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CCPR-S1 Supplementary comparison for spectral radiance in the range of 220 nm to 2500 nm

Boris Khlevnoy[1], Victor Sapritsky[1], Bernard Rougie[2], Charles Gibson[3], Howard Yoon[3], Arnold Gaertner[4], Dieter Taubert[5] and Juergen Hartmann[5]

[1] All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI), Moscow, Russia
[2] Bureau National de Métrologie/Institut National de Métrologie (BNM/INM, now LNE-INM/Cnam), Paris, France
[3] National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA
[4] National Research Council of Canada (NRC), Ottawa, Canada
[5] Physikalisch-Technische Bundesanstalt (PTB), Braunschweig and Berlin, Germany

E-mail: khlevnoy-m4@vniiofi.ru

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Abstract

In 1997, the Consultative Committee for Photometry and Radiometry (CCPR) initiated a supplementary comparison of spectral radiance in the wavelength range from 220 nm to 2500 nm (CCPR-S1) using tungsten strip-filament lamps as transfer standards. Five national metrology institutes (NMIs) took part in the comparison: BNM/INM (France), NIST (USA), NRC (Canada), PTB (Germany) and VNIIOFI (Russia), with VNIIOFI as the pilot laboratory. Each NMI provided the transfer