodiode	**0.61**	**0.68**	**0.72**	**0.46**	**0.28**	**0.20**	**0.12**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**	**1.28**	**0.86**
Calibration of KC detectors																		
UV WS detector calibration (averaged)	0.57	0.64	0.81															
Vis WS detector calibration (averaged)				0.44	0.27	0.18	0.12	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.29	0.86
DVM uncertainty	0.008	0.008	0.008	0.629	0.329	0.171	0.055	0.030	0.022	0.017	0.019	0.021	0.026	0.038	0.044	0.026	0.018	0.014
UV & Vis WS detectors amplifier gain	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
KC photodiode amplifier gain	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wavelength calibration (± 0.1 nm)	0.033	0.024	0.018	0.039	0.115	0.073	0.055	0.043	0.034	0.025	0.019	0.013	0.007	0.000	0.009	0.026	0.063	0.126
Stray light	0.000	0.000	0.000	0.006	0.003	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001
Repeatability and reproducibility KC trap (expl.)	0.696	0.745	0.815	0.159	0.025	0.034	0.014	0.013	0.013	0.013	0.013	0.013	0.014	0.015	0.014	0.013	0.017	0.078
Combined std unc. for KC trap (example)	**0.90**	**0.98**	**1.15**	**0.79**	**0.45**	**0.27**	**0.15**	**0.13**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**1.29**	**0.87**
Repeatability and reproducibility KC phot. (expl.)	0.181	0.185	0.275	0.100	0.045	0.026	0.014	0.012	0.015	0.012	0.014	0.013	0.012	0.012	0.018	0.012	0.013	0.071
Combined std unc. for KC phot. (example)	**0.60**	**0.67**	**0.85**	**0.78**	**0.45**	**0.27**	**0.15**	**0.13**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**1.29**	**0.87**

Table 14 – NIST: uncertainty associated with the calibration of the transfer detectors.

3.5. NML – CSIRO

Primary reference: cryogenic radiometer at laser lines in the range 476 nm to 677 nm.
NML reference detectors:

Transmission trap detectors in the range 420 nm to 830 nm;
Gold black bolometers in the range 240 nm to 420 nm and 830 nm to 2400 nm;

Additional working standards: single photodiodes.

Experimental set-up:

Double-grating monochromator (using only first monochromator),
with predisperser and a QTH source;
Bandwidth: 4 nm
Spot size: 2mm x 2mm (f / 8)

Interpolation / extrapolation:

IQE and reflectance models in the range 420 nm to 830 nm;
Gold black bolometers in the UV and NIR

The KC detectors were calibrated by comparison with the NML reference Si detectors. The calibration is calculated as the average value of the results obtained for two orthogonal orientations of the KC detectors about the beam axis, in order to cancel beam polarization effects.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given Table 15.

NML - CSIRO	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R02	R03	F31	F14	Rel Std Dev	R02	R03	F14	F31
300	0.240815	0.240733	0.241193	0.241303	1.2E-03	0.282	0.312	0.271	0.308
320	0.250192	0.250198	0.250173	0.250421	4.7E-04	0.198	0.218	0.194	0.191
340	0.262909	0.262783	0.262749	0.262923	3.3E-04	0.169	0.181	0.162	0.159
360	0.275284	0.275021	0.275290	0.275411	6.0E-04	0.154	0.149	0.142	0.138
380	0.292041	0.292065	0.291532	0.291680	9.1E-04	0.136	0.146	0.127	0.124
400	0.312546	0.312557	0.312270	0.312377	4.4E-04	0.112	0.113	0.111	0.106
450	0.356512	0.356506	0.356371	0.356464	1.8E-04	0.096	0.091	0.088	0.086
500	0.398921	0.398831	0.398759	0.398909	1.9E-04	0.071	0.069	0.066	0.062
550	0.439961	0.439896	0.439917	0.440037	1.4E-04	0.064	0.064	0.060	0.056
600	0.481065	0.480980	0.481012	0.481143	1.5E-04	0.066	0.065	0.059	0.057
650	0.521422	0.521396	0.521371	0.521546	1.5E-04	0.067	0.067	0.061	0.057
700	0.562176	0.562125	0.562154	0.562227	7.7E-05	0.075	0.075	0.069	0.068
750	0.602688	0.602541	0.602552	0.602640	1.2E-04	0.082	0.084	0.077	0.076
800	0.643077	0.642963	0.642937	0.643010	9.6E-05	0.092	0.094	0.088	0.087
850	0.682880	0.682699	0.682725	0.682855	1.3E-04	0.097	0.097	0.090	0.090
900	0.722612	0.722344	0.722593	0.722546	1.7E-04	0.102	0.103	0.095	0.096
950	0.759420	0.759110	0.759006	0.759516	3.2E-04	0.109	0.110	0.104	0.102
1000	0.731121	0.730734	0.730227	0.730445	5.3E-04	0.169	0.167	0.166	0.164

Table 15 – NML-CSIRO: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NML's uncertainty and transfer.

Cryogenic radiometer and transfer to secondary standard Si trap detector 100 x standard uncertainty	laser lines / nm								
	476	477	488	514	531	568	633	647	677
	0.0124	0.0124	0.0124	0.0124	0.0124	0.0124	0.0124	0.0124	0.0124

Wavelength / nm	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Interpolation / extrapolation using models						0.1	0.04	0.015	0.015	0.015	0.015	0.02	0.04	0.06	0.08	0.1		
Transfer to secondary reference Si photodiode						0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.05				
Extrapolation using gold black bolometers	0.234	0.142	0.106	0.079	0.07	0.064	0.056	0.051	0	0.054	0.058	0.063	0.063	0.064	0.065	0.067	0.069	0.073
Combined uncertainty for secondary reference	**0.238**	**0.149**	**0.114**	**0.090**	**0.082**	**0.078**	**0.064**	**0.044**	**0.044**	**0.044**	**0.044**	**0.055**	**0.064**	**0.077**	**0.078**	**0.080**	**0.082**	**0.085**
Transfer to NML working standards	0.06	0.06	0.06	0.05	0.05	0.05	0.025	0.025	0.015	0.02	0.02	0.025	0.025	0.025	0.03	0.04	0.05	0.06
Transfer to KC detectors **repeatability** (average value)	0.07	0.05	0.05	0.05	0.05	0.04	0.04	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.08
Transfer to KC single diodes: temperature, stray light, etc .	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
Transfer to KC traps: wavelength	0.05	0.01	0.01	0.03	0.035	0.015	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Transfer to KC traps: including wavelength, polarization, temperature, etc.	0.089	0.065	0.056	0.063	0.058	0.041	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Combined standard uncertainty for KC diodes (example)	**0.260**	**0.183**	**0.151**	**0.132**	**0.118**	**0.105**	**0.085**	**0.062**	**0.057**	**0.057**	**0.058**	**0.067**	**0.076**	**0.086**	**0.088**	**0.094**	**0.100**	**0.114**
Combined standard uncertainty for KC traps (example)	**0.274**	**0.188**	**0.162**	**0.149**	**0.130**	**0.108**	**0.095**	**0.069**	**0.062**	**0.063**	**0.065**	**0.073**	**0.08**	**0.091**	**0.095**	**0.100**	**0.106**	**0.122**

Table 16 – Summary of the NML – CSIRO uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.6. NPL

Primary reference: mechanically cooled cryogenic radiometer at laser lines.
NPL reference detectors:
Two NPL reference trap detectors
Additional working standards: single elements photodiodes.

Experimental set-up:
Double-grating monochromator with two types of gratings (UV and Vis-NIR), second-order filters at the entrance;
Additional monitor detector at the output;
Sources: Argon arc and tungsten strip lamp;
Bandwidth: 5.5 nm;
Spot size: 1 mm x 2 mm (f / 10).

Interpolation / extrapolation:
interpolation by curve fitting in the range 450 nm to 900 nm;
extrapolation with a cavity pyroelectric detector for 300 nm to 400 nm and 950 nm to 1000 nm.

The KC detectors were calibrated by comparison with the NPL reference trap detectors in the range 450 nm to 900 nm. They were calibrated for relative spectral response in the 300 nm to 400 nm region using the cavity pyroelectric detector and then linked to the trap-based measurements.
A similar procedure was used in the wavelength range 950 nm to 1000 nm for the KC photodiodes, but the KC traps had to be calibrated against two NPL photodiodes calibrated for spectral responsivity as described above.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 17.

NPL	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R11	R17	F10	F39	Rel Std Dev	R11	R17	F10	F39
300	0.241453	0.241189	0.241118	0.240879	9.8E-04	0.146	0.164	0.151	0.158
320	0.250219	0.250131	0.250155	0.250085	2.2E-04	0.162	0.153	0.153	0.142
340	0.263165	0.263130	0.262992	0.262722	7.7E-04	0.167	0.149	0.151	0.150
360	0.275721	0.275392	0.275580	0.275611	5.0E-04	0.145	0.155	0.147	0.137
380	0.292192	0.292138	0.292060	0.291821	5.6E-04	0.145	0.145	0.137	0.137
400	0.312724	0.312802	0.312735	0.312454	4.9E-04	0.143	0.153	0.145	0.144
450	0.357789	0.357747	0.357404	0.357348	6.4E-04	0.057	0.057	0.060	0.060
500	0.399843	0.399787	0.399439	0.399394	5.8E-04	0.057	0.057	0.058	0.058
550	0.440990	0.440937	0.440640	0.440586	4.6E-04	0.057	0.057	0.057	0.058
600	0.481785	0.481715	0.481470	0.481419	3.7E-04	0.057	0.057	0.057	0.058
650	0.522296	0.522213	0.521960	0.521934	3.5E-04	0.057	0.057	0.057	0.058
700	0.562684	0.562594	0.562373	0.562316	3.1E-04	0.057	0.057	0.057	0.057
750	0.603026	0.602922	0.602772	0.602721	2.3E-04	0.057	0.057	0.056	0.057
800	0.643333	0.643212	0.643038	0.642987	2.5E-04	0.058	0.057	0.057	0.058
850	0.683562	0.683417	0.683393	0.683311	1.5E-04	0.058	0.057	0.057	0.058
900	0.723738	0.723565	0.723431	0.723405	2.1E-04	0.058	0.057	0.057	0.058
950	0.760348	0.760082	0.759885	0.759848	3.0E-04	0.133	0.133	0.132	0.132
1000	0.734575	0.733319	0.732779	0.732953	1.1E-03	0.174	0.174	0.172	0.172

Table 17 – NPL: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NPL's uncertainty and transfer.

		Wavelength / nm	**300 nm – 400 nm**	**450 nm – 900 nm**	**950 nm – 1000 nm**
Primary reference: mechanically cooled cryogenic radiometer calibration of NPL reference trap detectors at a set of laser lines				0.011	
Transfer to KC detectors	**Interpolation – extrapolation** by curve fitting			0.050	
	DVM linearity, amplifier gains, wavelength error			0.018	
	Extrapolation using a cavity pyroelectric detector, stray light, chopper stability, ..		0.11		0.11
	Responsivity at normalizing point, DVM linearity, amplifier gains, wavelength error, chopper stability, …		0.065		0.063
	Repeatability for KC trap detectors (standard deviation)		0.025 – 0.1	0.002 – 0.008	0.002 – 0.009
	Repeatability for KC single photodiodes (standard deviation)		0.025 – 0.06	0.001 – 0.014	0.02 – 0.028
	Calibration of KC transfer detectors (typical values)		**0.13**	**0.055**	**0.13**

Table 18 – Summary of the NPL uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.7. NRC

Primary reference:

cryogenic radiometer used in conjunction with a monochromator-based facility, covering the full range of the comparison (300 nm to 1000 nm).

NRC reference detectors:

- TRX type, including a single photodiode
- CTX type, including a three-element trap detector

The NRC reference detectors are calibrated under vacuum directly against the cryogenic radiometer using a double monochromator with a Xe source in the UV or a QTH source in the Vis and NIR.

The transfer to the KC detectors is performed by comparison, using a different facility:

Single monochromator with a Xe source in the range 300 nm to 400 nm or a QTH source in the range 450 nm to 1000 nm;
Bandwidth: 5 nm;
Spot size: 1.5 mm x 3 mm (f / 14);
Optical power: 1.5 µW to 15 µW.

Apertures of 6 mm in diameter were placed in front of the KC detectors to match the 6 mm limiting apertures of the NRC reference detectors.
The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 19.

NRC	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R18	R20	F05	F08	Rel Std Dev	R18	R20	F05	F08
300	0.241444	0.241238	0.240667	0.240796	1.5E-03	0.084	0.090	0.148	0.159
320	0.249907	0.249706	0.249541	0.249651	6.1E-04	0.086	0.090	0.085	0.109
340	0.262669	0.262459	0.262432	0.262524	4.0E-04	0.072	0.076	0.077	0.104
360	0.275135	0.274968	0.275229	0.275329	5.6E-04	0.066	0.070	0.073	0.095
380	0.291695	0.291503	0.291208	0.291332	7.3E-04	0.069	0.072	0.129	0.145
400	0.312160	0.311975	0.311854	0.311972	4.1E-04	0.057	0.061	0.081	0.092
450	0.357457	0.357206	0.357100	0.357034	5.2E-04	0.047	0.051	0.052	0.052
500	0.399691	0.399433	0.399399	0.399387	3.6E-04	0.042	0.046	0.044	0.044
550	0.440851	0.440560	0.440640	0.440630	2.9E-04	0.042	0.045	0.042	0.042
600	0.481539	0.481224	0.481313	0.481339	2.8E-04	0.040	0.043	0.040	0.040
650	0.521991	0.521674	0.521848	0.521813	2.5E-04	0.040	0.042	0.039	0.040
700	0.562353	0.562028	0.562207	0.562172	2.4E-04	0.039	0.042	0.038	0.038
750	0.602862	0.602494	0.602580	0.602677	2.6E-04	0.039	0.042	0.040	0.039
800	0.643228	0.642840	0.642980	0.643075	2.5E-04	0.053	0.055	0.053	0.053
850	0.683674	0.683274	0.683460	0.683598	2.6E-04	0.052	0.054	0.052	0.052
900	0.723452	0.723052	0.723431	0.723484	2.8E-04	0.045	0.047	0.046	0.046
950	0.759785	0.759363	0.759576	0.759794	2.7E-04	0.048	0.049	0.042	0.042
1000	0.734078	0.733517	0.731886	0.731438	1.7E-03	0.207	0.207	0.192	0.192

Table 19 – NRC: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NRC's uncertainty and transfer.

Two transfer detectors, R20 and F08, showed relative changes in responsivity in the UV significantly larger than usually observed: -1.3 x 10^{-3} and + 1.2 x 10^{-3} respectively. However, as the changes are of about the same amplitude with opposite signs, the overall average value is very similar to that obtained without the contribution of these two detectors.

Wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
Primary reference: cryogenic radiometer and calibration of electronic equipment	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**	**0.020**
NRC reference trap & single diode: repeatability	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.03	0.02	0.02
NRC reference trap (CTX): wavelength calibration and bandwidth effects	0.033	0.047	0.035	0.034	0.040	0.027	0.029	0.021	0.018	0.016	0.016	0.016	0.014	0.013	0.014	0.010	0.015	0.071
NRC reference single diode (TRX): wavelength calibration and bandwidth effects	0.116	0.035	0.020	0.041	0.109	0.054	0.036	0.025	0.021	0.018	0.017	0.016	0.016	0.014	0.012	0.011	0.007	0.045
NRC reference trap (CTX): combined uncertainty	**0.049**	**0.059**	**0.051**	**0.049**	**0.054**	**0.045**	**0.041**	**0.035**	**0.034**	**0.033**	**0.033**	**0.032**	**0.032**	**0.047**	**0.047**	**0.038**	**0.032**	**0.076**
NRC reference single diode (TRX): combined uncertainty	**0.122**	**0.050**	**0.041**	**0.055**	**0.114**	**0.065**	**0.046**	**0.038**	**0.035**	**0.034**	**0.033**	**0.032**	**0.032**	**0.047**	**0.046**	**0.038**	**0.029**	**0.053**
Transfer NRC references to KC detectors																		
temperature variations, photocurrent measurement	0.013	0.010	0.010	0.019	0.018	0.017	0.013	0.012	0.011	0.011	0.011	0.010	0.011	0.010	0.010	0.010	0.013	0.128
trap detectors: repeatability	0.009	0.007	0.008	0.006	0.006	0.005	0.004	0.003	0.01	0.003	0.003	0.003	0.005	0.009	0.007	0.014	0.016	0.083
Single diode F05: repeatability	0.044	0.041	0.040	0.017	0.042	0.031	0.006	0.005	0.011	0.006	0.005	0.005	0.011	0.014	0.008	0.014	0.014	0.055
Combined uncertainty for KC trap detectors	**0.051**	**0.06**	**0.052**	**0.053**	**0.057**	**0.049**	**0.043**	**0.037**	**0.037**	**0.035**	**0.035**	**0.034**	**0.034**	**0.049**	**0.048**	**0.041**	**0.039**	**0.171**
Combined uncertainty for KC F05	**0.130**	**0.065**	**0.059**	**0.061**	**0.123**	**0.074**	**0.048**	**0.04**	**0.038**	**0.036**	**0.035**	**0.034**	**0.036**	**0.05**	**0.048**	**0.042**	**0.035**	**0.149**

Table 20 – Summary of the NRC uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.8. OMH

Primary reference:

Group of QED200 trap detectors, having a calculable spectral responsivity in the range 420 nm – 650 nm.

OMH reference detectors: group of trap detectors.

Interpolation / extrapolation using models in the range 420 nm to 940 nm.

Outside this range (300 nm to 400 nm and 950nm to 1000 nm), measurements are based on detectors calibrated by another laboratory.

Experimental set-up:

Double-grating monochromator with filter-wheel and parabolic mirror at the output;
Bandwidth: from 3.3 nm in the UV to 5.2 nm in the infrared.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 21.

OMH	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R01	R14	F34	F47	Rel Std Dev	R01	R14	F34	F47
300	0.237819	0.238065	0.239182	0.238885	2.7E-03	1.207	1.144	1.339	1.263
320	0.249330	0.249610	0.249757	0.249563	7.1E-04	0.946	0.964	1.109	0.989
340	0.263816	0.264057	0.263834	0.263677	6.0E-04	0.818	0.828	0.990	0.841
360	0.277105	0.277179	0.276520	0.276177	1.7E-03	0.810	0.813	0.834	0.828
380	0.291172	0.291169	0.292377	0.292126	2.2E-03	0.718	0.721	0.722	0.721
400	0.313512	0.313546	0.314151	0.314078	1.1E-03	0.520	0.522	0.533	0.524
450	0.357417	0.357524	0.357688	0.357667	3.6E-04	0.316	0.322	0.312	0.317
500	0.399359	0.399447	0.399477	0.399485	1.4E-04	0.309	0.313	0.313	0.311
550	0.440511	0.440627	0.440654	0.440669	1.6E-04	0.309	0.313	0.311	0.312
600	0.481575	0.481552	0.481358	0.481484	2.0E-04	0.313	0.319	0.311	0.316
650	0.522236	0.522399	0.522082	0.521990	3.4E-04	0.313	0.316	0.311	0.315
700	0.562634	0.562770	0.562591	0.562650	1.4E-04	0.361	0.363	0.359	0.362
750	0.602953	0.603089	0.603018	0.603068	1.0E-04	0.397	0.405	0.396	0.406
800	0.643100	0.643350	0.643387	0.643375	2.1E-04	0.464	0.483	0.447	0.457
850	0.683463	0.683601	0.683860	0.683899	3.1E-04	0.476	0.486	0.480	0.488
900	0.723718	0.723978	0.724102	0.723814	2.4E-04	0.538	0.557	0.531	0.530
950	0.759820	0.760060	0.760781	0.760245	5.4E-04	1.320	1.322	1.338	1.321
1000	0.732903	0.733459	0.735852	0.734985	1.8E-03	0.913	0.915	0.930	0.905

Table 21 – OMH: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including OMH's uncertainty and transfer.

Wavelength / nm	**300 - 350**	**350 - 400**	**420 - 650**	**660 - 940**	**950 - 1000**
Primary reference (NIST calibrated detector)	0.80 – 1.05	0.50 – 0.80			0.85 – 1.3
Long-term stability of reference (NIST calibrated detector)	0.02 – 0.4	0.10 – 0.20			0.20
OMH primary reference: OMH QED group			0.17 – 0.22	0.17 – 0.22	
Calibration of OMH transfer trap detectors			0.18 – 0.28	0.23 – 0.49	
Calibration of KC detectors: repeatability	0.13 – 0.80	0.06 – 0.21	0.05 – 0.10	0.07 – 0.23	0.20 – 0.33
Calibration of KC detectors : stray light, wavelength, electrical current measurements, bandwidth effects	0.19	0.07 – 0.09	0.07	0.07	0.10 – 0.16
Calibration of KC detectors: combined standard uncertainty	**0.86 – 1.38**	**0.52 – 0.86**	**0.27 – 0.38**	**0.35 – 0.58**	**0.9 – 1.34**

Table 22 – Summary of the OMH uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.9. PTB

Primary references:

Laser-based cryogenic radiometer for wavelengths equal to or above 400 nm and monochromator-based cryogenic radiometer operated with dispersed synchrotron radiation.

PTB reference detectors:

A set of trap detectors calibrated and used in the visible and near-infrared,
another set of trap detectors calibrated and used at wavelengths shorter than 400 nm.

Interpolation / extrapolation:

In the visible and near-infrared a physical model is used for spectral interpolation;
In the UV the interpolation and/or extrapolation is achieved by calibration against the cryogenic radiometer operated with dispersed synchrotron radiation.

Experimental set-up:

Double monochromator equipped with four sets of gratings;
QTH source, order-sorting filters and shutter at the entrance;
Bandwidth: 3.4 nm (300 nm to 700 nm range) and 6.9 nm (750 nm to 1000 nm range).
Sources for laser-based calibrations: Kr and Ar lasers, and a continuously tunable Ti:sapphire laser.

The KC detectors were calibrated by comparison with the PTB reference detectors using the monochromator-based facility. The calibration is calculated as the average value of the results obtained for two orthogonal orientations of the KC detectors about the beam axis, in order to cancel beam polarization effects. In addition, the KC trap detectors were calibrated with laser radiation against four PTB reference trap detectors. The spectral responsivity of the KC trap detectors was then calculated by interpolation using the physical model. In the wavelength range 400 nm to 1000 nm, the weighted mean of the results of the monochromator-based calibrations against both sets of PTB reference detectors and of the laser-based calibration was calculated.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 23.

In the data published in Draft A, the results obtained at the PTB from the transfer detector R13 were found to be significantly inconsistent with those obtained from the other three detectors.
Tests and checks were performed at the PTB and at the BIPM [4] confirming an abnormal behaviour of this detector during its stay at the PTB.
However, R13 did not show instabilities after its return to the BIPM, nor during its subsequent use in other laboratories. The most probable explanation is a contamination (perhaps by a dust particle) of the inner photodiodes during the transport to the PTB. It is likely that the particle fell out during the return transport, because the return measurements at the BIPM showed no abnormal change in responsivity.
The PTB proposed therefore to discard the results obtained with REF13 and to use only REF10 (and the two single photodiodes) for the transfer of the PTB calibrations to the BIPM reference detector.
This proposal was discussed by the WG on K2.b and accepted by the WG and the K2.b participants.
For the determination of the reference value, the average of the three remaining detectors was calculated as follows:

$$x_{PTB} = \frac{1}{2}\left(C_{R10} + \frac{C_{F09} + C_{F24}}{2} \right)$$

The PTB also sent to the pilot laboratory a refined version of its uncertainty budget, but as it was transmitted after publication of Draft A, the CCPR-WG-KC did not accept the PTB proposal to use it in the final report. However, the WG-KC asked the pilot to include this revised uncertainty budget in the Appendix (see section 8.2).

PTB	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R10	R13	F09	F24	Rel Std Dev	R10	R13	F09	F24
300	0.240974	*0.240507*	0.240065	0.240061	1.8E-03	0.171	*0.171*	0.207	0.206
320	0.249752	*0.249342*	0.249050	0.249083	1.3E-03	0.147	*0.148*	0.169	0.168
340	0.262726	*0.262319*	0.262116	0.262143	1.1E-03	0.100	*0.100*	0.131	0.130
360	0.275552	*0.275117*	0.275180	0.275199	7.1E-04	0.077	*0.076*	0.112	0.109
380	0.292008	*0.291599*	0.291634	0.291667	6.5E-04	0.129	*0.129*	0.143	0.142
400	0.312676	*0.312328*	0.312374	0.312403	5.0E-04	0.067	*0.071*	0.084	0.083
450	0.357353	*0.356935*	0.356809	0.356828	7.1E-04	0.050	*0.059*	0.068	0.067
500	0.399585	*0.399118*	0.399130	0.399142	5.7E-04	0.024	*0.024*	0.029	0.028
550	0.440752	*0.440270*	0.440347	0.440352	5.0E-04	0.021	*0.021*	0.024	0.023
600	0.481493	*0.481154*	0.481122	0.481125	3.7E-04	0.022	*0.023*	0.025	0.024
650	0.521996	*0.521718*	0.521685	0.521680	2.9E-04	0.021	*0.021*	0.023	0.023
700	0.562377	*0.562128*	0.562067	0.562048	2.7E-04	0.021	*0.021*	0.023	0.023
750	0.602677	*0.602409*	0.602358	0.602381	2.5E-04	0.021	*0.021*	0.023	0.022
800	0.642894	*0.642621*	0.642626	0.642665	2.0E-04	0.021	*0.021*	0.022	0.022
850	0.683119	*0.682752*	0.682911	0.682889	2.2E-04	0.022	*0.022*	0.025	0.025
900	0.723205	*0.722859*	0.723058	0.722795	2.6E-04	0.022	*0.022*	0.026	0.027
950	0.759796	*0.759424*	0.759467	0.759420	2.4E-04	0.032	*0.032*	0.032	0.033
1000	0.733906	*0.732685*	0.731882	0.731994	1.3E-03	0.133	*0.131*	0.152	0.152

Table 23 – PTB: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including PTB's uncertainty and transfer. The results obtained from REF 13 have been discarded (see text).

Primary reference: Cryogenic radiometers	Wavelength (range) / nm	**257**	**334**	**351, 356**	**407**	**476 - 900**	**950**	**1000**
Calibration of the PTB reference detectors using laser sources		**0.096**	**0.060**	**0.045**	**0.016**	**0.010**	**0.011**	**0.019**

Calibration of the PTB reference detectors	**300**	**320**	**340**	**360**	**380**	**400**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Interpolation between laser lines with a physical model							0.136	0.061	0.018	0.011	0.014	0.011	0.012	0.012	0.012	0.013	0.014	0.017	0.027
Interpolation and extrapolation with a cryogenic radiometer	0.148	0.127	0.077	0.053	0.118	0.071													
Monochromator-based transfer to the KC detectors																			
Repeatability	0.026	0.011	0.008	0.007	0.006	0.008	0.008	0.006	0.007	0.005	0.007	0.005	0.006	0.004	0.006	0.005	0.005	0.005	0.004
Wavelength	0.013	0.002	0.001	0.001	0.011	0.007	0.006	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.037
Temperature, bandwidth, polarization, stray light, uniformity	0.051	0.044	0.040	0.040	0.029	0.017	0.017	0.009	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.007	0.057
Combined	**0.160**	**0.135**	**0.087**	**0.067**	**0.123**	**0.073**	**0.138**	**0.062**	**0.020**	**0.013**	**0.017**	**0.014**	**0.015**	**0.014**	**0.014**	**0.015**	**0.016**	**0.020**	**0.073**

Transfer to KC traps using laser sources	wavelength (range) / nm	**407**	**476 - 799**	**850**	**900**	**950**	**1000**
Uncertainty		**0.018**	**0.010**	**0.011**	**0.010**	**0.013**	**0.028**

Source of uncertainty	wavelength / nm	400	450	500	550	600	650	700	750	800	850	900	950	1000
Interpolation between laser lines with a physical model for KC trap REF10		0.116	0.053	0.016	0.011	0.014	0.011	0.012	0.012	0.013	0.014	0.014	0.017	0.055

Combined uncertainty	wavelength / nm	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
KC traps		**0.158**	**0.134**	**0.087**	**0.066**	**0.123**	**0.06**	**0.046**	**0.015**	**0.01**	**0.012**	**0.01**	**0.011**	**0.011**	**0.011**	**0.012**	**0.013**	**0.015**	**0.04**
KC single photodiodes		**0.19**	**0.155**	**0.114**	**0.096**	**0.134**	**0.074**	**0.063**	**0.02**	**0.015**	**0.017**	**0.015**	**0.015**	**0.015**	**0.015**	**0.016**	**0.017**	**0.021**	**0.065**

Table 24 – Summary of the PTB uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.10. BNM-INM

Primary reference: cryogenic radiometer at five laser wavelengths in the visible.

BNM-INM reference detectors: QED-150 trap detector (calibrated against the cryogenic radiometer) and large-area trap detector.

Interpolation / extrapolation using a pyroelectric detector. The reference trap detector is then used either as an absolute reference or as a relative spectral reference.

Experimental set-up:

Double prism-grating monochromator with a Hg-Xe source. Field aperture placed close to the source, imaged onto the detectors at the output;
Spot size: 3 mm
Bandwidth: 2.08 nm to 6.25 nm, depending on the wavelength range
Optical power: 2 µW to 15 µW.

Transfer to the KC single-element detectors by direct comparison with the BNM-INM large-area reference trap detector.
Transfer to the KC trap detectors at five laser lines first and then extrapolation using the large area trap detector as reference of relative spectral responsivity.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors, and the corresponding uncertainties are given in Table 25.

BNM-INM	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R10	R13	F09	F24	Rel Std Dev	R10	R13	F09	F24
300	0.241406	0.241348	0.241967	0.241814	1.3E-03	0.232	0.234	0.236	0.240
320	0.250528	0.250752	0.250989	0.250825	7.6E-04	0.153	0.157	0.154	0.157
340	0.263362	0.263468	0.263901	0.263770	9.6E-04	0.137	0.140	0.137	0.138
360	0.274933	0.274935	0.275629	0.275469	1.3E-03	0.168	0.169	0.166	0.166
380	0.292640	0.292714	0.293134	0.292905	7.5E-04	0.128	0.130	0.125	0.123
400	0.312675	0.312710	0.313761	0.313464	1.7E-03	0.135	0.142	0.136	0.137
450	0.357717	0.357712	0.358845	0.358758	1.8E-03	0.117	0.126	0.119	0.117
500	0.399642	0.399576	0.400915	0.400717	1.8E-03	0.117	0.122	0.116	0.117
550	0.441167	0.441128	0.443007	0.442755	2.3E-03	0.221	0.224	0.220	0.219
600	0.481490	0.481399	0.483155	0.483050	2.0E-03	0.123	0.130	0.120	0.121
650	0.520713	0.520577	0.522053	0.522042	1.6E-03	0.112	0.119	0.109	0.110
700	0.561001	0.560862	0.562278	0.562512	1.5E-03	0.097	0.106	0.095	0.094
750	0.601560	0.601589	0.602857	0.602675	1.1E-03	0.094	0.097	0.090	0.090
800	0.642236	0.641946	0.643482	0.643808	1.4E-03	0.116	0.122	0.112	0.112
850	0.681141	0.681121	0.683574	0.683352	2.0E-03	0.130	0.137	0.127	0.131
900	0.721787	0.721399	0.724518	0.723729	2.1E-03	0.090	0.096	0.088	0.090
950	0.758494	0.758949	0.763003	0.762500	3.1E-03	0.102	0.108	0.096	0.097
1000	0.739059	0.737622	0.743998	0.745065	4.9E-03	0.192	0.194	0.190	0.186

Table 25 – BNM-INM: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including BNM-INM's uncertainty and transfer.

Primary reference: cryogenic radiometer at five wavelengths in the visible.

	300 nm – 1000 nm
	100 x standard uncertainty
Transfer cryogenic radiometer to BNM-INM reference trap detector and interpolation and extrapolation using a pyroelectric detector. Standard uncertainty on absolute responsivity of reference trap:	0.022 – 0.081
Transfer BNM-INM reference trap to KC single elements detectors:	
Repeatability (standard deviation)	0.01 – 0.05
Wavelength setting, bandwidth effects, stray light, photocurrent measurement	0.03
Combined standard uncertainty for KC single element detectors	**0.22 – 0.08**
Transfer BNM-INM reference trap to KC trap detectors of **relative** spectral responsivity:	
Uncertainty on the relative spectral responsivity of reference trap	0.021 – 0.08
Repeatability (standard deviation)	0.01 – 0.05
Bandwidth effects, stray light, photocurrent measurement	0.024
Calibration at five laser wavelengths	0.024 – 0.027
Connection between relative and absolute measurements	0.036 – 0.051
Combined standard uncertainty for KC trap detectors	**0.22 – 0.09**

Wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
100 x combined uncertainty for KC single elements	0.22	0.13	0.12	0.15	0.11	0.13	0.11	0.11	0.22	0.12	0.11	0.09	0.09	0.11	0.13	0.09	0.09	0.10
100 x combined uncertainty for KC traps	0.22	0.13	0.12	0.16	0.12	0.13	0.12	0.11	0.22	0.12	0.11	0.09	0.09	0.11	0.13	0.09	0.10	0.11

Table 26 – Summary of the BNM-INM uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.11. CSIR – NML

Primary reference: cryogenic radiometer at four laser lines in the range 488 nm to 633 nm.

CSIR reference detector: silicon photodiode.

Interpolation / extrapolation using a pyroelectric detector.

Experimental set-up:

Double-grating monochromator with a QTH source, order-sorting filters at the input
Spot size: 2 mm (f / 2.5) and 4.5 mm (f / 7.5), depending on KC detector
Bandwidth: 2.9 nm to 7.2 nm, depending on gratings used and wavelength range.

Transfer to the KC single element detectors by comparison with the CSIR reference detector, using 2 mm and 4.5 mm spot sizes.
Transfer to the KC trap detectors by comparison with the CSIR reference detector, using the 4.5 mm (f / 7.5) spot.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 27.

CSIR	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R04	R15	F18	F43	Rel Std Dev	R04	R15	F18	F43
300									
320									
340									
360									
380									
400	0.321200	0.315508	0.317610	0.317709	7.4E-03	2.70	2.70	2.70	2.70
450	0.359704	0.360442	0.361295	0.361423	2.2E-03	1.50	1.50	1.50	1.50
500	0.403173	0.402843	0.403226	0.403111	4.2E-04	0.90	0.90	1.00	1.00
550	0.444587	0.443971	0.445272	0.444885	1.2E-03	1.00	1.00	1.00	1.00
600	0.483424	0.484018	0.484962	0.484290	1.3E-03	1.10	1.10	1.10	1.10
650	0.518687	0.519487	0.520764	0.520127	1.7E-03	1.00	1.00	1.00	1.00
700	0.564979	0.564283	0.567622	0.565500	2.5E-03	1.20	1.10	1.10	1.10
750	0.605054	0.605366	0.607353	0.607814	2.3E-03	0.80	0.80	0.80	0.80
800	0.645192	0.645199	0.647106	0.647711	2.0E-03	0.80	0.80	0.80	0.80
850	0.687211	0.687622	0.689553	0.690034	2.0E-03	0.80	0.80	0.80	0.80
900	0.725542	0.725778	0.728239	0.728931	2.4E-03	0.80	0.80	0.80	0.80
950	0.761381	0.761764	0.764474	0.765195	2.5E-03	0.90	0.90	0.90	1.00
1000	0.735891	0.735764	0.738537	0.739110	2.4E-03	1.21	1.21	1.21	1.21

Table 27 – CSIR: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including CSIR's uncertainty and transfer.

Laser lines / nm	488	515	543	633
Primary reference: cryogenic radiometer 100 x standard uncertainty	0.56	0.56	0.56	0.56

Calibration of CSIR reference detector (single element)	
Transfer from cryogenic radiometer	0.56
Interpolation – extrapolation using a pyroelectric detector	
Reference detector: uniformity, linearity, polarisation effects, electrical calibrations, temperature effects Pyroelectric detector: stability, window transmission, linearity, flatness of response, wavelength calibration	0.48 – 2.6
Combined uncertainty for CSIR reference detector	**0.74 – 2.67**
Transfer CSIR reference detector to KC single element detectors	
Reference detector: uniformity, linearity, polarisation effects, electrical calibrations, temperature effects	0.03
Repeatability, stability of source, wavelength calibration, alignment, stray light, bandwidth effects	0.28 – 0.60
KC detectors: uniformity, linearity, polarisation effects, electrical calibrations, temperature effects	0.03
Combined uncertainty for KC single element detectors	**0.79 – 2.70**
Transfer CSIR reference detector to KC trap detectors	
Reference detector: uniformity, linearity, polarisation effects, electrical calibrations, temperature effects	0.03
Repeatability, stability of source, wavelength calibration, alignment, stray light, bandwidth effects	0.24 – 0.63
KC detectors: uniformity, linearity, electrical calibrations; polarisation, temperature, vignetting effects	0.12
Combined uncertainty for KC trap detectors	**0.78 – 2.70**

wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
100 x combined uncertainty for KC single elements						2.7	1.5	1	1	1.1	1	1.1	0.8	0.8	0.8	0.8	1	1.2
100 x combined uncertainty for KC traps						2.7	1.5	0.9	1	1.1	1	1.1	0.8	0.8	0.8	0.8	0.9	1.2

Table 28 – Summary of the CSIR uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.12. NMi-VSL

Primary reference:

Cryogenic radiometer used in conjunction with a monochromator-based facility, covering the full range of the comparison (300 nm to 1000 nm).

NMi-VSL reference detectors:

Set of three Si reflection trap detectors. The NMi reference detectors are calibrated under vacuum directly against the cryogenic radiometer using a double monochromator with a Xe source in the UV or a QTH source in the Vis and NIR.

Experimental set-up:

Double monochromator in subtractive mode, with order sorting filters and shutter at the output.
The circular output of the monochromator is imaged onto the detectors by spherical mirrors.
Bandwidth: 5 nm;
Spot size: 4.5 mm in diameter (f / 8).

The transfer to the KC detectors is performed by comparison with the NMi reference detectors, using the same facility: a bending mirror redirects the output beam to a secondary translation stage.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 29.

NMi-VSL	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R02	R03	F31	F14	Rel Std Dev	R02	R03	F31	F14
300	0.241160	0.241189	0.240601	0.240665	1.3E-03	0.123	0.123	0.269	0.249
320	0.250081	0.250140	0.249597	0.249644	1.1E-03	0.127	0.128	0.166	0.163
340	0.262721	0.262768	0.262118	0.262198	1.3E-03	0.108	0.108	0.139	0.153
360	0.275162	0.275197	0.274671	0.274765	9.8E-04	0.124	0.124	0.171	0.184
380	0.291736	0.291773	0.291307	0.291346	8.5E-04	0.110	0.110	0.164	0.176
400	0.312574	0.312555	0.312282	0.312250	5.5E-04	0.047	0.047	0.074	0.089
450	0.357699	0.357667	0.357329	0.357269	6.2E-04	0.034	0.034	0.058	0.066
500	0.399829	0.399804	0.399507	0.399462	4.8E-04	0.034	0.034	0.067	0.051
550	0.441001	0.440951	0.440768	0.440714	3.2E-04	0.033	0.033	0.061	0.047
600	0.481664	0.481621	0.481470	0.481413	2.5E-04	0.033	0.033	0.055	0.045
650	0.522198	0.522155	0.522014	0.521976	2.1E-04	0.033	0.033	0.050	0.043
700	0.562609	0.562551	0.562428	0.562374	1.9E-04	0.033	0.033	0.047	0.041
750	0.603012	0.602930	0.602809	0.602728	2.1E-04	0.033	0.033	0.046	0.040
800	0.643290	0.643202	0.643075	0.643035	1.8E-04	0.033	0.033	0.044	0.039
850	0.683468	0.683341	0.683177	0.683316	1.8E-04	0.033	0.033	0.044	0.039
900	0.723463	0.723311	0.723448	0.723313	1.1E-04	0.033	0.033	0.051	0.041
950	0.759952	0.759748	0.759897	0.760071	1.8E-04	0.049	0.049	0.087	0.059
1000	0.733546	0.733602	0.733630	0.733579	4.9E-05	0.260	0.261	0.312	0.262

Table 29 – NMi-VSL: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NMi's uncertainty and transfer.

Wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
Calibration of the NMi-VSL reference detectors	0.086	0.100	0.083	0.109	0.094	0.027	0.021	0.020	0.020	0.020	0.019	0.019	0.020	0.020	0.020	0.020	0.028	0.179
Transfer to KC traps																		
wavelength	0.007	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.047
Bandwidth, current, uniformity, stray light, temperature, linearity	0.041	0.029	0.029	0.030	0.028	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.019	0.099
Repeatability (Std dev. mean)	0.012	0.003	0.011	0.007	0.017	0.006	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.009
Combined for KC trap	0.096	0.104	0.088	0.113	0.098	0.030	0.025	0.025	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.035	0.210

Wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
Calibration of the NMi-VSL reference detectors	0.087	0.100	0.083	0.109	0.094	0.027	0.021	0.021	0.020	0.020	0.019	0.020	0.020	0.020	0.020	0.020	0.028	0.180
Transfer to KC single elements																		
wavelength	0.138	0.011	0.028	0.088	0.103	0.011	0.004	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.005	0.029
Bandwidth, current, uniformity, stray light, temperature, linearity, angle	0.168	0.104	0.106	0.106	0.093	0.074	0.058	0.041	0.036	0.034	0.032	0.029	0.026	0.025	0.024	0.027	0.042	0.114
Repeatability (Std dev. mean)	0.012	0.002	0.010	0.007	0.017	0.006	0.001	0.000	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.017
Combined for KC single detectors	0.234	0.146	0.138	0.176	0.168	0.079	0.061	0.046	0.041	0.039	0.037	0.035	0.033	0.032	0.031	0.034	0.050	0.214

Table 30 – Summary of the NMi-VSL uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.13. NMIJ – ETL

Primary reference: cryogenic radiometer at five laser lines in the range 488 nm to 647 nm

NMIJ reference detectors:

set of trap detectors, and built-in monochromator monitor detectors (Si and InGaAS)

Interpolation / extrapolation using models in the range 450 nm to 650 nm, and a thermal radiometer over the 300 nm to 1000 nm range.

Experimental set-up:

Zero-dispersion type double-grating monochromator.
Bandwidth: 5 nm

Transfer to the KC detectors by comparison with the NMIJ reference detectors.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 31.

NMIJ	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R12	R16	F07	F48	Rel Std Dev	R12	R16	F07	F48
300	0.242451	0.242514	0.243047	0.243138	1.5E-03	0.824	0.824	0.824	0.824
320	0.253374	0.253454	0.253655	0.253758	7.0E-04	0.823	0.823	0.823	0.823
340	0.264283	0.264371	0.264485	0.264614	5.4E-04	0.822	0.822	0.823	0.823
360	0.278646	0.278787	0.278958	0.279088	6.9E-04	0.822	0.822	0.822	0.822
380	0.293256	0.293387	0.293642	0.293817	8.6E-04	0.822	0.822	0.822	0.822
400	0.313541	0.313697	0.314111	0.314299	1.1E-03	0.821	0.821	0.821	0.821
450	0.358837	0.358994	0.359592	0.359689	1.2E-03	0.820	0.820	0.820	0.820
500	0.400538	0.400727	0.401360	0.401594	1.3E-03	0.820	0.820	0.820	0.820
550	0.441549	0.441732	0.442471	0.442740	1.3E-03	0.441	0.441	0.441	0.441
600	0.482156	0.482376	0.483310	0.483489	1.4E-03	0.441	0.441	0.441	0.441
650	0.522593	0.522787	0.523781	0.523988	1.3E-03	0.441	0.441	0.441	0.441
700	0.563008	0.563257	0.564361	0.564517	1.4E-03	0.441	0.441	0.441	0.441
750	0.603633	0.603875	0.605007	0.605113	1.3E-03	0.620	0.620	0.620	0.620
800	0.643928	0.644147	0.645189	0.645319	1.1E-03	0.620	0.620	0.621	0.620
850	0.683494	0.683672	0.684900	0.684820	1.1E-03	0.620	0.620	0.620	0.621
900	0.722574	0.722807	0.724308	0.724533	1.4E-03	0.620	0.620	0.620	0.620
950	0.757818	0.758023	0.759869	0.759885	1.5E-03	0.621	0.621	0.621	0.621
1000	0.731876	0.731663	0.733338	0.733894	1.5E-03	0.638	0.638	0.639	0.638

Table 31 – NMIJ: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including NMIJ's uncertainty and transfer.

Wavelength / nm	**300 nm – 400 nm**	**450 nm - 650 nm**	**700 nm - 1000 nm**
Primary reference: cryogenic radiometer at five laser wavelengths (488 nm to 647 nm)		0.05	
Interpolation / extrapolation using a spectrally flat detector: Spectral flatness, repeatability, linearity and internal transfer	0.81	0.44	0.62
Calibration of NMIJ reference detectors			
Repeatability	0.03	0.01	0.05
Polarization dependence, electrical calibrations, temperature, wavelength, bandwidth	0.009	0.009	0.009
Calibration of KC detectors			
Repeatability	0.05	0.03	0.003
Temperature, wavelength calibration, bandwidth effects, stray light	0.051	0.031	0.032
Combined uncertainty for KC detectors	**0.82**	**0.44**	**0.62**

Table 32 – Summary of the NMIJ uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.14. IEN-GF

No description of the experimental arrangement.
The full IEN uncertainty budget is given below.

Wavelength range / nm	**360**	**380**	**400**	**450 - 650**	**700 - 750**	**800 - 900**
100 x relative uncertainty						
B						
Cryogenic radiometer	0.12	0.12	0.12	0.12	0.12	0.12
Model	0.19	0.18	0.15	0.06	0.09	0.15
DVM	0.34	0.24	0.12	0.02	0.02	0.02
Wavelength calibration	0.06	0.06	0.06	0.05	0.05	0.05
Stray light	0.01	0.01	0.01	0.01	0.01	0.01
Long-term stability	0.10	0.10	0.09	0.02	0.04	0.09
Bandwidth	0.01	0.01	0.01	0.01	0.01	0.01
A						
Reproducibility	0.89	0.65	0.25	0.06	0.06	0.08
Repeatability	0.12	0.12	0.9	0.4	0.4	0.5
Combined uncertainty	**0.99**	**0.75**	**0.37**	**0.16**	**0.18**	**0.24**

Table 33 – Uncertainty budget of the IENGF. Uncertainties are expressed as 100 x standard uncertainty

IEN	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R18	R20	F05	F08	Rel Std Dev	R18	R20	F05	F08
300									
320									
340									
360	0.280406	0.281003	0.276262	0.276965	2.4E-03	1.001	1.001	1.022	1.012
380	0.296932	0.297352	0.293523	0.294062	2.0E-03	0.762	0.762	0.782	0.793
400	0.314686	0.314968	0.313198	0.313411	8.9E-04	0.402	0.392	0.423	0.414
450	0.357669	0.357759	0.358594	0.358489	4.8E-04	0.181	0.191	0.202	0.203
500	0.399234	0.399335	0.400079	0.400503	6.1E-04	0.181	0.181	0.202	0.202
550	0.440278	0.440372	0.439006	0.439479	6.6E-04	0.181	0.181	0.211	0.212
600	0.481243	0.481246	0.483214	0.483767	1.3E-03	0.191	0.182	0.211	0.212
650	0.522097	0.522003	0.524708	0.525020	1.6E-03	0.182	0.182	0.191	0.192
700	0.562810	0.562725	0.564780	0.564127	1.0E-03	0.211	0.291	0.221	0.231
750	0.603601	0.603425	0.604525	0.605202	8.3E-04	0.201	0.201	0.231	0.231
800	0.644349	0.644091	0.645365	0.645453	7.0E-04	0.261	0.261	0.271	0.271
850	0.684965	0.684715	0.684775	0.685523	3.7E-04	0.261	0.251	0.301	0.301
900	0.725625	0.725291	0.724643	0.725118	4.1E-04	0.261	0.251	0.301	0.301
950									
1000									

Table 34 – IEN: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including IEN's uncertainty and transfer.

3.15. KRISS

Primary reference:

Laser-based cryogenic radiometer.

Interpolation / extrapolation for KRISS transfer detectors:

300 nm to 380 nm: pyroelectric detector
400 nm to 700 nm: QED200
750 nm to 1000 nm: pyroelectric detector

Experimental set-up:

Double monochromator with Xe source or QTH lamps;
Shutter and order-sorting filters at the entrance;
Monitor detector at the output;
Max power: 100 µW;
Bandwidth: 1.4 nm to 3 nm, depending on wavelength
Spot size: circular, 2.5 mm in diameter imaged onto the detectors (f / 8)

Transfer to the KC detectors by comparison with the KRISS reference detectors.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 35.

KRISS	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R05	R09	F03	F16	Rel Std Dev	R05	R09	F03	F16
300	0.243065	0.242842	0.242978	0.243011	9.5E-05	0.281	0.271	0.278	0.274
320	0.251098	0.251029	0.250967	0.250883	9.1E-05	0.270	0.270	0.273	0.271
340	0.263009	0.262870	0.262820	0.262719	1.2E-04	0.268	0.268	0.262	0.270
360	0.276031	0.275966	0.276192	0.275973	1.1E-04	0.236	0.236	0.239	0.237
380	0.291674	0.291752	0.292871	0.293004	7.1E-04	0.245	0.236	0.239	0.237
400	0.314797	0.314774	0.314649	0.314626	8.6E-05	0.088	0.088	0.095	0.091
450	0.357611	0.357624	0.357498	0.357541	6.0E-05	0.074	0.083	0.077	0.075
500	0.399168	0.399179	0.399118	0.399176	2.8E-05	0.074	0.074	0.075	0.075
550	0.440456	0.440396	0.440420	0.440295	6.9E-05	0.074	0.074	0.075	0.074
600	0.481147	0.481143	0.481073	0.481077	4.0E-05	0.074	0.074	0.075	0.074
650	0.521564	0.521584	0.521514	0.521427	7.0E-05	0.074	0.074	0.075	0.074
700	0.561861	0.561861	0.561794	0.561783	4.2E-05	0.074	0.074	0.074	0.074
750	0.602368	0.602415	0.602218	0.602248	9.5E-05	0.231	0.221	0.231	0.231
800	0.642897	0.642907	0.642807	0.642830	4.9E-05	0.231	0.221	0.231	0.221
850	0.683259	0.683240	0.683213	0.683209	2.4E-05	0.231	0.231	0.232	0.231
900	0.722462	0.722557	0.722664	0.722732	1.2E-04	0.231	0.231	0.231	0.232
950	0.758804	0.758953	0.758705	0.758889	1.1E-04	0.233	0.233	0.232	0.233
1000	0.733159	0.734139	0.732854	0.733302	5.5E-04	0.280	0.282	0.282	0.280

Table 35 – KRISS: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including KRISS's uncertainty and transfer.

Source of uncertainty	100 x Standard uncertainty		
Primary reference	0.01		
Wavelength range / nm	**300 – 380**	**400 – 700**	**750 – 1000**
Interpolation and / or extrapolation Spectrally flat detector (residual wavelength dependence, uniformity, stability, …)	0.2	0.04	0.2
Calibration of the KRISS reference detectors			
Uniformity	0.005 - 0.01	0.003 - 0.005	0.003
Linearity	0.001	0.001	0.001
Polarization dependence	-	0.1	-
Vignetting effects	-	-	-
Repeatability (stability of source, alignment, ...)	0.1 - 0.15	0.03	0.1
Electrical calibrations (amplifiers, voltmeters, ...)	0.004	0.004	0.004
Temperature	0.004	0.004	0.1
Wavelength calibration	0.03	0.03	0.02
Bandwidth effects	-	-	-
Stray light	0.001	0.001	0.001
Calibration of KC transfer detectors			
Repeatability (stability of source, alignment, ...)	0.04 – 0.08	0.002 – 0.05	0.005 – 0.04
Temperature	0.001	0.001	0.001
Wavelength calibration	-	-	-
Bandwidth effects	-	-	-
Stray light	-	-	-
Other …			
Combined standard uncertainty	**0.23 – 0.27**	**0.07 –0.08**	**0.22 – 0.23**

Table 36 – Summary of the KRISS uncertainty budget.

3.16. MSL

Primary reference: cryogenic radiometer at five laser lines (458 nm to 647 nm).

MSL reference detectors: set of trap detectors.

Interpolation / extrapolation using IQE and reflectance models in the range 440 nm to 900 nm.
Extrapolation using a pyroelectric detector in the range 300 nm to 440 nm.

Experimental set-up:

- Double monochromator with a predisperser and a QTH source.
- Output beam collimated and then refocused using an off-axis parabolic mirror
- Bandwidth: 3.1 nm
- Spot size: 3 mm diameter at the detector entrance (f / 10)
- Optical power: 0.01 µW to 0.3 µW.

Transfer to the KC detectors by comparison with the MSL reference detectors.
The measurements were made at 20 nm intervals from 300 nm to 900 nm. The values at 550 nm, 650 nm, 750 nm and 850 nm were derived from a cubic spline interpolation.

After publication of Draft A, the MSL discovered a calculation error in the data transmitted to the pilot laboratory. This calculation error affected the calibration values in the range 300 nm to 400 nm.
The MSL corrected therefore the data and submitted a new set of values in this wavelength range.

However, some participants did not accept a modification of the data after circulation of Draft A, and after discussions among the participants and in the WG-K2.b, the WG did not allow the MSL to correct the data in the final report.
Although the results in the range 300 nm to 400 nm are known to be wrong, they still have to be used for the determination of the degrees of equivalence (but not included in the calculation of the reference value).

The MSL corrected data is given in the Appendix (see section 8.1), showing a much better agreement of the MSL calibrations with the reference value.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors (without correction) and the corresponding uncertainties are given in Table 37.

MSL	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R08	R19	F19	F45	Rel Std Dev	R08	R19	F19	F45
300	0.246829	0.245822	0.246138	0.246150	1.7E-03	0.583	0.583	0.610	0.574
320	0.254717	0.254740	0.254342	0.254333	8.9E-04	0.552	0.552	0.551	0.551
340	0.266777	0.266743	0.266378	0.266381	8.3E-04	0.547	0.547	0.547	0.547
360	0.278507	0.278542	0.278331	0.278254	5.0E-04	0.555	0.555	0.555	0.555
380	0.294377	0.294402	0.293864	0.293786	1.1E-03	0.556	0.556	0.556	0.556
400	0.314497	0.314517	0.314128	0.314003	8.3E-04	0.549	0.549	0.550	0.550
450	0.357626	0.357638	0.357365	0.357263	5.3E-04	0.039	0.039	0.037	0.036
500	0.399980	0.400005	0.399749	0.399642	4.4E-04	0.036	0.036	0.034	0.034
550	0.441199	0.441284	0.441041	0.440952	3.4E-04	0.039	0.039	0.046	0.044
600	0.481939	0.481971	0.481861	0.481739	2.1E-04	0.034	0.034	0.033	0.033
650	0.522469	0.522552	0.522441	0.522309	1.9E-04	0.047	0.047	0.045	0.044
700	0.562784	0.562881	0.562872	0.562699	1.5E-04	0.046	0.046	0.045	0.043
750	0.603142	0.603161	0.603173	0.602975	1.5E-04	0.055	0.055	0.054	0.053
800	0.643153	0.643230	0.643172	0.643016	1.4E-04	0.048	0.048	0.045	0.046
850	0.683008	0.683059	0.683128	0.682922	1.3E-04	0.080	0.079	0.079	0.079
900	0.722724	0.722682	0.722731	0.722803	7.0E-05	0.079	0.079	0.077	0.081
950									
1000									

Table 37 – MSL: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including MSL's uncertainty and transfer.

Primary reference: cryogenic radiometer at five laser lines 457.9 nm, 488.0 nm, 514.5 nm, 568.2 nm, 647.1 nm	100 x relative uncertainty
Calibration of MSL reference trap detectors	0.009 to 0.011

Wavelength / nm	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	950	1000
Extrapolation: pyroelectric detector including residual non-flatness, stability, bandwidth effects, ...	0.57	0.55	0.54	0.55	0.55	0.55												
Interpolation – extrapolation using models							0.02	0.02	0.04	0.02	0.04	0.04	0.05	0.04	0.08	0.06		
Stray light , bandwidth effects	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
wavelength (typical)	0.008	0.008	0.011	0.011	0.013	0.015	0.012	0.01	-	0.009	-	0.009	-	0.008	-	0.007		
I / V converters, temperature, non-linearity wavelength setting included	0.009	0.009	0.012	0.011	0.014	0.016	0.013	0.011		0.010		0.010		0.009		0.008		
Repeatability (typical values)	0.11	0.02	0.02	0.02	0.02	0.01	0.02	0.01		0.01		0.01		0.02		0.04		
Combined for the calibration of KC transfer detectors (typical)	**0.58**	**0.55**	**0.54**	**0.55**	**0.55**	**0.55**	**0.03**	**0.03**	**0.04**	**0.02**	**0.04**	**0.04**	**0.05**	**0.04**	**0.08**	**0.08**		

Table 38 – Summary of the MSL uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.17. SMU

Primary reference: QED200 trap detector, having a calculable spectral responsivity in the range 400 nm to 720 nm.

Extrapolation in the UV (300 nm to 380 nm) and NIR (750 nm to 1000 nm) using a pyroelectric detector.

Experimental set-up:

Double monochromator with a Xe source or a QTH lamp;
Bandwidth: from 3.5 nm in the UV to 5 nm in the Vis and NIR.
Spot size: 4 mm (beam divergence 6° full angle), imaged on the third inner photodiode for trap detectors.

Transfer to the KC detectors by comparison with the SMU reference detectors.

After publication of Draft A, the SMU discovered that the relatively large difference observed in the UV between their calibrations and the reference value was due to an experimental problem. The SMU values in the range 300 nm to 380 nm are therefore not used in the calculation of the KCRV.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 39.

SMU	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R01	R14	F34	F47	Rel Std Dev	R01	R14	F34	F47
300	0.237029	0.236650	0.228071	0.235529	1.8E-02	0.417	0.417	0.418	0.418
320	0.246475	0.245861	0.245193	0.245464	2.3E-03	0.358	0.358	0.357	0.357
340	0.259292	0.258663	0.258465	0.258353	1.6E-03	0.258	0.258	0.258	0.258
360	0.272256	0.271066	0.271759	0.272047	1.9E-03	0.265	0.265	0.265	0.265
380	0.289753	0.288116	0.287625	0.288038	3.3E-03	0.226	0.226	0.226	0.226
400	0.313018	0.313152	0.312136	0.311874	2.0E-03	0.174	0.174	0.175	0.175
450	0.358356	0.358544	0.357426	0.357483	1.6E-03	0.172	0.172	0.172	0.172
500	0.399760	0.400094	0.400049	0.399803	4.2E-04	0.172	0.172	0.172	0.172
550	0.441287	0.441814	0.441002	0.441546	7.9E-04	0.172	0.172	0.171	0.171
600	0.481430	0.481957	0.481715	0.481487	5.0E-04	0.152	0.152	0.152	0.152
650	0.521490	0.522315	0.522306	0.522055	7.4E-04	0.152	0.152	0.152	0.152
700	0.562488	0.562908	0.562264	0.562140	6.0E-04	0.152	0.152	0.152	0.152
750	0.602662	0.603274	0.602869	0.602586	5.1E-04	0.152	0.152	0.152	0.152
800	0.642401	0.644013	0.642475	0.642054	1.4E-03	0.152	0.152	0.152	0.152
850	0.682812	0.683932	0.682955	0.682911	7.7E-04	0.152	0.152	0.152	0.152
900	0.722459	0.723495	0.722993	0.723306	6.3E-04	0.152	0.152	0.152	0.152
950	0.758559	0.760025	0.759913	0.759234	8.9E-04	0.203	0.203	0.202	0.202
1000	0.732694	0.735011	0.733182	0.732196	1.7E-03	0.261	0.261	0.260	0.261

Table 39 – SMU: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including SMU's uncertainty and transfer.

Wavelength / nm	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Primary reference : QED 200						0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07		
Extrapolation using pyroelectric detector	0.2	0.15	0.12	0.12	0.12												0.1	0.15
Signal measurement: SMU reference detector	0.1	0.1	0.1	0.1	0.1	0.07	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.1
Signal measurement: KC detector	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Stray light	0.3	0.25	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Wavelength calibration and bandwidth effects	0.05	0.05	0.08	0.1	0.08	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.07	0.1
Repeatability (alignment)	0.15	0.15	0.15	0.15	0.12	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Combined uncertainty for KC detectors	**0.41**	**0.35**	**0.25**	**0.26**	**0.22**	**0.17**	**0.17**	**0.17**	**0.17**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.20**	**0.21**

Table 40 – Summary of the SMU uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.18. VNIIOFI

Primary reference: room temperature absolute radiometer;
QED200 trap detectors, having a calculable spectral responsivity in the visible wavelength range.

VNIIOFI reference detectors: set of S1337 photodiodes.

Extrapolation: non-selective thermo-detectors.

Experimental set-up:
Double monochromator with a tungsten source
Bandwidth: 0.24 nm to 0.5 nm with the KC single element detectors
0.9 nm to 1.8 nm with the KC trap detectors

Transfer to the KC detectors by comparison with the VNIIOFI reference detectors.

The transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in Table 41.

VNIIOFI	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R11	R17	F10	F39	Rel Std Dev	R11	R17	F10	F39
300	0.238475	0.238795	0.235778	0.237855	5.7E-03	1.003	1.004	1.004	1.502
320	0.248583	0.248697	0.246242	0.248292	4.7E-03	1.003	1.003	1.003	0.703
340	0.260890	0.261264	0.258954	0.260547	3.9E-03	1.002	1.002	1.003	0.703
360	0.274477	0.274505	0.272502	0.274306	3.5E-03	1.001	1.001	0.702	0.702
380	0.291688	0.292546	0.288448	0.291044	6.1E-03	1.001	1.001	0.703	0.702
400	0.312170	0.313513	0.309827	0.311406	4.9E-03	1.001	1.001	0.502	0.701
450	0.356398	0.358226	0.357032	0.356123	2.6E-03	0.501	0.501	0.501	0.700
500	0.399992	0.400119	0.398518	0.399231	1.9E-03	0.501	0.501	0.501	0.501
550	0.440523	0.440639	0.439899	0.439715	1.0E-03	0.501	0.501	0.501	0.501
600	0.481864	0.481884	0.480570	0.480732	1.5E-03	0.501	0.501	0.301	0.301
650	0.522623	0.522039	0.520962	0.521184	1.5E-03	0.301	0.251	0.241	0.241
700	0.562925	0.562938	0.561031	0.561752	1.7E-03	0.301	0.251	0.241	0.241
750	0.603204	0.603310	0.601549	0.601829	1.5E-03	0.301	0.251	0.241	0.241
800	0.642842	0.642955	0.641634	0.641652	1.1E-03	0.301	0.251	0.241	0.241
850	0.683139	0.683055	0.682188	0.682283	7.3E-04	0.301	0.251	0.241	0.241
900	0.723597	0.723395	0.722203	0.722737	8.8E-04	0.301	0.251	0.301	0.301
950	0.760806	0.761278	0.759704	0.759855	9.9E-04	0.302	0.252	0.501	0.501
1000	0.737524	0.738188	0.733430	0.733711	3.4E-03	0.429	0.429	0.523	0.523

Table 41 – VNIIOFI: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including VNIIOFI's uncertainty and transfer.

Absolute measurements			Relative measurements		
	A	B		A	B
Absolute radiometer	0.01	0.06	Thermo-detectors	0.03 – 0.15	0.1 – 0.3
QED200	0.05	0.1	Wavelength accuracy		0.1

	A	B
Calibration of VNIIOFI reference photodiodes	0.1 – 0.93	0.21 – 0.37
Stability		0.1
KC detectors calibration	**0.24 – 1.0**	

wavelength / nm	300	320	340	360	380	400	450	500	550	600	650	700	750	800	850	900	950	1000
uncertainty for KC single elements (typical values)	1.25	0.85	0.85	0.70	0.70	0.60	0.60	0.50	0.50	0.30	0.24	0.24	0.24	0.24	0.24	0.30	0.50	0.50
uncertainty for KC traps (typical values)	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.40

Table 42 – Summary of the VNIIOFI uncertainty budget. Uncertainties are expressed as 100 x standard uncertainty.

3.19. BIPM

Absolute calibrations at the BIPM.

Primary reference:

laser-based cryogenic radiometer, at twelve laser lines in the range 351 nm to 799 nm.

Interpolation / extrapolation: fit in the range 380 nm to 850 nm

Extrapolation of the absolute calibration at 351 nm using a pyroelectric detector in the range 300 nm to 360 nm. Same procedure between the laser line at 799 nm and the range 900 nm to 1000 nm.

The monochromator facility is the same as that described for the comparison of detectors in section 2.1.1, except that a Xe arc source was used for the measurements of relative spectral responsivity based on a pyroelectric detector in the range 300 nm to 400 nm.
The relative spectral responsivity measurements in the range 900 nm to 1000 nm were performed with the same pyroelectric detector and the QTH source.

The absolute calibration of the reference detector is given in Table 48 and the uncertainty budget is detailed in Table 43.

Source of uncertainty 100 x standard uncertainty																		
Cryogenic radiometer		λ / nm	351	364	407	413	476	488	515	568	633	647	676	753	799			
Calibration of BIPM reference trap detectors			**0.04**	**0.04**	**0.02**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.02**	**0.03**			
Interpolation and / or extrapolation	**300**	**320**	**340**	**360**	**380**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**
Spectrally flat detector: wavelength depend. , uniformity	0.2	0.2	0.2	0.2													0.2	0.2
Spectrally flat detector: wavelength calibration	0.028	0.019	0.003	0.008													0.006	0.006
Spectrally flat detector: repeatability	0.22	0.22	0.22	0.22													0.22	0.25
Model (fit)					0.1	0.08	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.1	0.2		
Contribution of CR uncertainty	0.04	0.04	0.04	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.03
Calibration of the BIPM reference detectors																		
uniformity, polarization, temperature, repeatability,..																		
Combined	**0.303**	**0.302**	**0.299**	**0.298**	**0.104**	**0.085**	**0.026**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.031**	**0.038**	**0.105**	**0.203**	**0.300**	**0.337**
Stability of reference	0.04	0.04	0.04	0.032	0.032	0.022	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.02	0.1
Calibration of KC trap detectors																		
Uniformity	0.030	0.030	0.020	0.010	0.010	0.010	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.020
Repeatability	0.012	0.012	0.011	0.009	0.008	0.006	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003	0.004	0.003	0.007	0.035
Temperature	0.003	0.000	0.000	0.001	0.002	0.003	0.002	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.008	0.085
Wavelength calibration	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.004
Polarization dependence	0.040	0.033	0.017	0.017	0.017	0.017	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.017	0.033
Calibration of KC single photodiodes																		
Uniformity	0.030	0.030	0.020	0.010	0.010	0.010	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.020
Repeatability	0.046	0.021	0.021	0.021	0.021	0.020	0.011	0.009	0.008	0.008	0.007	0.005	0.007	0.006	0.011	0.011	0.009	0.041
Temperature	0.007	0.001	0.003	0.003	0.002	0.006	0.004	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.004	0.005
Wavelength calibration	0.009	0.004	0.006	0.004	0.007	0.008	0.003	0.001	8E-04	5E-04	3E-04	2E-04	2E-04	1E-04	1E-04	6E-05	5E-04	9E-04
Combined standard uncertainty for KC trap detectors	**0.44**	**0.43**	**0.43**	**0.43**	**0.15**	**0.12**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.05**	**0.06**	**0.15**	**0.29**	**0.42**	**0.50**
Combined standard uncertainty for KC single photodiodes	**0.44**	**0.43**	**0.43**	**0.43**	**0.15**	**0.12**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.06**	**0.15**	**0.29**	**0.42**	**0.49**

Table 43 – Summary of the BIPM uncertainty budget for absolute calibrations.

4. Determination of a Key Comparison Reference value

4.1. Choice of a reference value

It is the view of the pilot laboratory that the choice of a calculation method should be based on scientific and statistical considerations.
Five different methods have been presented and discussed in Draft A and its Supplement: arithmetic mean, classical weighted mean, weighted mean with “uncertainty cut-off” or limited weights, median, median based on Monte-Carlo re-sampling.
The pilot laboratory followed the recommendation of the BIPM Director's Advisory Group on Uncertainties [5], which advised that a weighted mean should be used as reference value and the overall consistency checked with a chi-squared test. If the test fails, alternative procedures should be used.
The statistical consistency checks fail over a large part of the wavelength range with both the classical weighted mean and the weighted mean with cut-off, indicating that they should be rejected as reference values. As a consequence, the pilot laboratory proposed in Draft A either the median or the re-sampled median.

However, after the publication of Draft A more pieces of information became available:

a) Two laboratories, MSL and SMU, have discovered errors in the data they have submitted to the pilot laboratory (see section 3 for details). It is therefore reasonable to exclude from the calculation the data declared erroneous by the laboratories themselves. In that case, the consistency checks pass over most of the wavelength range, which allows the weighted mean to be used, according to the data analysis procedure described in [5].
b) The CCPR WG-KC recommended[1] that a weighted mean with cut-off be used for the calculation of the KCRV. This recommendation was also followed by the CCPR WG on K2.b [6].

As pointed out in the minutes of the WG on K2.b, an uncertainty cut-off or a limitation of the weights has no statistical justification in the present case: it will not improve the consistency nor change significantly the reference value. However, some participants insisted on limiting the weights to a maximum value to avoid giving too large a weight to any single participant in the calculation of the KCRV. The WG on K2.b finally decided that the individual weights should be limited to 20%.

The KCRV used in the present report was approved by the CCPR-K2.b participants and the by the CCPR. It is based on a weighted mean, after removal of the erroneous data, with individual weights limited to a maximum of 20%.

4.2. Calculation of the modified weighted mean

Please note that the following data were excluded from the calculations described hereafter:

- the OMH results in the ranges 300 nm to 400 nm and 950 nm to 1000 nm, for which the primary reference of this laboratory is not independent;
- the SMU results in the range 300 nm to 380 nm;
- the MSL results in the range 300 nm to 400 nm.

1 “The CCPR WG-KC recommends that Working Groups for specific comparisons use a weighted mean with cut-off for the calculation of the KCRV. They are free, however, to present arguments in favour of alternative methods to the WG-KC if there appear to be compelling reasons to do so. This recommendation will be reviewed whenever there are new guidelines on this subject from the BIPM Director’s statistical advisory group. The WG-KC reserves the right to review this position at any time in the light of new evidence and/or convergence of approaches by different CIPM Consultative Committees.”

Three values were calculated from the four results C_i (see section 2) obtained for each laboratory: the average value of the calibrations of the BIPM reference detector derived from the traps $X_{\mathrm{T}i}$, the average value derived from the single diodes $X_{\mathrm{D}i}$ and the average value derived from the four detectors X_i, where i is the *i*-th laboratory.
As the four results obtained from any one laboratory are assumed to be strongly correlated, the uncertainty associated with the average values u_{i} is calculated as the average of the corresponding uncertainties, including the uncertainty associated with the transfer.

In the classical weighted mean the weight w_i is proportional to the inverse square of the uncertainty u_i. In this modified version, an uncertainty v_i is defined at each wavelength according to:
$v_i = \max(u_i \, ; u_{\min})$ where $u_{\min}$ is a minimum uncertainty (or cut-off uncertainty).

The calculation is then the same as for the classical weighted mean:

$$w_i = \frac{\frac{1}{v_i^2}}{\sum_{j=1}^{n} \frac{1}{v_j^2}}$$ and the weighted mean $$x_w = \sum_i w_i \, x_i$$

At each wavelength, the minimum value $u_{\min}$ is first set to zero and then progressively increased until the maximum weight of any laboratory does not exceed 20 % (± 0.001%).
The $u_{\min}$ obtained by iteration and the corresponding weights are shown in Table 44.

The relative differences $\frac{(x_i - x_w)}{x_w}, \frac{(x_{Ti} - x_w)}{x_w}, \frac{(x_{Di} - x_w)}{x_w}$ are given in Table 49, Table 50 and Table 51, respectively.

4.3. Statistical checks

The overall consistency of the actual dispersion with the uncertainties is checked by means of a chi-squared test.
The observed chi-squared value is formed with:

$$\chi^2_{\mathrm{obs}} = \sum_{i=1}^{N} \frac{\left(\frac{x_i - x_w}{x_w} \right)^2}{u_i^2}$$

where N is the number of independent results.

The degrees of freedom depend on the number of independent results: $\upsilon = N - 1$
The consistency check fails if

$$\Pr \left\{ \chi^2(\upsilon) > \chi^2_{\mathrm{obs}} \right\} < 0.05$$

For the selected subset of data, Table 45 shows that the actual dispersion is consistent with the uncertainties over almost the whole wavelength range.

100 x Rel. unc. u_{min} (cut-off)	Weights obtained for the calculation of the weighted mean with limited weights																		
	λ / nm	CSIRO	NRC	IFA	NPL	HUT	OMH	SMU	NMi	NIST	NMIJ	VNIIOFI	CSIR	BNM/INM	MSL	PTB	IEN	KRISS	BIPM
0.164093	300	0.0626	0.2000	0.0112	0.2000	0.0077	0.0000	0.0000	0.1477	0.0115	0.0079	0.0042	0.0000	0.0971	0.0000	0.1511	0.0000	0.0707	0.0282
0.134187	320	0.0897	0.2000	0.0025	0.1546	0.0066	0.0000	0.0000	0.1688	0.0064	0.0053	0.0042	0.0000	0.1495	0.0000	0.1443	0.0000	0.0490	0.0192
0.117414	340	0.0979	0.2000	0.0014	0.1163	0.0054	0.0000	0.0000	0.1702	0.0031	0.0041	0.0032	0.0000	0.1447	0.0000	0.2000	0.0000	0.0387	0.0150
0.121068	360	0.1381	0.2000	0.0001	0.1377	0.0057	0.0000	0.0000	0.1294	0.0048	0.0043	0.0040	0.0000	0.1046	0.0000	0.2000	0.0029	0.0523	0.0161
0.107059	380	0.1292	0.2000	0.0019	0.1151	0.0097	0.0000	0.0000	0.1167	0.0112	0.0034	0.0032	0.0000	0.1426	0.0000	0.1243	0.0038	0.0400	0.0989
0.070336	400	0.0809	0.1871	0.0018	0.0463	0.0153	0.0000	0.0326	0.2000	0.0133	0.0015	0.0015	0.0001	0.0523	0.0000	0.1765	0.0060	0.1206	0.0642
0.039874	450	0.0388	0.1241	0.0012	0.0933	0.0094	0.0032	0.0108	0.1369	0.0137	0.0005	0.0010	0.0001	0.0222	0.2000	0.0925	0.0084	0.0532	0.1908
0.034326	500	0.0525	0.1230	0.0018	0.0712	0.0107	0.0024	0.0080	0.1083	0.0135	0.0004	0.0009	0.0003	0.0169	0.1924	0.2000	0.0064	0.0426	0.1486
0.035018	550	0.0654	0.1359	0.0021	0.0747	0.0119	0.0025	0.0083	0.1282	0.0165	0.0013	0.0010	0.0002	0.0050	0.1405	0.2000	0.0063	0.0446	0.1554
0.032671	600	0.0557	0.1285	0.0018	0.0651	0.0115	0.0022	0.0093	0.1233	0.0144	0.0011	0.0013	0.0002	0.0140	0.1909	0.2000	0.0054	0.0389	0.1364
0.034296	650	0.0594	0.1461	0.0024	0.0722	0.0110	0.0024	0.0102	0.1469	0.0159	0.0012	0.0035	0.0002	0.0185	0.1128	0.2000	0.0068	0.0429	0.1475
0.034088	700	0.0451	0.1513	0.0024	0.0715	0.0109	0.0018	0.0101	0.1537	0.0157	0.0012	0.0035	0.0002	0.0241	0.1152	0.2000	0.0041	0.0426	0.1465
0.036790	750	0.0423	0.1707	0.0023	0.0835	0.0146	0.0017	0.0118	0.1858	0.0183	0.0007	0.0040	0.0004	0.0315	0.0917	0.2000	0.0058	0.0052	0.1297
0.040423	800	0.0402	0.1154	0.0004	0.0995	0.0164	0.0015	0.0142	0.2000	0.0221	0.0008	0.0049	0.0005	0.0245	0.1484	0.2000	0.0046	0.0064	0.1000
0.048813	850	0.0545	0.1729	0.0007	0.1430	0.0248	0.0020	0.0207	0.2000	0.0321	0.0012	0.0071	0.0007	0.0277	0.0763	0.2000	0.0061	0.0089	0.0211
0.046866	900	0.0447	0.2000	0.0006	0.1328	0.0220	0.0015	0.0190	0.2000	0.0297	0.0011	0.0053	0.0007	0.0530	0.0703	0.2000	0.0057	0.0082	0.0053
0.079811	950	0.1126	0.2000	0.0018	0.0727	0.0111	0.0000	0.0310	0.2000	0.0008	0.0033	0.0084	0.0015	0.1262	0.0000	0.2000	0.0000	0.0235	0.0071
0.149980	1000	0.1624	0.1130	0.0063	0.1504	0.0027	0.0000	0.0661	0.0600	0.0058	0.0110	0.0199	0.0031	0.1243	0.0000	0.2000	0.0000	0.0570	0.0182

Table 44 - Relative uncertainty threshold u_{min} obtained by iteration (left column) to limit the individual weights to a maximum of 20 %.

λ / nm	χ^2_{obs}	υ	$\chi^2_{0.05}(\upsilon)$
300	15.8	12	21.0
320	16.3	12	21.0
340	11.7	12	21.0
360	8.0	13	22.4
380	15.2	13	22.4
400	69.7	15	25.0
450	22.6	17	27.6
500	23.6	17	27.6
550	24.3	17	27.6
600	16.9	17	27.6
650	15.4	17	27.6
700	13.1	17	27.6
750	11.0	17	27.6
800	6.9	17	27.6
850	7.9	17	27.6
900	9.7	17	27.6
950	3.9	14	23.7
1000	40.4	14	23.7

Table 45 – Chi-squared test: consistency check of the weighted mean. Grey shading indicates values that fail the consistency test.

This consistency is also confirmed by the Birge ratio [7] formed with the ratio of the external consistency to the internal consistency, as follows:

- internal consistency : $u_{\text{int}}^2 = \dfrac{1}{\sum_{i=1}^{N} u_i^{-2}}$

- external consistency: $u_{\text{ext}}^2 = \dfrac{\sum_{i=1}^{N}\left(\left(\dfrac{x_i - x_w}{x_w}\right)^2 \cdot u_i^{-2}\right)}{(N-1)\cdot\sum_{i=1}^{N} u_i^{-2}}$

- Birge ratio: $R_{\text{B}} = \dfrac{u_{\text{ext}}}{u_{\text{int}}}$

The Birge ratio for the weighted mean presented in Table 46 leads to the same result as the chi-squared test, as R_{B} is reasonably close to 1, except at 400 nm.

λ / nm	Birge ratio
300	1.14
320	1.12
340	0.96
360	0.77
380	1.08
400	2.08

450	1.15
500	1.15
550	1.16
600	0.95
650	0.93
700	0.86
750	0.76
800	0.56
850	0.64
900	0.74
950	0.51
1000	1.70

Table 46 – Birge ratio calculated for the weighted mean.

4.4. Uncertainties

a) Uncertainty of the weighted mean with limited weights
The uncertainty is calculated according to the procedure described in the Appendix 4 of the Report on CCPR-K3.b [8], for which a weighted mean with cut-off was already used.

The weights attributed to the x_i with the cut-off limit are applied to the uncertainty associated with the NMI's results u_i to calculate the combined uncertainty $u(x_w)$:

$$u^2(x_w) = \sum_i w_i^2 \cdot u_i^2 \qquad \text{that is:} \qquad u^2(x_w) = \frac{\sum_i \frac{u_i^2}{\nu_i^4}}{\left(\sum_j \frac{1}{\nu_j^2}\right)^2}$$

where $\nu_i = \max(u_i ; u_{\min})$ and $u_{\min}$ is the cut-off uncertainty.
The uncertainty $u(x_w)$ as function of wavelength is given in Table 47.

b) Uncertainty of the differences from the reference
The individual differences are: $D_i = x_i - x_w$
The uncertainty associated with D_i is then [8]:

$$u^2(D_i) = u_i^2 + u^2(x_w) - 2 \cdot w_i \cdot u_i^2$$

If no cut-off is applied ($u_i = \nu_i$), the expressions reduce to the well-known formulae:

$$u^2(x_w) = \frac{1}{\sum_i u_i^{-2}} \qquad \text{and} \qquad u^2(D_i) = u_i^2 - u^2(x_w)$$

If the x_i is excluded from the calculation of the weighted mean, w_i is equal to zero: the correlation term is null, leading to the formula for the combination of uncorrelated uncertainties.

$$u^2(D_i) = u_i^2 + u^2(x_w)$$

c) Uncertainty of the differences between pairs of laboratories
The difference between the i-th and the j-th laboratories is:

$$D_{ij} = D_i - D_j = x_i - x_j$$

It does not depend on the reference value.
The uncertainties u_i and u_j include the uncertainty of the transfer to the BIPM. The uncertainty of the transfer is in most cases small compared to the uncertainty of the calibration, and it is dominated by non-systematic effects. The correlation between u_i and u_j is therefore assumed to be negligible, and $u(D_{ij})$ is calculated as:

$$u^2(D_{ij}) = u_i^2 + u_j^2$$

It does not depend on the uncertainty of the reference value.

λ / nm	KCRV x_w / (A / W)	100 x Rel. Std. uncertainty
300	0.24122	0.069
320	0.25008	0.057
340	0.26277	0.050
360	0.27533	0.048
380	0.29192	0.048
400	0.31269	0.031
450	0.35742	0.018
500	0.39956	0.015
550	0.44071	0.015
600	0.48152	0.014
650	0.52196	0.014
700	0.56236	0.014
750	0.60272	0.015
800	0.64301	0.016
850	0.68321	0.019
900	0.72320	0.019
950	0.75980	0.028
1000	0.73382	0.066

Table 47 – The key comparison reference value, and its relative standard uncertainty.

5. Degrees of equivalence

At each wavelength, the key comparison reference value x_{KCRV} is equal to the corresponding weighted mean x_w (with weights limited to 20%), and the degree of equivalence of the i-th laboratory with respect to the reference value is given by a pair of terms, calculated as explained in 4.4.:
$D_i = (x_i - x_{KCRV})$ and U_i its expanded uncertainty (k = 2), both expressed in relative units.
$U_i = 2 \cdot u(D_i)$

The degree of equivalence between two laboratories is also given by a pair of terms:
$D_{ij} = D_i - D_j$ and U_{ij} its expanded uncertainty (k = 2), both expressed in relative units.
$U_{ij} = 2 \cdot u(D_{ij})$

The D_i and U_i can be found in Table 49, and the degrees of equivalence presented according the normalised Key Comparison Data Base[2] format are given in a separate appendix.

2 http://kcdb.bipm.org on the Internet.

λ / nm	CSIRO	NRC	IFA	NPL	HUT	OMH	SMU	NMi	NIST	NMIJ	VNIIOFI	CSIR	BNM/INM	MSL	PTB	IEN	KRISS	BIPM
300	0.241011	0.241036	0.240498	0.241160	0.242660	0.238488	0.234320	0.240904	0.241668	0.242787	0.237726		0.241634	0.246235	0.240518		0.242974	0.242696
320	0.250246	0.249701	0.248186	0.250148	0.251258	0.249565	0.245748	0.249866	0.251820	0.253560	0.247954		0.250773	0.254533	0.249410		0.250994	0.250516
340	0.262841	0.262521	0.263155	0.263002	0.264076	0.263846	0.258694	0.262451	0.264088	0.264438	0.260414		0.263625	0.266570	0.262428		0.262855	0.263101
360	0.275252	0.275165	0.273861	0.275576	0.276932	0.276745	0.271782	0.274949	0.275073	0.278870	0.273947		0.275241	0.278408	0.275371	0.278659	0.276041	0.275179
380	0.291830	0.291435	0.293413	0.292053	0.293522	0.291711	0.288383	0.291540	0.291562	0.293526	0.290932		0.292848	0.294107	0.291829	0.295467	0.292325	0.291660
400	0.312438	0.311990	0.310581	0.312679	0.313170	0.313822	0.312545	0.312415	0.312454	0.313912	0.311729	0.318007	0.313152	0.314286	0.312532	0.314066	0.314712	0.312144
450	0.356463	0.357200	0.356706	0.357572	0.357911	0.357574	0.357952	0.357491	0.358038	0.359278	0.356945	0.360716	0.358258	0.357473	0.357086	0.358128	0.357569	0.357485
500	0.398855	0.399478	0.398176	0.399616	0.399946	0.399442	0.399927	0.399650	0.400329	0.401055	0.399465	0.403088	0.400212	0.399844	0.399361	0.399788	0.399160	0.399575
550	0.439953	0.440670	0.439541	0.440788	0.440921	0.440615	0.441412	0.440858	0.441370	0.442123	0.440194	0.444679	0.442014	0.441119	0.440551	0.439784	0.440392	0.440735
600	0.481050	0.481354	0.480766	0.481597	0.481422	0.481492	0.481647	0.481542	0.482033	0.482833	0.481262	0.484174	0.482274	0.481877	0.481308	0.482368	0.481110	0.481554
650	0.521434	0.521832	0.520800	0.522101	0.521788	0.522177	0.522041	0.522086	0.522545	0.523287	0.521702	0.519766	0.521346	0.522443	0.521839	0.523457	0.521522	0.522011
700	0.562170	0.562190	0.560176	0.562492	0.561964	0.562661	0.562450	0.562491	0.562943	0.563786	0.562161	0.565596	0.561663	0.562809	0.562217	0.563611	0.561824	0.562441
750	0.602605	0.602653	0.599418	0.602860	0.602024	0.603032	0.602848	0.602870	0.603227	0.604407	0.602473	0.606397	0.602170	0.603113	0.602523	0.604188	0.602312	0.602714
800	0.642997	0.643031	0.641383	0.643142	0.641941	0.643303	0.642736	0.643150	0.643496	0.644646	0.642271	0.646302	0.642868	0.643143	0.642770	0.644815	0.642860	0.642928
850	0.682790	0.683501	0.681077	0.683421	0.682115	0.683706	0.683153	0.683325	0.683726	0.684221	0.682666	0.688605	0.682297	0.683029	0.683010	0.684995	0.683230	0.683199
900	0.722524	0.723355	0.718658	0.723535	0.721429	0.723903	0.723063	0.723384	0.724007	0.723556	0.722983	0.727123	0.722858	0.722735	0.723066	0.725169	0.722604	0.723711
950	0.759263	0.759629	0.755132	0.760041	0.759886	0.760227	0.759433	0.759917	0.758955	0.758899	0.760411	0.763203	0.760737		0.759620		0.758838	0.761072
1000	0.730632	0.732730	0.726228	0.733406	0.733078	0.734300	0.733271	0.733589	0.732618	0.732693	0.735713	0.737326	0.741436		0.732922		0.733364	0.735671
	100 x relative standard uncertainty																	
300	0.293	0.120	0.694	0.155	0.838	1.239	0.418	0.191	0.685	0.824	1.128		0.236	0.587	0.189		0.276	0.437
320	0.200	0.093	1.192	0.153	0.740	1.002	0.357	0.146	0.750	0.823	0.928		0.155	0.551	0.158		0.271	0.434
340	0.168	0.082	1.391	0.154	0.717	0.869	0.258	0.127	0.937	0.823	0.928		0.138	0.547	0.115		0.267	0.428
360	0.146	0.076	5.310	0.146	0.716	0.821	0.265	0.151	0.784	0.822	0.852		0.167	0.555	0.094	1.009	0.237	0.427
380	0.133	0.104	1.091	0.141	0.487	0.721	0.226	0.140	0.452	0.822	0.852		0.127	0.556	0.136	0.775	0.239	0.152
400	0.111	0.073	0.751	0.146	0.255	0.525	0.174	0.064	0.273	0.821	0.801	2.700	0.138	0.550	0.075	0.407	0.091	0.124
450	0.091	0.051	0.520	0.058	0.184	0.317	0.172	0.048	0.152	0.820	0.551	1.500	0.120	0.037	0.059	0.195	0.077	0.041
500	0.067	0.044	0.360	0.058	0.149	0.312	0.172	0.047	0.132	0.820	0.501	0.950	0.118	0.035	0.026	0.192	0.074	0.040
550	0.061	0.042	0.340	0.057	0.144	0.311	0.172	0.044	0.122	0.441	0.501	1.000	0.221	0.042	0.022	0.197	0.074	0.040
600	0.062	0.041	0.340	0.057	0.136	0.315	0.152	0.042	0.122	0.441	0.401	1.100	0.123	0.033	0.023	0.199	0.074	0.040
650	0.063	0.040	0.310	0.057	0.146	0.314	0.152	0.040	0.122	0.441	0.259	1.000	0.113	0.046	0.022	0.187	0.074	0.040
700	0.072	0.039	0.310	0.057	0.146	0.361	0.152	0.039	0.122	0.441	0.259	1.125	0.098	0.045	0.022	0.239	0.074	0.040
750	0.080	0.040	0.340	0.057	0.136	0.401	0.152	0.038	0.122	0.620	0.259	0.800	0.093	0.054	0.022	0.216	0.229	0.046
800	0.090	0.053	0.860	0.057	0.141	0.463	0.152	0.037	0.122	0.620	0.259	0.800	0.116	0.047	0.022	0.266	0.226	0.057
850	0.093	0.052	0.840	0.058	0.139	0.482	0.152	0.037	0.122	0.620	0.259	0.800	0.131	0.079	0.023	0.279	0.231	0.150
900	0.099	0.046	0.830	0.058	0.141	0.539	0.152	0.040	0.122	0.620	0.289	0.800	0.091	0.079	0.024	0.279	0.231	0.287
950	0.106	0.045	0.840	0.132	0.338	1.325	0.203	0.061	1.290	0.621	0.389	0.926	0.100		0.032		0.233	0.425
1000	0.166	0.200	0.848	0.173	1.295	0.916	0.261	0.274	0.882	0.639	0.476	1.210	0.190		0.143		0.281	0.497

Table 48 - Calibration in A / W of the BIPM reference by transfer from the KC detectors (average value x_i from four detectors per laboratory), and (grey table) associated uncertainties u_i (NMI's uncertainty and uncertainty associated with the transfer).

/ nm	CSIRO	NRC	IFA	NPL	HUT	OMH	SMU	NMi	NIST	NMIJ	VNIIOFI	CSIR	BNM/INM	MSL	PTB	IEN	KRISS	BIPM
300	-0.085	-0.075	-0.298	-0.024	0.598	-1.131	-2.859	-0.130	0.187	0.651	-1.447		0.173	2.080	-0.290		0.728	0.613
320	0.067	-0.150	-0.756	0.028	0.472	-0.205	-1.731	-0.085	0.697	1.393	-0.849		0.278	1.782	-0.267		0.367	0.176
340	0.025	-0.096	0.145	0.087	0.495	0.408	-1.553	-0.123	0.500	0.633	-0.898		0.324	1.444	-0.132		0.031	0.124
360	-0.029	-0.060	-0.534	0.089	0.581	0.513	-1.289	-0.139	-0.094	1.285	-0.503		-0.033	1.117	0.014	1.209	0.258	-0.055
380	-0.032	-0.168	0.510	0.044	0.547	-0.073	-1.213	-0.131	-0.124	0.549	-0.340		0.317	0.748	-0.033	1.214	0.137	-0.090
400	-0.082	-0.225	-0.676	-0.005	0.152	0.361	-0.047	-0.089	-0.076	0.390	-0.308	1.699	0.147	0.509	-0.052	0.439	0.645	-0.176
450	-0.269	-0.063	-0.201	0.042	0.136	0.042	0.148	0.019	0.172	0.519	-0.134	0.921	0.233	0.014	-0.094	0.197	0.041	0.017
500	-0.175	-0.019	-0.345	0.015	0.098	-0.028	0.093	0.024	0.194	0.375	-0.023	0.884	0.165	0.072	-0.049	0.058	-0.099	0.005
550	-0.173	-0.010	-0.266	0.017	0.047	-0.023	0.158	0.033	0.149	0.320	-0.118	0.900	0.295	0.092	-0.037	-0.211	-0.073	0.005
600	-0.097	-0.034	-0.156	0.017	-0.020	-0.005	0.027	0.005	0.107	0.273	-0.053	0.552	0.157	0.075	-0.043	0.177	-0.085	0.008
650	-0.101	-0.025	-0.223	0.026	-0.034	0.041	0.015	0.024	0.112	0.254	-0.050	-0.421	-0.118	0.092	-0.024	0.286	-0.084	0.009
700	-0.033	-0.030	-0.388	0.024	-0.070	0.054	0.016	0.024	0.104	0.254	-0.035	0.576	-0.124	0.080	-0.025	0.223	-0.095	0.015
750	-0.020	-0.012	-0.548	0.023	-0.116	0.051	0.021	0.024	0.084	0.279	-0.042	0.609	-0.092	0.065	-0.033	0.243	-0.068	-0.002
800	-0.002	0.003	-0.253	0.021	-0.166	0.046	-0.043	0.022	0.076	0.255	-0.115	0.512	-0.022	0.021	-0.037	0.281	-0.023	-0.013
850	-0.062	0.042	-0.313	0.031	-0.161	0.072	-0.009	0.017	0.075	0.148	-0.080	0.789	-0.134	-0.027	-0.030	0.261	0.003	-0.002
900	-0.093	0.022	-0.627	0.047	-0.244	0.098	-0.018	0.026	0.112	0.050	-0.029	0.543	-0.047	-0.064	-0.018	0.273	-0.082	0.071
950	-0.071	-0.023	-0.615	0.031	0.011	0.056	-0.049	0.015	-0.111	-0.119	0.080	0.448	0.123		-0.024		-0.127	0.167
1000	-0.435	-0.149	-1.035	-0.056	-0.101	0.065	-0.075	-0.032	-0.164	-0.154	0.258	0.478	1.038		-0.122		-0.062	0.252
100 x relative standard uncertainty of the difference from the KCRV																		
300	0.283	0.116	0.689	0.138	0.834	1.240	0.423	0.175	0.680	0.820	1.125		0.222	0.591	0.172		0.265	0.430
320	0.190	0.092	1.190	0.139	0.737	1.004	0.362	0.132	0.748	0.821	0.926		0.142	0.554	0.145		0.264	0.429
340	0.158	0.081	1.390	0.144	0.715	0.871	0.263	0.115	0.935	0.821	0.926		0.126	0.549	0.102		0.261	0.425
360	0.133	0.076	5.310	0.133	0.714	0.823	0.269	0.138	0.782	0.820	0.850		0.157	0.557	0.087	1.007	0.229	0.423
380	0.124	0.094	1.090	0.133	0.484	0.722	0.231	0.132	0.450	0.820	0.850		0.117	0.558	0.127	0.773	0.234	0.144
400	0.106	0.065	0.750	0.143	0.253	0.525	0.171	0.059	0.271	0.820	0.800	2.700	0.134	0.551	0.068	0.406	0.085	0.120
450	0.089	0.047	0.520	0.056	0.183	0.316	0.171	0.045	0.151	0.820	0.550	1.500	0.118	0.034	0.056	0.194	0.075	0.037
500	0.065	0.041	0.360	0.055	0.148	0.311	0.171	0.044	0.131	0.820	0.500	0.950	0.117	0.031	0.025	0.191	0.073	0.036
550	0.059	0.039	0.340	0.055	0.143	0.311	0.171	0.040	0.121	0.440	0.500	1.000	0.220	0.038	0.023	0.196	0.072	0.036
600	0.060	0.038	0.340	0.055	0.135	0.314	0.151	0.039	0.121	0.440	0.400	1.100	0.123	0.030	0.023	0.198	0.072	0.036
650	0.061	0.037	0.310	0.055	0.145	0.313	0.151	0.037	0.121	0.440	0.258	1.000	0.112	0.043	0.022	0.186	0.072	0.036
700	0.070	0.036	0.310	0.055	0.145	0.361	0.151	0.035	0.121	0.440	0.258	1.125	0.097	0.042	0.022	0.238	0.072	0.036
750	0.078	0.036	0.340	0.054	0.135	0.401	0.151	0.034	0.120	0.620	0.258	0.800	0.091	0.051	0.023	0.216	0.228	0.042
800	0.088	0.049	0.860	0.054	0.140	0.462	0.150	0.033	0.120	0.620	0.258	0.800	0.114	0.043	0.024	0.265	0.225	0.054
850	0.090	0.047	0.840	0.052	0.137	0.482	0.150	0.035	0.119	0.620	0.258	0.800	0.129	0.075	0.026	0.278	0.230	0.148
900	0.096	0.040	0.830	0.053	0.139	0.539	0.150	0.036	0.119	0.620	0.288	0.800	0.088	0.076	0.027	0.278	0.230	0.286
950	0.098	0.045	0.839	0.126	0.336	1.326	0.198	0.055	1.290	0.620	0.387	0.925	0.091		0.037		0.229	0.423
1000	0.152	0.188	0.845	0.159	1.293	0.918	0.252	0.265	0.880	0.635	0.471	1.208	0.178		0.129		0.273	0.493

Table 49 – 100 x relative difference D_i from the KCRV, using the average value x_i of four detectors per laboratory, and (grey table) the associated relative standard uncertainty u_i.

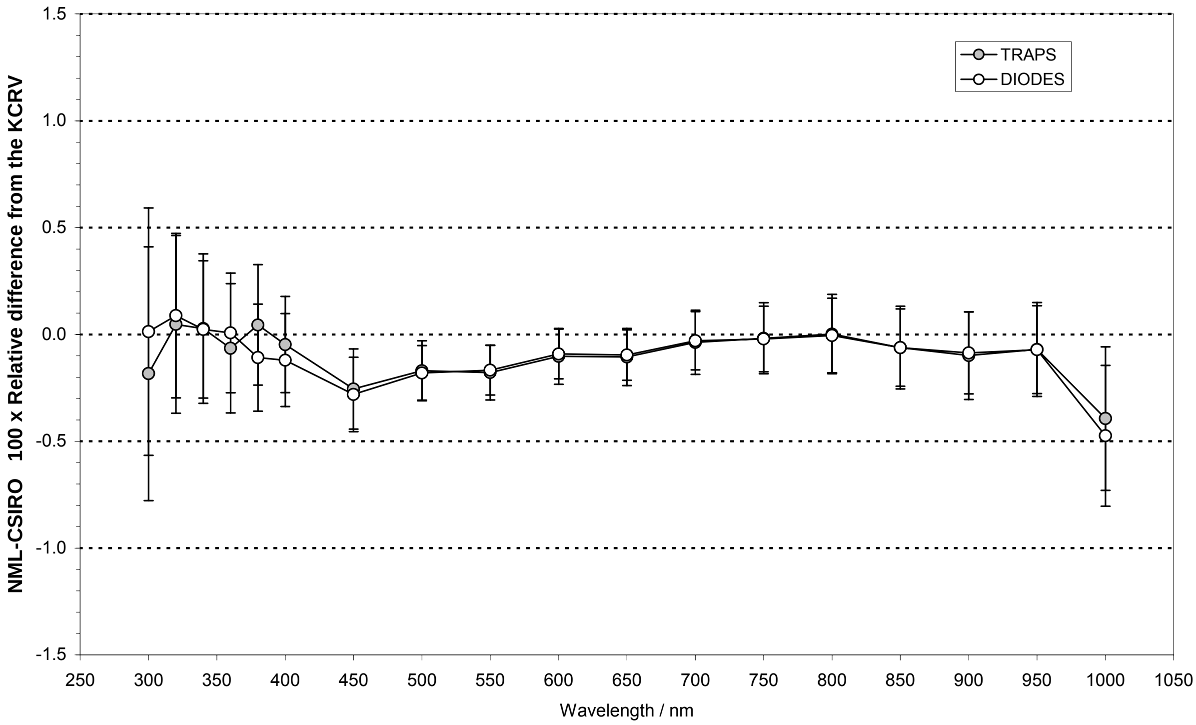
100 x relative difference from the KCRV, using the Trap detectors																	
/ nm	**CSIRO**	**NRC**	**IFA**	**NPL**	**HUT**	**OMH**	**SMU**	**NMi**	**NIST**	**NMIJ**	**VNIIOFI**	**CSIR**	**BNM/INM**	**MSL**	**PTB**	**IEN**	**KRISS**	**BIPM**
300	-0.184	0.051	-0.847	0.043	0.610	-1.358	-1.815	-0.018	0.042	0.525	-1.070		0.066	2.118	-0.101		0.720	0.618
320	0.047	-0.108	-1.063	0.039	0.581	-0.243	-1.563	0.013	0.620	1.334	-0.575		0.225	1.860	-0.130		0.394	0.185
340	0.027	-0.080	0.238	0.142	0.604	0.442	-1.445	-0.011	0.451	0.591	-0.646		0.244	1.517	-0.018		0.063	0.130
360	-0.065	-0.102	-0.292	0.082	0.719	0.658	-1.333	-0.055	-0.039	1.229	-0.305		-0.144	1.160	0.080	1.951	0.242	-0.049
380	0.044	-0.111	0.681	0.083	0.589	-0.258	-1.024	-0.058	-0.126	0.479	0.066		0.258	0.845	0.029	1.787	-0.072	-0.101
400	-0.045	-0.200	-0.479	0.022	0.183	0.267	0.125	-0.041	-0.043	0.296	0.047	1.810	0.000	0.580	-0.006	0.682	0.669	-0.181
450	-0.256	-0.026	-0.221	0.096	0.144	0.013	0.287	0.073	0.213	0.417	-0.031	0.741	0.081	0.058	-0.020	0.081	0.054	0.024
500	-0.170	0.002	-0.358	0.065	0.090	-0.038	0.093	0.065	0.226	0.270	0.125	0.864	0.013	0.109	0.007	-0.068	-0.096	0.001
550	-0.178	-0.002	-0.282	0.056	0.006	-0.033	0.190	0.059	0.172	0.210	-0.030	0.809	0.098	0.119	0.009	-0.088	-0.065	0.002
600	-0.103	-0.028	-0.161	0.048	-0.062	0.010	0.037	0.026	0.125	0.155	0.074	0.458	-0.015	0.091	-0.005	-0.057	-0.077	0.004
650	-0.106	-0.025	-0.225	0.056	-0.065	0.068	-0.012	0.041	0.124	0.139	0.071	-0.551	-0.252	0.105	0.006	0.017	-0.074	0.007
700	-0.037	-0.030	-0.395	0.050	-0.106	0.061	0.060	0.039	0.112	0.138	0.102	0.404	-0.254	0.084	0.003	0.073	-0.089	0.013
750	-0.018	-0.008	-0.562	0.042	-0.175	0.049	0.041	0.041	0.091	0.171	0.089	0.413	-0.191	0.071	-0.008	0.131	-0.055	-0.005
800	0.002	0.004	-0.337	0.041	-0.211	0.034	0.031	0.037	0.079	0.160	-0.017	0.340	-0.143	0.028	-0.018	0.188	-0.017	-0.018
850	-0.062	0.038	-0.408	0.041	-0.206	0.047	0.023	0.028	0.078	0.054	-0.017	0.615	-0.305	-0.026	-0.014	0.238	0.006	-0.008
900	-0.099	0.008	-0.730	0.063	-0.262	0.090	-0.030	0.026	0.100	-0.070	0.041	0.341	-0.222	-0.068	0.001	0.313	-0.095	0.060
950	-0.071	-0.030	-0.687	0.054	-0.163	0.018	-0.067	0.006	-0.126	-0.248	0.163	0.233	-0.142		-0.001		-0.122	0.161
1000	-0.394	-0.003	-0.983	0.017	-0.070	-0.087	0.004	-0.034	-0.285	-0.279	0.550	0.274	0.616		0.012		-0.023	0.214

Table 50 - 100 x relative difference from the KCRV, using the Trap detectors

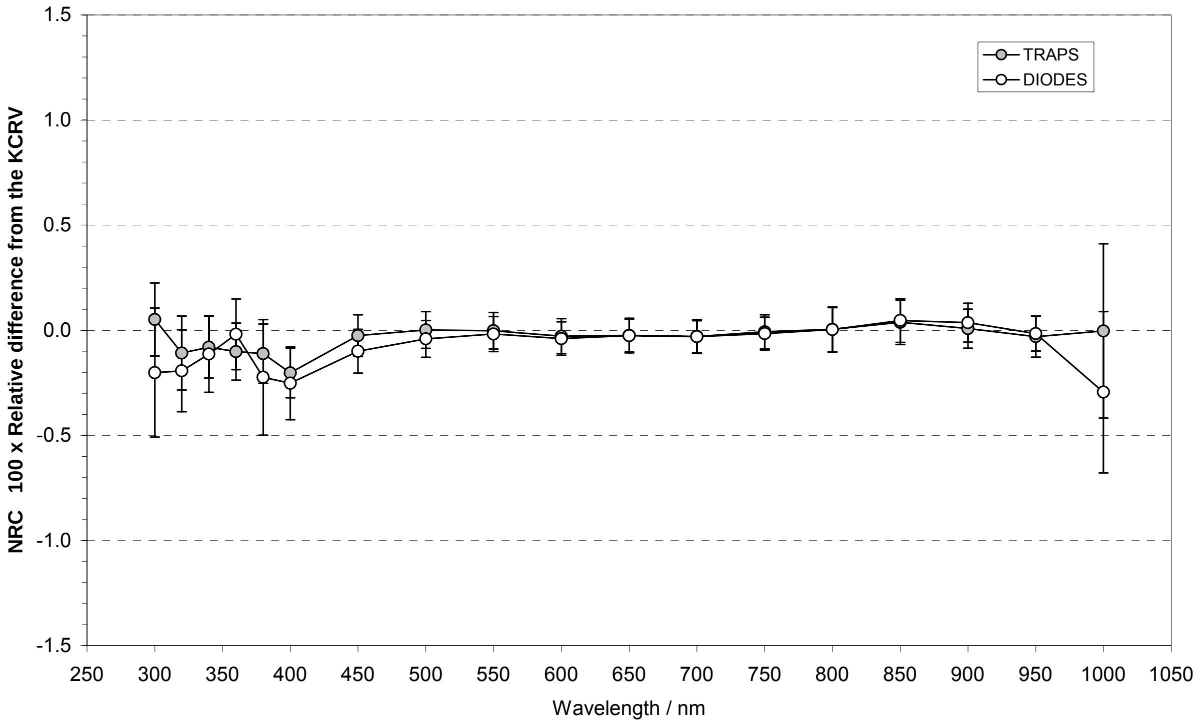
100 x relative difference from the KCRV, using the single element detectors																	
	CSIRO	**NRC**	**IFA**	**NPL**	**HUT**	**OMH**	**SMU**	**NMi**	**NIST**	**NMIJ**	**VNIIOFI**	**CSIR**	**BNM/INM**	**MSL**	**PTB**	**IEN**	**KRISS**	**BIPM**
300	0.013	-0.201	0.251	-0.091	0.586	-0.905	-3.904	-0.242	0.332	0.778	-1.824		0.279	2.043	-0.478		0.737	0.609
320	0.088	-0.193	-0.450	0.017	0.363	-0.167	-1.899	-0.183	0.773	1.451	-1.124		0.332	1.704	-0.404		0.339	0.167
340	0.023	-0.113	0.052	0.031	0.387	0.373	-1.661	-0.235	0.549	0.676	-1.151		0.404	1.372	-0.245		-0.002	0.118
360	0.007	-0.019	-0.776	0.096	0.443	0.369	-1.245	-0.223	-0.148	1.341	-0.700		0.079	1.075	-0.052	0.466	0.273	-0.062
380	-0.109	-0.224	0.339	0.006	0.506	0.112	-1.402	-0.205	-0.122	0.618	-0.746		0.375	0.651	-0.094	0.640	0.347	-0.080
400	-0.118	-0.250	-0.872	-0.031	0.122	0.454	-0.220	-0.137	-0.109	0.483	-0.664	1.588	0.294	0.439	-0.097	0.196	0.622	-0.170
450	-0.281	-0.100	-0.181	-0.013	0.129	0.071	0.009	-0.035	0.132	0.620	-0.237	1.101	0.385	-0.031	-0.169	0.313	0.027	0.010
500	-0.180	-0.041	-0.332	-0.035	0.105	-0.019	0.093	-0.018	0.162	0.481	-0.170	0.904	0.316	0.035	-0.105	0.184	-0.102	0.009
550	-0.167	-0.018	-0.250	-0.023	0.087	-0.012	0.127	0.006	0.125	0.429	-0.206	0.990	0.491	0.064	-0.083	-0.334	-0.081	0.007
600	-0.091	-0.040	-0.151	-0.015	0.023	-0.020	0.017	-0.016	0.089	0.391	-0.180	0.646	0.329	0.059	-0.082	0.410	-0.092	0.011
650	-0.097	-0.025	-0.220	-0.003	-0.002	0.014	0.042	0.006	0.099	0.368	-0.170	-0.291	0.016	0.079	-0.054	0.556	-0.094	0.011
700	-0.030	-0.030	-0.381	-0.002	-0.034	0.047	-0.028	0.008	0.096	0.370	-0.172	0.747	0.006	0.076	-0.054	0.373	-0.101	0.017
750	-0.021	-0.016	-0.535	0.004	-0.057	0.053	0.001	0.007	0.076	0.388	-0.172	0.806	0.007	0.058	-0.059	0.355	-0.081	0.001
800	-0.006	0.003	-0.168	0.001	-0.122	0.058	-0.116	0.007	0.073	0.349	-0.212	0.684	0.099	0.013	-0.057	0.373	-0.030	-0.007
850	-0.062	0.046	-0.217	0.021	-0.116	0.098	-0.041	0.005	0.073	0.241	-0.143	0.963	0.037	-0.027	-0.046	0.284	0.000	0.004
900	-0.087	0.036	-0.524	0.031	-0.227	0.105	-0.006	0.026	0.124	0.169	-0.100	0.745	0.128	-0.059	-0.037	0.233	-0.069	0.082
950	-0.071	-0.015	-0.543	0.008	0.185	0.094	-0.030	0.024	-0.097	0.010	-0.003	0.662	0.388		-0.047		-0.132	0.173
1000	-0.475	-0.294	-1.087	-0.130	-0.132	0.218	-0.154	-0.029	-0.043	-0.028	-0.034	0.682	1.460		-0.257		-0.101	0.290

Table 51 - 100 x relative difference from the KCRV, using the single photodiodes

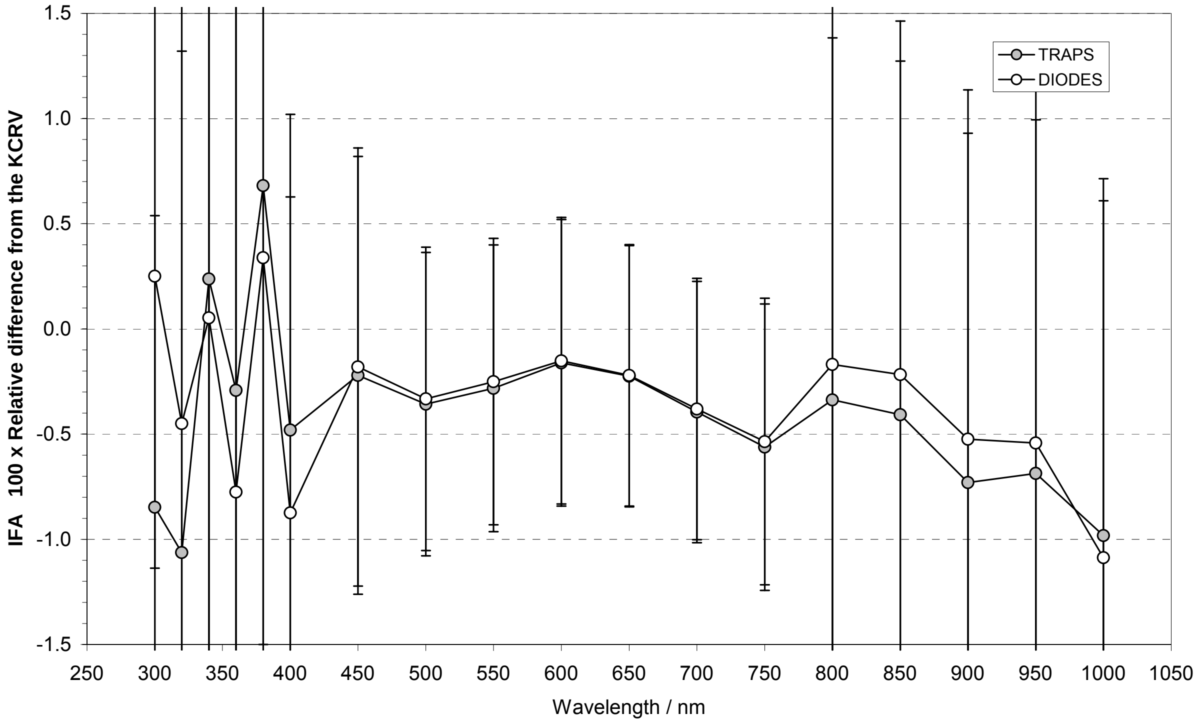
The following graphs are given to provide the laboratories with more information on the transfer detectors (they are *not* graphs of equivalence): they show the relative differences from the KCRV (base line) when either traps or single diodes are used as transfer detectors. The uncertainty bars (coverage factor k = 2) correspond to the NMI's uncertainty combined with the uncertainty of the transfer. They do not include the uncertainty of the reference.



NML-CSIRO

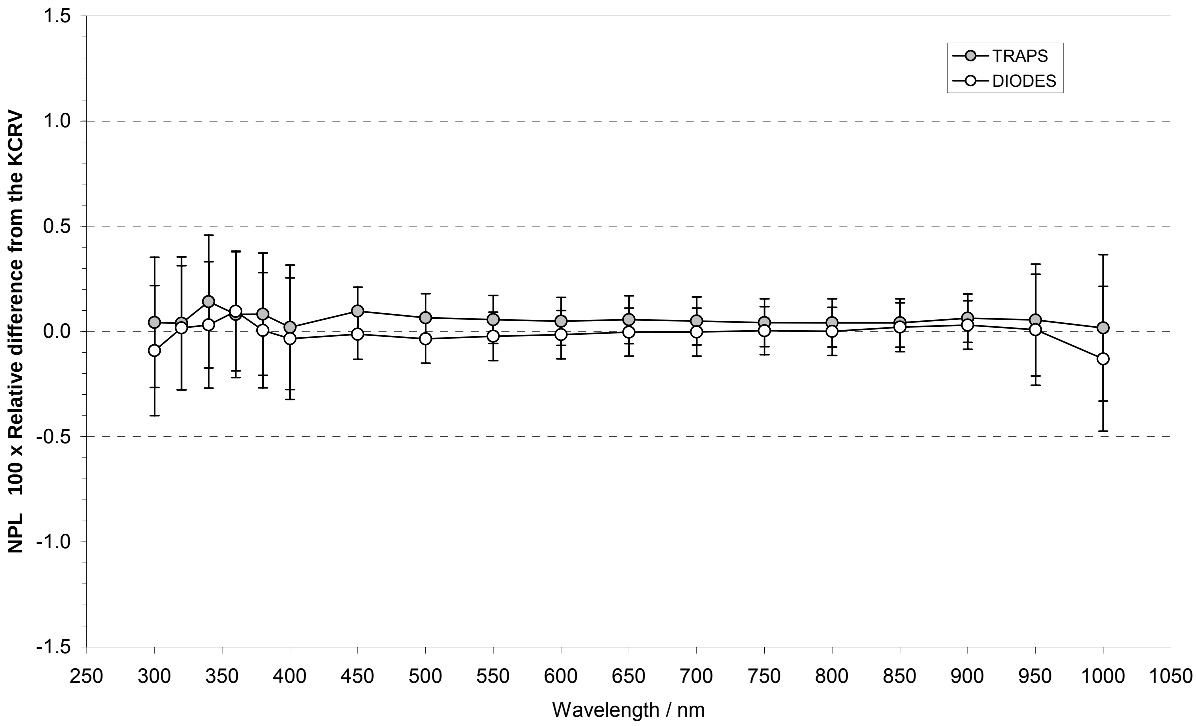


NRC



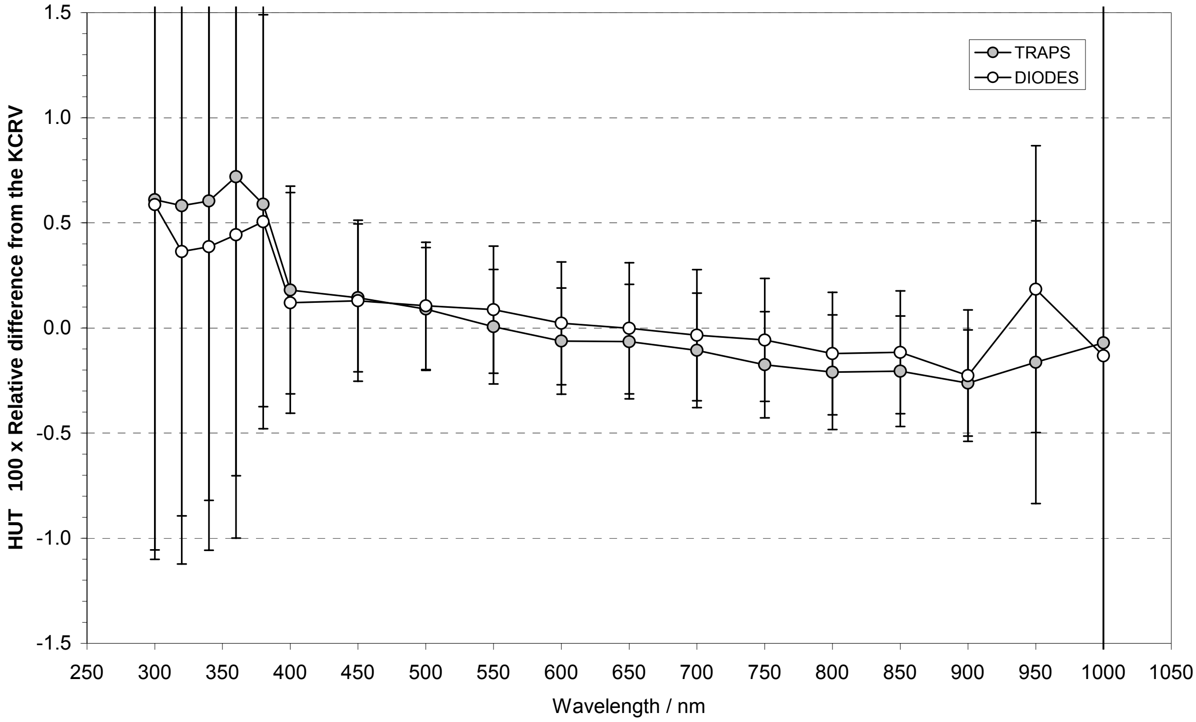
TRAPS
DIODES
IFA 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

IFA



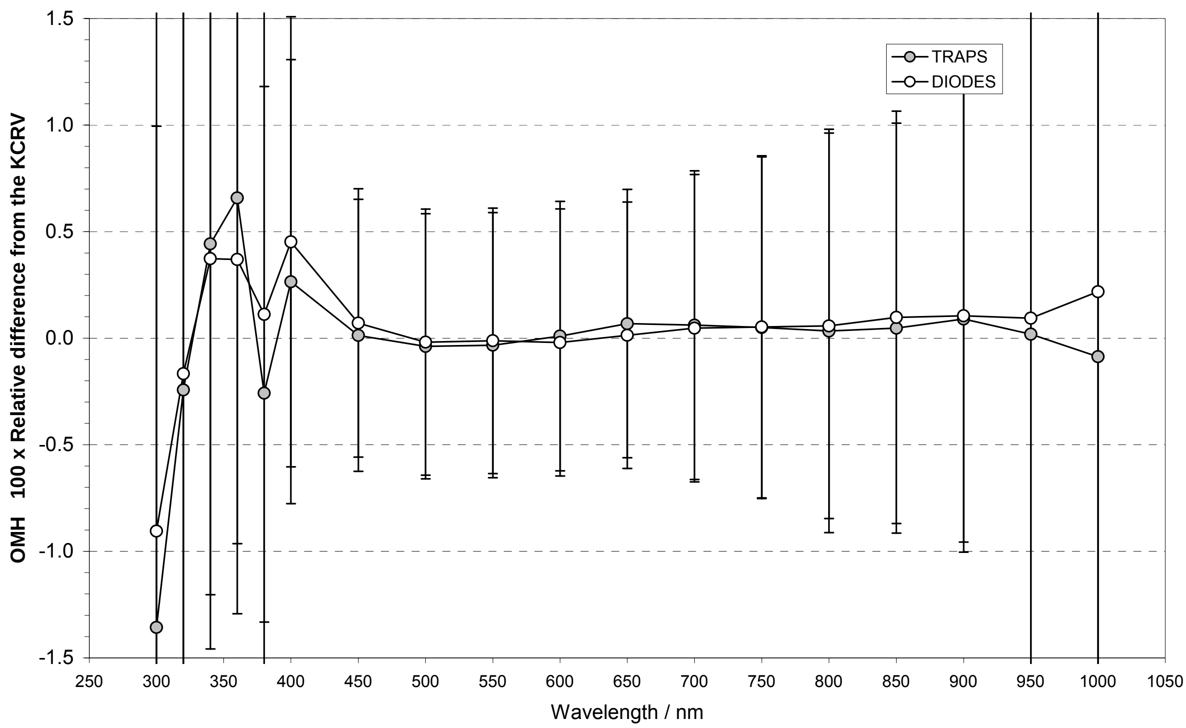
TRAPS
DIODES
NPL 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

NPL



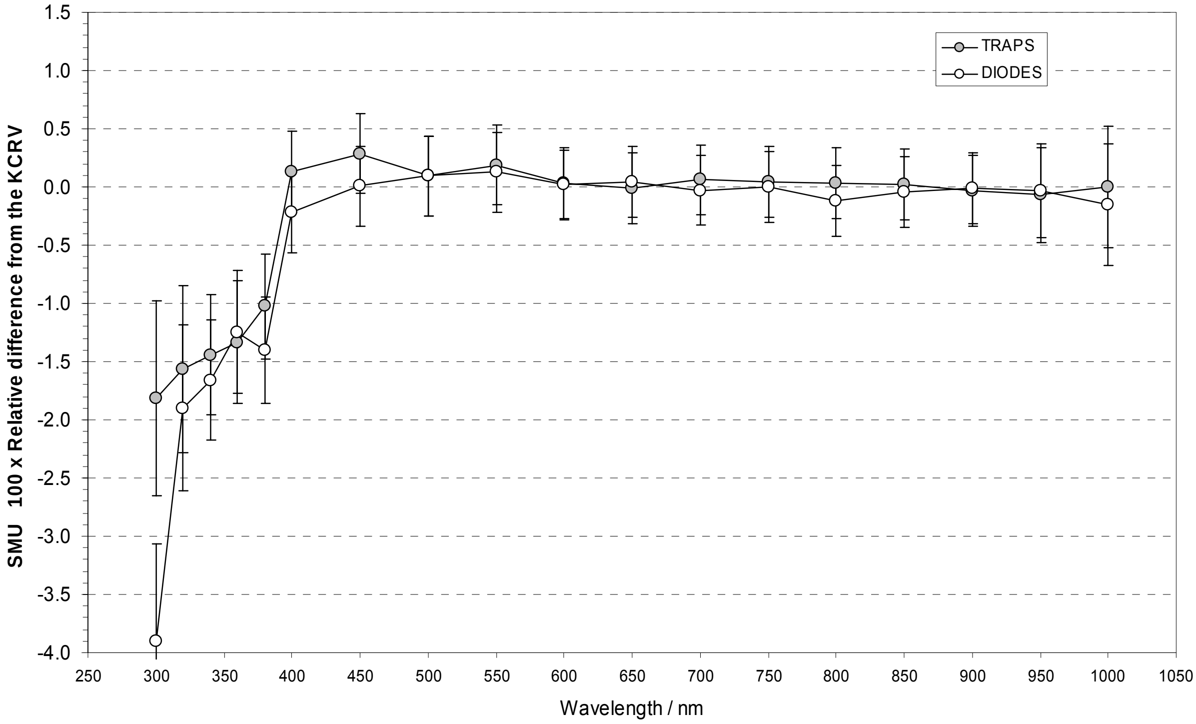
TRAPS
DIODES
HUT 100 x Relative difference from the KCRV
Wavelength / nm

HUT

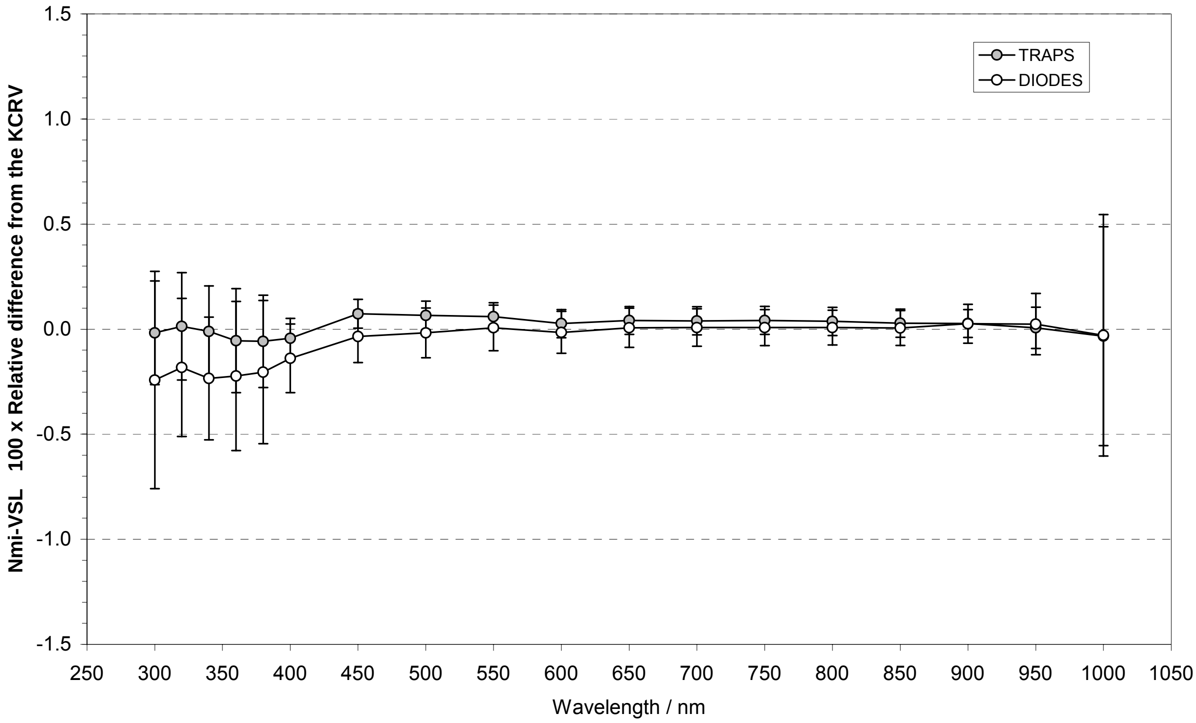


TRAPS
DIODES
OMH 100 x Relative difference from the KCRV
Wavelength / nm

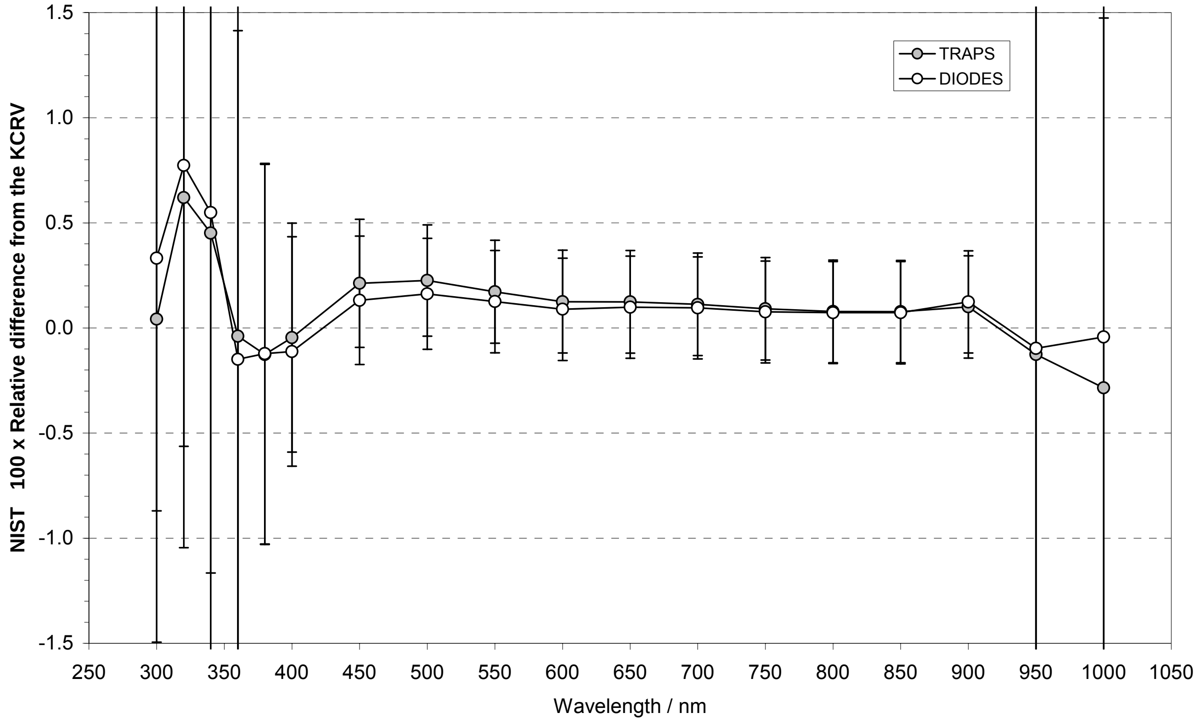
OMH


TRAPS
DIODES
SMU 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

SMU

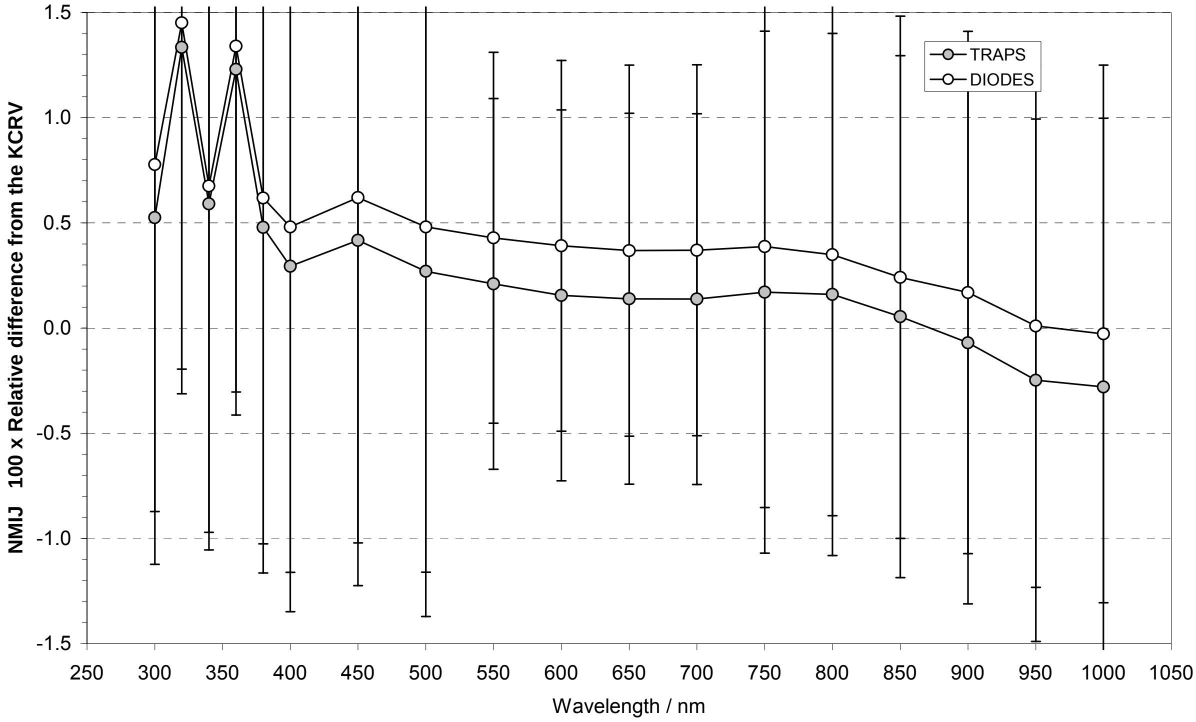

TRAPS
DIODES
NMi-VSL 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

NMi-VSL



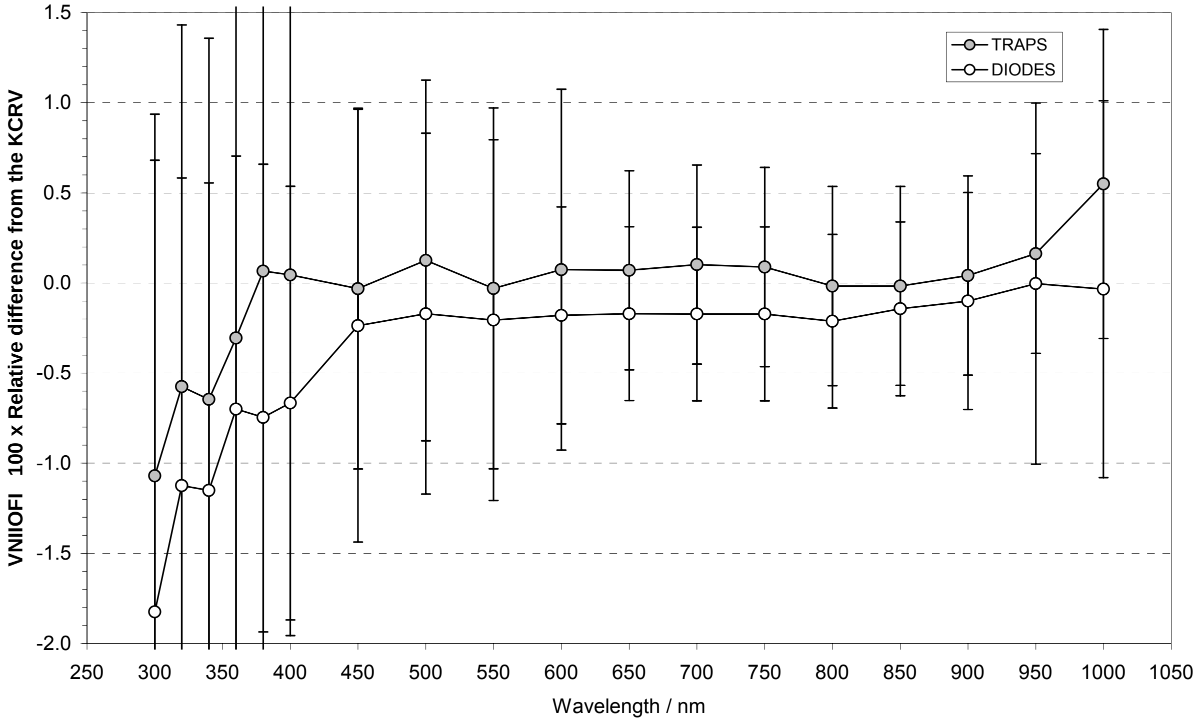
NIST 100 x Relative difference from the KCRV
Wavelength / nm
TRAPS
DIODES
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

NIST

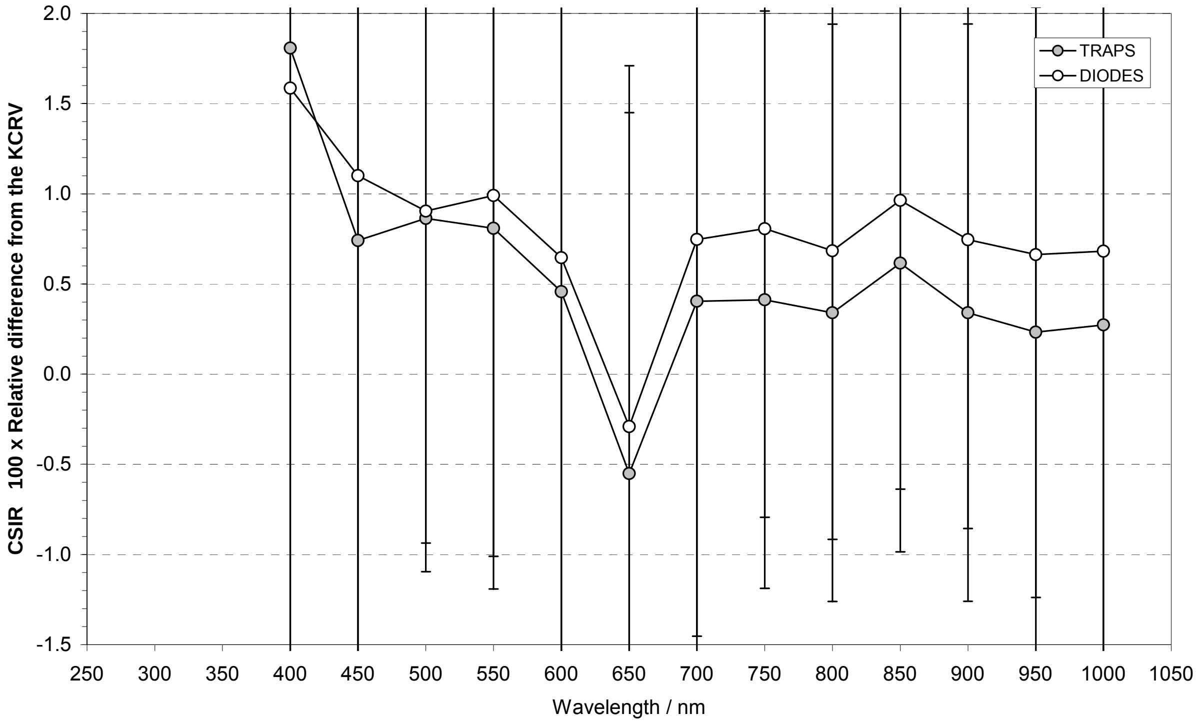


NMIJ 100 x Relative difference from the KCRV
Wavelength / nm
TRAPS
DIODES
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

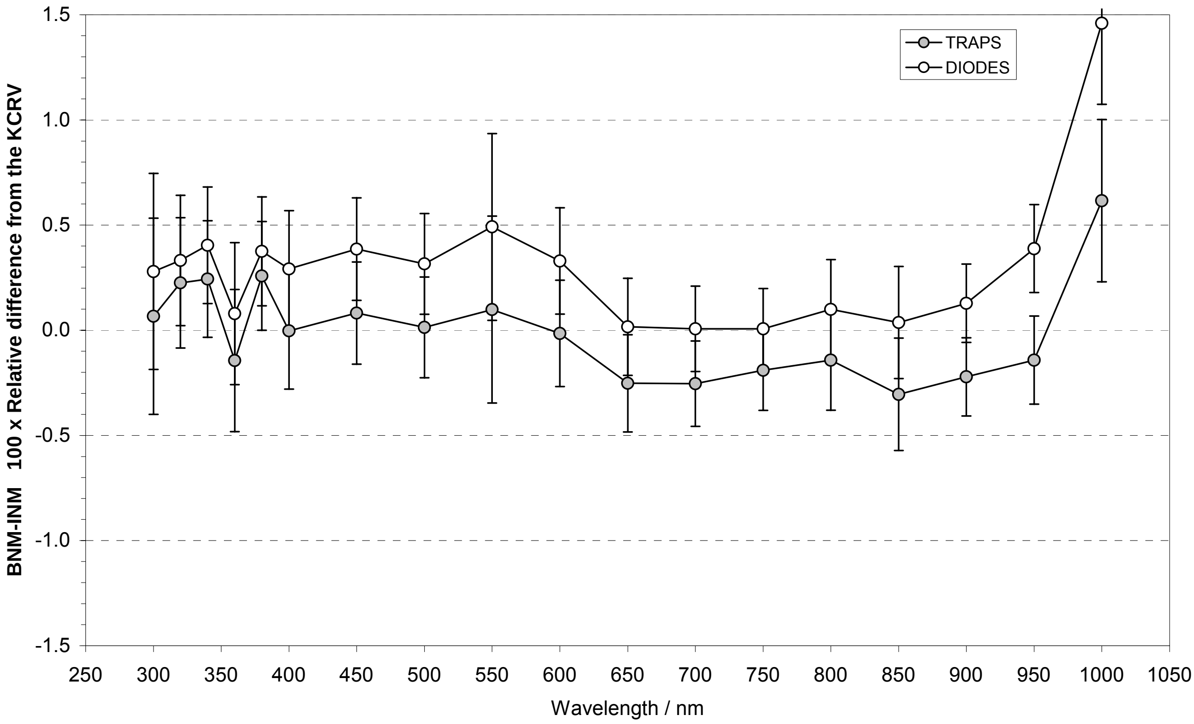
NMIJ



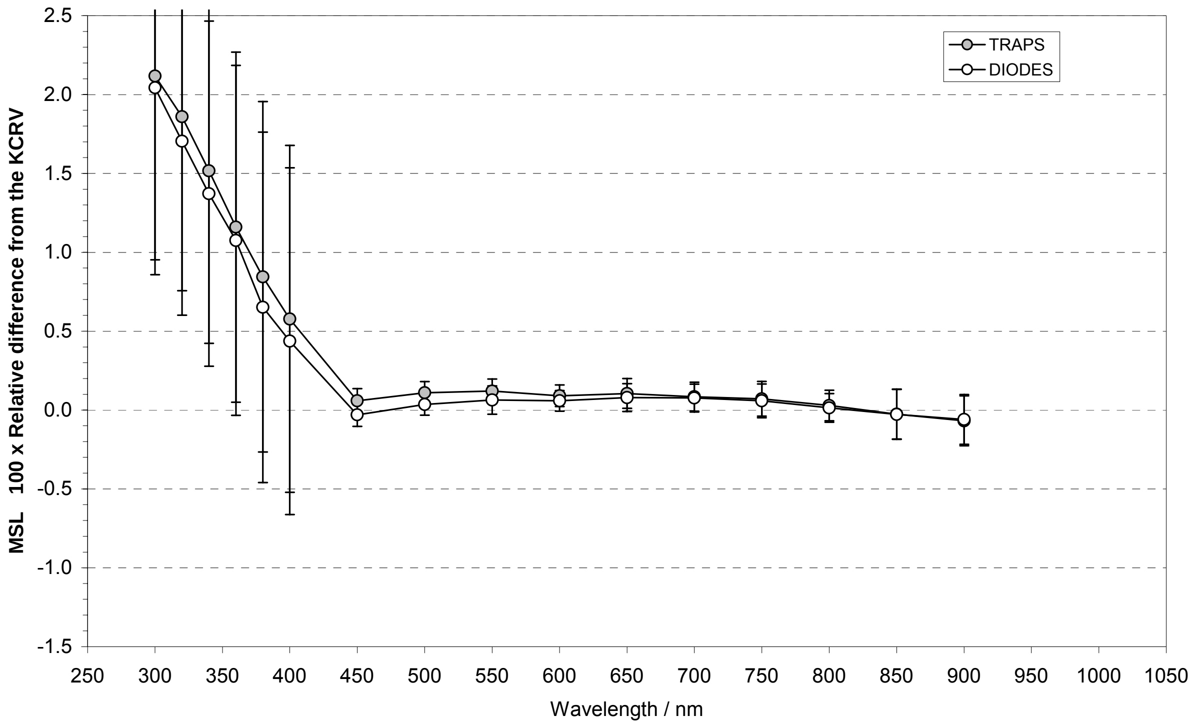
VNIIOFI



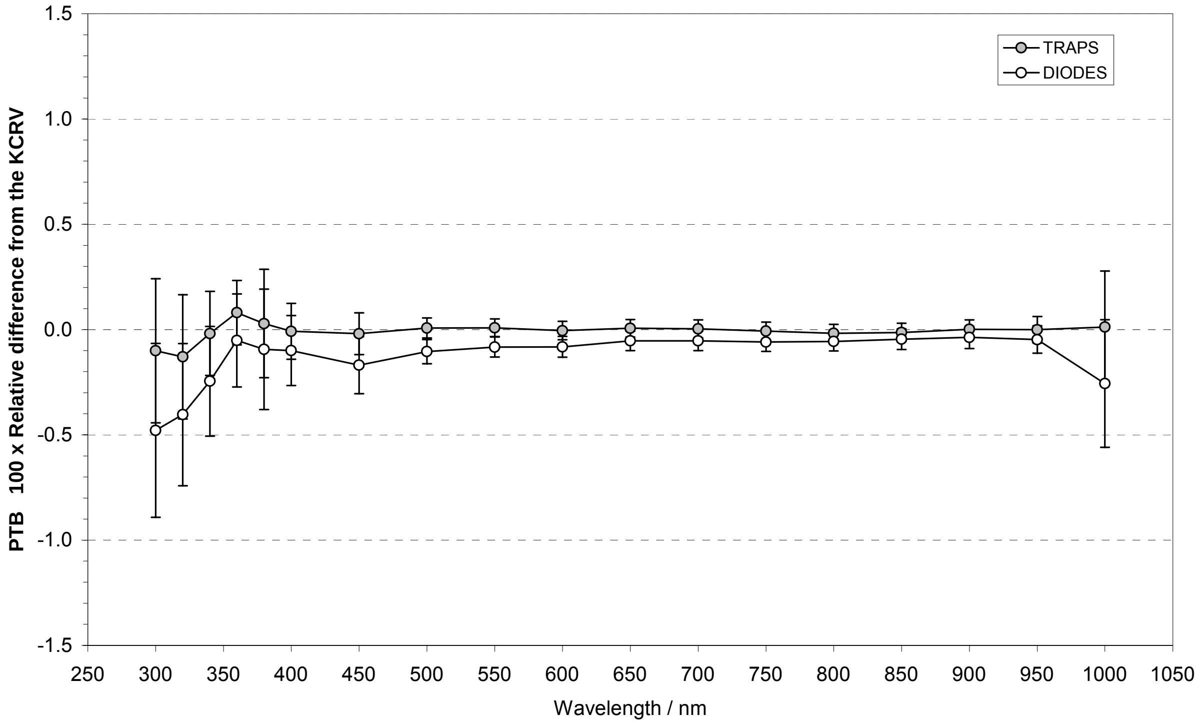
CSIR


TRAPS
DIODES
BNM-INM 100 x Relative difference from the KCRV
Wavelength / nm

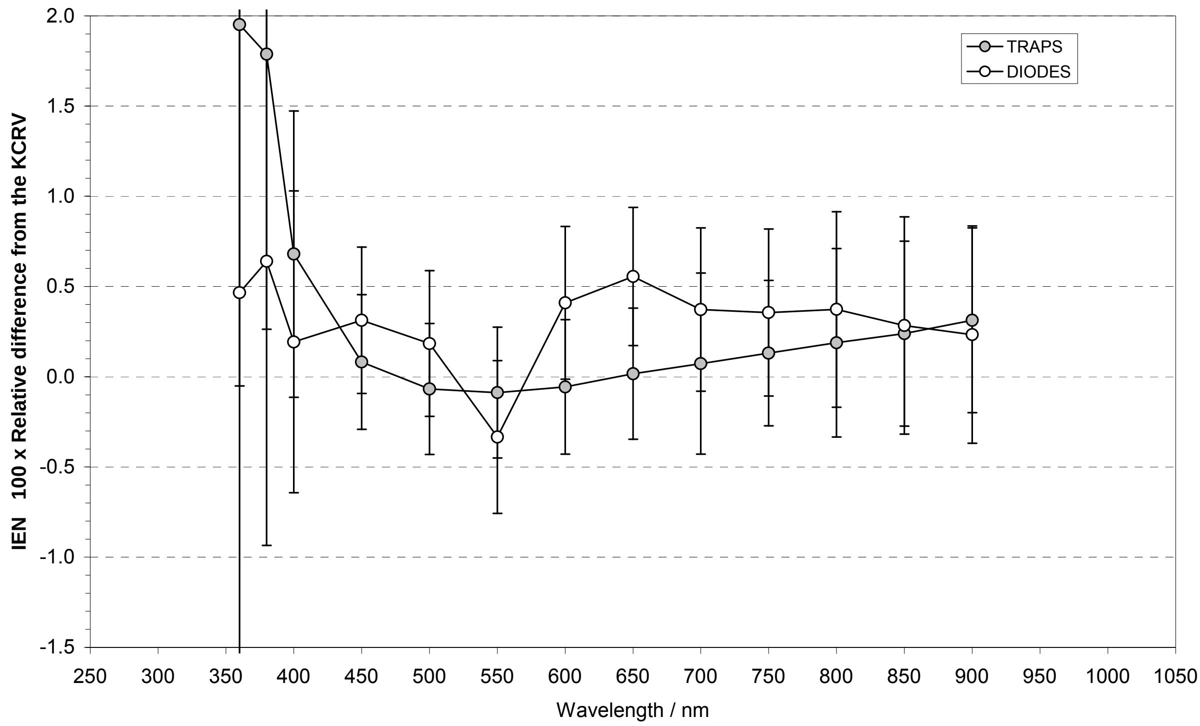
BNM-INM


TRAPS
DIODES
MSL 100 x Relative difference from the KCRV
Wavelength / nm

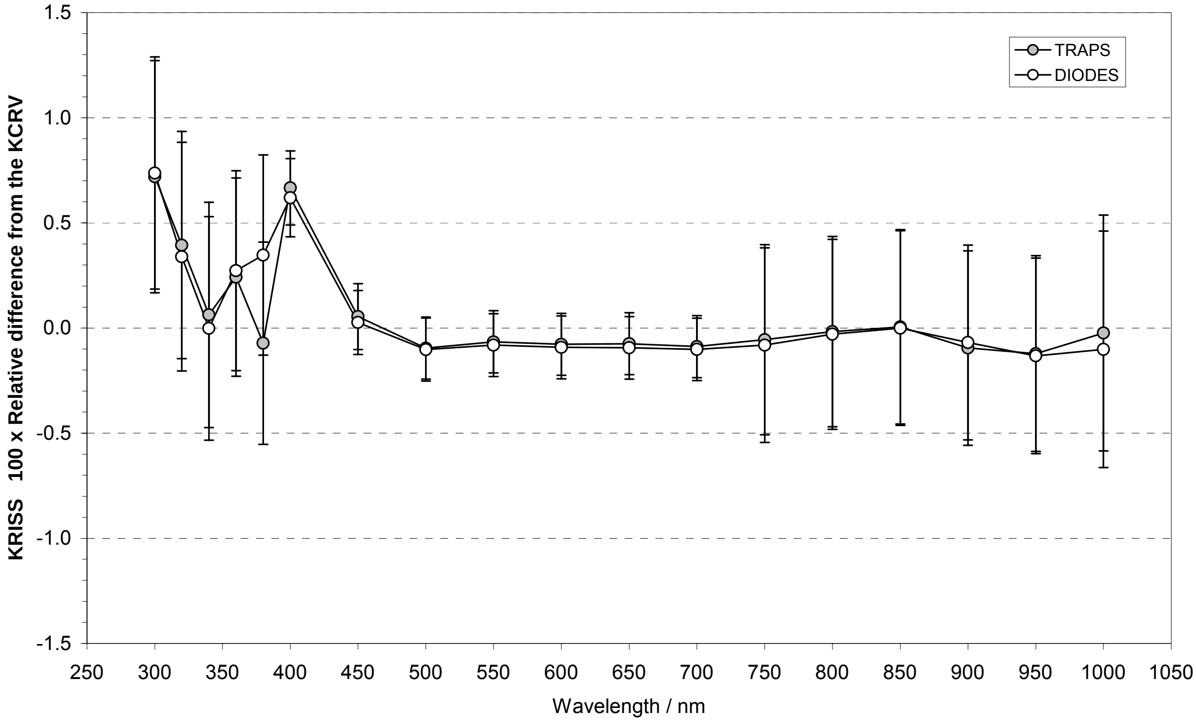
MSL


TRAPS
DIODES
PTB 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

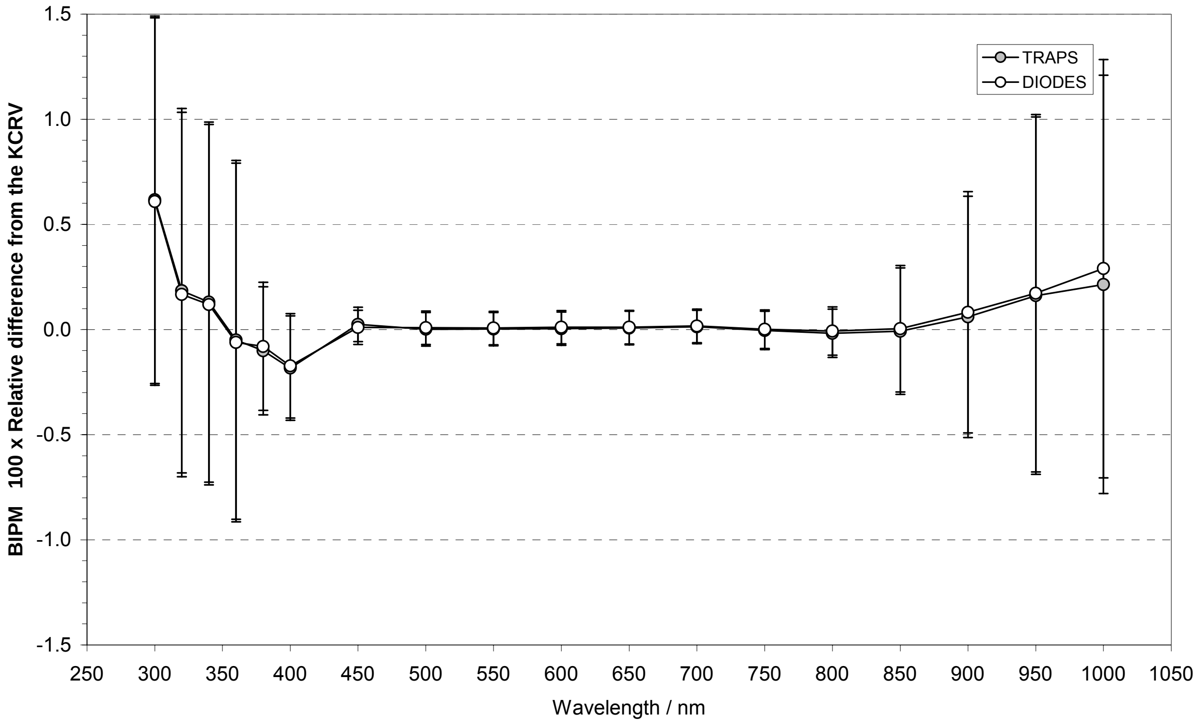
PTB


TRAPS
DIODES
IEN 100 x Relative difference from the KCRV
Wavelength / nm
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

IEN


TRAPS
DIODES
KRISS 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

KRISS


TRAPS
DIODES
BIPM 100 x Relative difference from the KCRV
Wavelength / nm
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050

BIPM

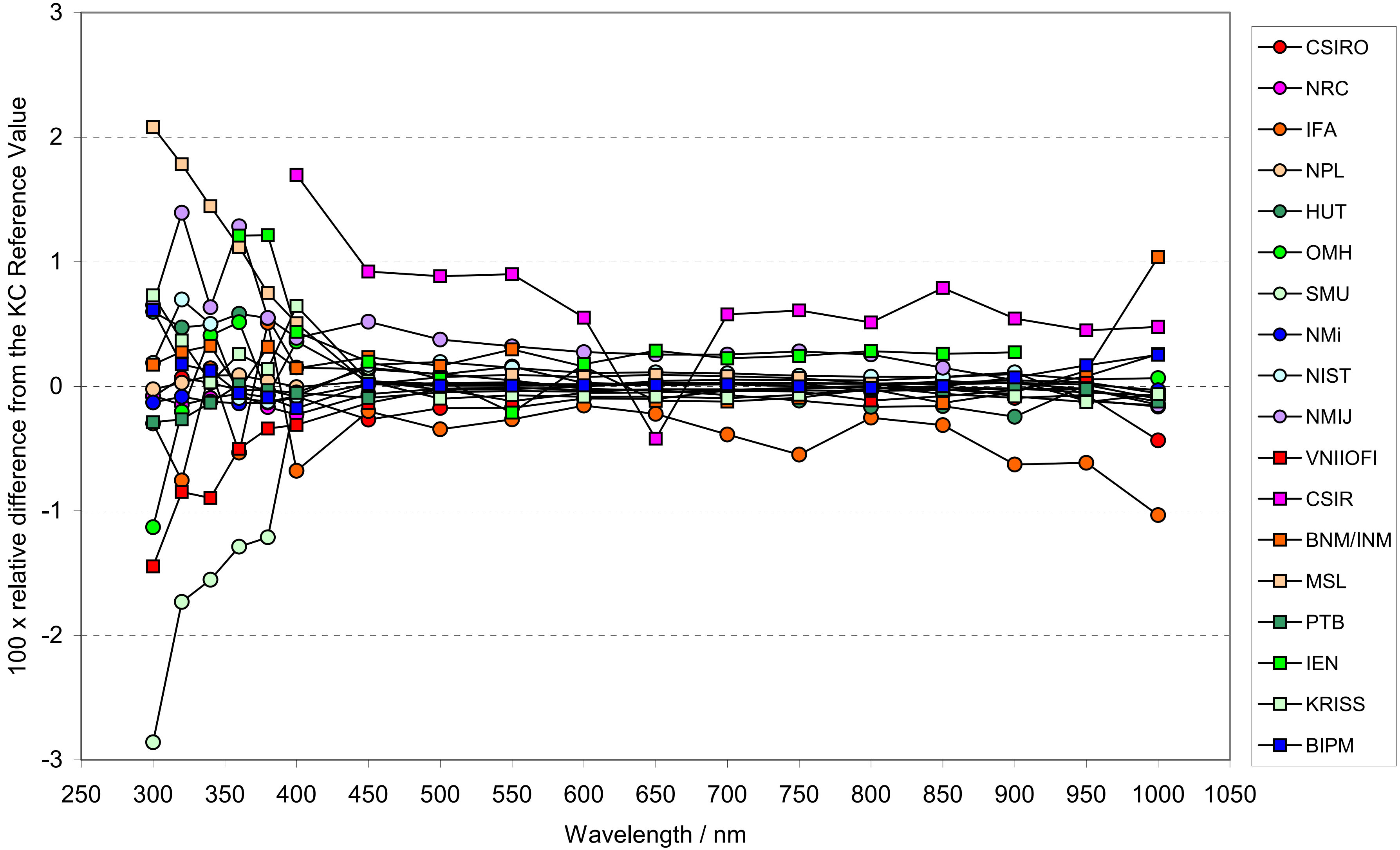


Figure 8 – Relative difference from the KCRV: each individual result is derived from four calibrated detectors by laboratory.

6. Discussion of the results

6.1. Dispersion

Considering the overall agreement among the participants, the relative standard deviations of the calibrations obtained from either traps or single photodiodes are very similar (slightly smaller for traps) over the whole range, as shown in Figure 9.

These standard deviations are of the order of 2×10^{-3} to 3×10^{-3} in the range 450 nm to 950 nm. In this part of the spectrum, the overall dispersion is also globally consistent with the uncertainties estimated by the participating laboratories. This is a clear improvement over the situation observed in 1993, for at least three reasons:

- results obtained from both types of transfer detectors are consistent, whereas in 1993 the dispersion associated with the single photodiodes was much larger (in the visible region of the spectrum) than that associated with the trap detectors;
- the dispersion has been reduced globally by a factor of 2 to 5 for photodiodes; this reduction is about the same for traps in the range 700 nm to 1000 nm;
- in 1993, only a fraction of the laboratories had calibrated trap transfer detectors; the dispersion observed in 2001 for the same sub-group of laboratories is even smaller, by about an order of magnitude in the IR.

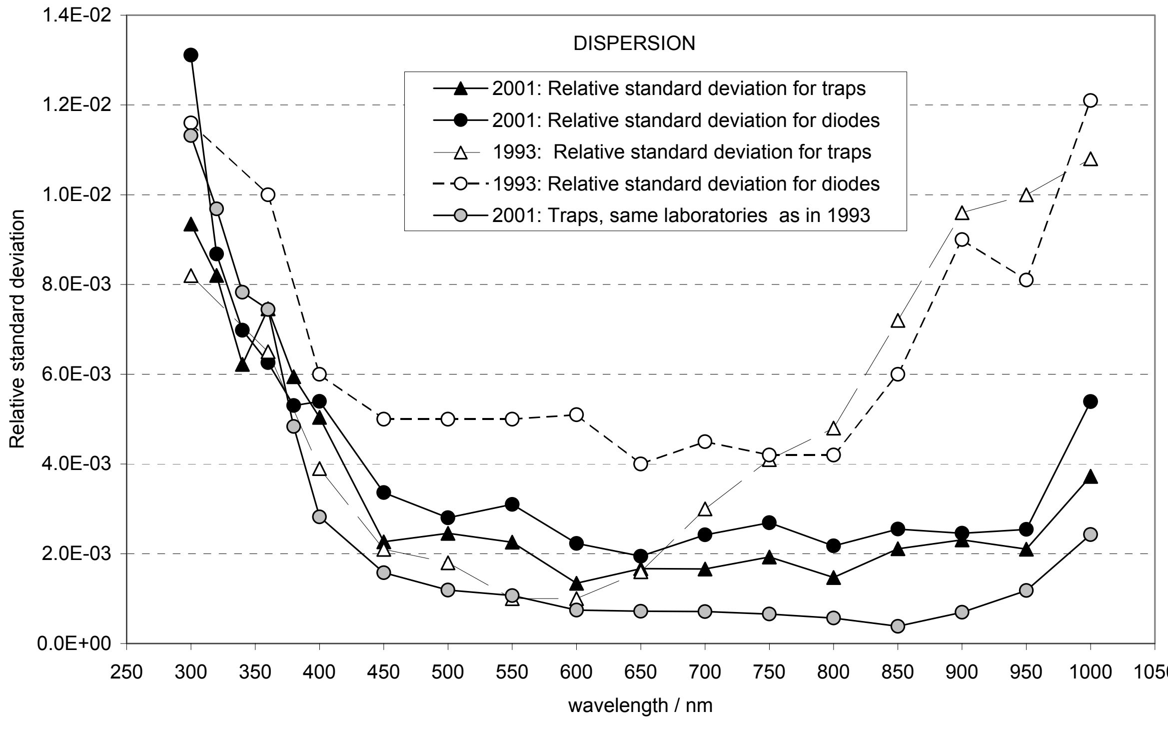


Figure 9 – Dispersion estimated with the relative standard deviation of the calibrations obtained by transfer from either trap or single element transfer detectors. The dispersion observed for the previous comparison of the same type in 1993 is also shown.

In the near-UV (300 nm to 400 nm), the overall dispersion is almost exactly the same as that observed in 1993. The experience gained in the use of trap detectors and of more accurate primary references has not improved the global agreement among the national laboratories.

Some possible explanations may be found in the uncertainty budgets and in the description of the measurement facilities. Most of the laboratories use cryogenic radiometers as primary references, but only two of them (the NMi-VSL and the NRC) have a monochromator-based system over the whole wavelength range or covering the UV range (the PTB). For the other laboratories using laser-based cryogenic radiometers, it is crucial to have accurate interpolation and extrapolation techniques to transfer the accuracy obtained at laser wavelengths to the rest of the range. In the 400 nm to 900 nm range, interpolation/extrapolation methods based on mathematical or physical models seem to be reliable, but the associated uncertainty is already much larger (by a factor of up to 10) than the uncertainty of the calibration at laser wavelengths.

The situation is more critical above 950 nm or in the UV, where physical models are more difficult to assess, and where laboratories have to use wavelength-independent detectors with an even larger degradation of the initial accuracy obtained at laser wavelengths. Apart from laboratories which have cryogenic radiometers operated in this range or considerable experience in the use of room-temperature wavelength-independent detectors, the degradation of the initial accuracy is of the order of one or two orders of magnitude.
As a consequence, for a large number of laboratories, calibrations performed in the UV range do not really benefit from the improvements made with their primary references in the visible region.

Possible improvements include:
- using as many laser lines as possible in the UV range;
- improving the facilities based on room-temperature wavelength-independent detectors;
- using monochromator-based cryogenic radiometers.

6.2. Uncertainty budgets

Detailed uncertainty budgets are very important for tracing the possible causes of dispersion of the results among the participants, as shown in the previous section. They have also shown that in many cases parameters contributing to the variability of the results are not dominant, meaning that significant differences found between participants are probably related to systematic effects.

However, the way some parameters are estimated can vary widely from one laboratory to another. The influence of the wavelength calibration of the monochromators can be chosen as an example and it is detailed hereafter.
All the laboratories used monochromators, at least over a part of the spectrum, to compare the KC detectors to their reference detector (or their primary reference). The influence of the wavelength setting will therefore be related to the differential rate of change of the responsivities of the detectors being compared: trap to single element, Si or Ge detector to pyroelectric detector, etc.
One can expect this parameter to have approximately the same order of magnitude in most of the uncertainty budgets, but:
- in some cases only a single wavelength-independent value is stated;
- in some cases it is estimated to be of the order of 10^{-4} (very small) and in others of the order of several parts in 10^{2} (when using sources with emission lines);
- in some cases it is not stated in the uncertainty of the NMI's reference detectors calibration;
- in some cases its magnitude is not explicitly stated.

In the Technical Protocol for the present comparison, the paragraph concerning the reporting of the uncertainty budget gives many influence parameters that should be considered, depending on the type of facility used, and a calibration form. The technical protocols for future international comparisons of this type should perhaps prepare even more precisely the form of the detailed uncertainty budget to be reported.

6.3. Time schedule

Due to their heavy workload, several laboratories had difficulty returning the KC transfer detectors or their calibration report within the time allotted. The delays were often of several months, and in some cases up to one year. This should certainly be considered in the preparation of future international comparisons.

7. Conclusions

Seventeen laboratories have participated in an international comparison of spectral responsivity measurements in the wavelength range 300 nm to 1000 nm. The results showed good overall agreement among the participants in the range 450 nm to 1000 nm. In this range, the dispersion of the results estimated by the relative standard deviation is of the order of 2×10^{-3} to 3×10^{-3}, which is a factor of 2 to 5 smaller than that observed in the previous comparison of the same type in 1993. This is not the case in the UV (300 nm to 400 nm) where the dispersion in 2001 is the same as that observed in 1993, ranging from 5 parts in 10^3 to about 1 part in 10^2. The analysis of the uncertainty budgets gives some possible explanations for these results.

The degrees of equivalence which have been calculated from the data are to be used within the framework of the Mutual Recognition Arrangement.

8. APPENDIX

8.1. Results submitted by the MSL after correction of a calculation error in the wavelength range 300 nm to 400 nm.

After publication of Draft A, the MSL discovered a calculation error in the data transmitted to the pilot laboratory. This calculation error affected the calibration values in the range 300 nm to 400 nm.

The MSL corrected its error and submitted a new set of values in this wavelength range.

The new transfer (in A / W) to the BIPM common reference detector from the four KC detectors and the corresponding uncertainties are given in **Table 52**, showing a much better agreement of the MSL calibrations with the reference value.

The graph showing the relative differences from the KCRV obtained from the corrected MSL calibrations is given in Figure 10.

MSL	Responsivity / (A/ W), of the BIPM reference detector obtained by transfer from the KC detectors:					100 x combined relative uncertainty			
λ / nm	R08	R19	F19	F45	Rel Std Dev	R08	R19	F19	F45
300	0.243578	0.242668	0.242915	0.243006	1.7E-03	0.583	0.583	0.610	0.574
320	0.252080	0.252070	0.251618	0.251629	8.9E-04	0.552	0.552	0.551	0.551
340	0.264689	0.264695	0.264388	0.264342	8.3E-04	0.547	0.547	0.547	0.547
360	0.276921	0.276912	0.276703	0.276674	5.0E-04	0.555	0.555	0.555	0.555
380	0.293120	0.293168	0.292697	0.292467	1.1E-03	0.556	0.556	0.556	0.556
400	0.313584	0.313683	0.313316	0.313207	8.3E-04	0.549	0.549	0.550	0.550
450	0.357626	0.357638	0.357365	0.357263	5.3E-04	0.039	0.039	0.037	0.036
500	0.399980	0.400005	0.399749	0.399642	4.4E-04	0.036	0.036	0.034	0.034
550	0.441199	0.441284	0.441041	0.440952	3.4E-04	0.039	0.039	0.046	0.044
600	0.481939	0.481971	0.481861	0.481739	2.1E-04	0.034	0.034	0.033	0.033
650	0.522469	0.522552	0.522441	0.522309	1.9E-04	0.047	0.047	0.045	0.044
700	0.562784	0.562881	0.562872	0.562699	1.5E-04	0.046	0.046	0.045	0.043
750	0.603142	0.603161	0.603173	0.602975	1.5E-04	0.055	0.055	0.054	0.053
800	0.643153	0.643230	0.643172	0.643016	1.4E-04	0.048	0.048	0.045	0.046
850	0.683008	0.683059	0.683128	0.682922	1.3E-04	0.080	0.079	0.079	0.079
900	0.722724	0.722682	0.722731	0.722803	7.0E-05	0.079	0.079	0.077	0.081

Table 52 - MSL: Transfer (in A / W) to the BIPM common reference detector from the four KC detectors and corresponding uncertainties, including MSL's uncertainty and transfer, after correction of a calculation error in the range 300 nm to 400 nm.

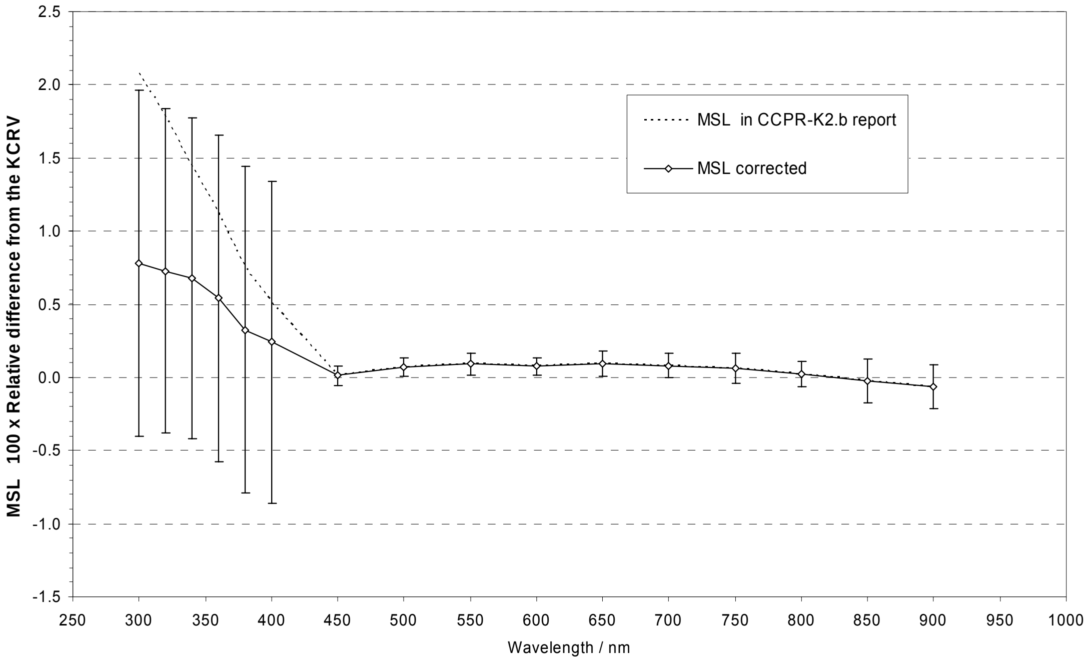


Figure 10 – Relative difference from the KCRV obtained from the corrected MSL calibrations. Uncertainty bars correspond to a coverage factor *k* = 2.

8.2. Revised PTB uncertainty budget

The PTB sent to the pilot laboratory a refined version of its uncertainty budget, but as it was transmitted after publication of Draft A, the CCPR-WG-KC did not accept the PTB proposal to use it in the final report. However, the WG-KC asked the pilot to include this revised uncertainty budget in the Appendix.
It is reproduced hereafter.

Uncertainty budget of PTB

The uncertainties are given as relative standard uncertainties in parts in 10^5.
Changed values are bold with the value given in Draft A following in parentheses.
Table "1.4 Monochromator-based calibration of KC transfer detectors" has previously shown the contributions for trap detectors and has now been subdivided into "1.4.1 Monochromator-based calibration of KC transfer detectors (trap detectors)" and"1.4.2 Monochromator-based calibration of KC transfer detectors (single element photodiodes)" to show the different contributions arising from non-uniformity and from the uncertainty in the wavelength.

1. Monochromator-based calibration

1.1 Primary reference *(no modification)*

Source of uncertainty wavelength (range) / nm	257	334	351, 356	407	476 - 900	950 - 1000
Window transmittance	20	15	10	5	3	3
Scattered and diffracted light	60	40	12.5	5	3	3
Cavity absorptance	3	3	3	3	3	3
Non-equivalence electrical / optical power	1.2	0.6	0.6	0.6	0.6	0.6
Electrical power measurement	9	5	5	4	4	4
Background radiation	10	2.5	2.5	1.25	1.25	1.25
Repeatability	36	9.5	9.5	5	5	5
Sum	**74.1**	**44.2**	**19.7**	**10.1**	**8.4**	**8.4**

1.2 Calibration of PTB reference detectors at laser lines *(no modification)*

Source of uncertainty wavelength (range) / nm	257	334	351, 356	407	476 - 900	950	1000
Primary reference	74.1	44.2	19.7	10.1	8.4	8.4	8.4
Stability of laser source	2.0	1.0	1.0	0.5	0.2	0.2	1.0
Photocurrent measurement	10	2	2	0.8	0.4 - 0.7	0.3	0.3
Linearity	4	3	3	2	1 - 2	2	2
Temperature	1.5	0.5	0.5	0	0	2	15
Wavelength	0	0	0	0	0	1.1	2.3
Stray light	2	2	2	2	2	2	2
Polarization dependence	2	2	2	1	0	4	4
Uniformity	60	40	40	12	4	5	5
Electrical calibrations	2	1.8	1.8	1.6	1.6	1.6	1.6
Repeatability	1	1	1	0.5	0.5	1	1
Bandwidth effects	0	0	0	0	0	0	0
Vignetting effects	0	0	0	0	0	0	0
Sum	**96**	**60**	**45**	**16**	**10**	**11**	**19**

1.3 Calibration of PTB reference detectors at the wavelengths of the key comparison (including the uncertainty of the calibration of PTB reference detectors at laser lines)

Source of uncertainty wavelength / nm	300	320	340	360	380	400	400	450	500	550	600	650	700	750	800	850	900	950	1000
Interpolation between laser lines with a physical model							136	61	18	**21** (11)	**22** (14)	**17** (11)	12	12	12	13	**16** (14)	**26** (17)	**27**
Interpolation and extrapolation with a cryogenic radiometer operated with dispersed synchrotron radiation	148	127	77	53	118	71													

1.4.1 Monochromator-based calibration of KC transfer detectors (trap detectors)

Source of uncertainty wavelength / nm	300	320	340	360	380	400	400	450	500	550	600	650	700	750	800	850	900	950	1000
Calibration of PTB reference detectors at the wavelengths of the KC2b	148	127	77	53	118	71	136	61	18	**21** (11)	**22** (14)	**17** (11)	12	12	12	13	**16** (14)	**26** (17)	27
Repeatability	26	11	8	7	6	8	8	6	7	5	7	5	6	4	6	5	5	5	4
Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	56
Wavelength	13	2	1	1	11	7	6	2	1	0	0	0	0	0	0	0	0	6	**45** (37)
Bandwidth effects	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	6
Polarization dependence	9	5	4	4	3	3	4	4	2	0	3	3	3	1	1	1	3	1	6
Stray light	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Uniformity	50	44	40	40	29	16	16	7	4	4	4	4	4	4	4	4	4	5	5
Sum	160	135	87	67	123	73	138	62	20	**22** (13)	**24** (17)	**19** (14)	15	14	14	15	**18** (16)	**28** (20)	**78** (73)

1.4.2 Monochromator-based calibration of KC transfer detectors (single element photodiodes)

Source of uncertainty wavelength / nm	300	320	340	360	380	400	400	450	500	550	600	650	700	750	800	850	900	950	1000
Calibration of PTB reference detectors at the wavelengths of the KC2b	148	127	77	53	118	71	136	61	18	**21** (11)	**22** (14)	**17** (11)	12	12	12	13	**16** (14)	**26** (17)	27
Repeatability	26	11	8	7	6	8	8	6	7	5	7	5	6	4	6	5	5	5	4
Temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	56
Wavelength	63	16	23	7	21	22	20	7	3	2	1	1	1	1	1	1	1	14	56
Bandwidth effects	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	6
Polarization dependence	9	5	4	4	3	3	4	4	2	0	3	3	3	1	1	1	3	1	6
Stray light	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Uniformity	100	88	80	80	59	33	33	14	8	8	8	8	8	8	8	8	8	10	10
Sum	192	156	114	96	134	82	142	63	21	**24** (15)	**25** (18)	**20** (15)	16	16	16	17	**19** (18)	**32** (25)	85

2. Laser-based calibration of trap detectors in the range 400 nm - 1000 nm

2.1 Calibration of KC transfer detectors with laser radiation (against 4 PTB reference detectors) *(no modification)*

Source of uncertainty / wavelength (range) / nm	407	476 - 799	850	900	950	1000
Calibration of four PTB reference detectors (at laser lines) [1]	12	9	9	9	10	18
Correction of temperature and wavelength	0	0	4	0	0	3
Stability of laser source	0.5	0.2	0.2	0.2	0.2	1
Photocurrent measurement [3]	0.9	0.4 - 0.8	0.4	0.4	0.3	0.3
Linearity [2]	0	0	0	0	0	0
Temperature	0	0	0	0	1	20
Wavelength	0	0	0	0	0	2
Stray light	2.0	2.0	2.0	2.0	2.0	2.0
Polarization dependence [3]	1.1	0	0	0	4.5	4.5
Uniformity [3]	13.4	4.5	4.5	4.5	5.6	5.6
Electrical calibrations [2]	0	0	0	0	0	0
Repeatability	1	1	1	1	1	2
Bandwidth effects	0	0	0	0	0	0
Vignetting effects	0	0	0	0	0	0
Sum	**18**	**10**	**11**	**10**	**13**	**28**

2.2 Calibration of KC transfer detectors at the wavelengths of the key comparison (including the uncertainty of the calibration of KC transfer detectors with laser radiation)

Source of uncertainty / wavelength / nm	400	450	500	550	600	650	700	750	800	850	900	950	1000
Interpolation between laser lines with a physical model for transfer trap ref10	116	53	16	**12** (11)	14	11	12	12	13	14	**16** (14)	**36** (17)	55
Interpolation between laser lines with a physical model for transfer trap ref13	276	92	**27** (22)	**32** (11)	**27** (14)	**23** (11)	**24** (11)	**22** (12)	**19** (11)	**26** (14)	**37** (14)	**77** (17)	**85** (35)

[1] The given uncertainties are only slightly smaller than the uncertainty of one reference detector (see 1.2) because the uncertainty contributions of the four reference detectors are strongly correlated.

[2] The contributions of the transfer detector and the reference detectors are assumed to be totally correlated.

[3] The contributions of the transfer detector and the reference detectors are totally non-correlated. The contribution of the transfer detector is assumed to have the same value as the corresponding contribution of a reference trap given in 1.2. Since four PTB trap detectors are used as reference the contribution of these detectors is 0.5 times the corresponding value in 1.2.

9. LIST OF FIGURES

10. LIST OF TABLES

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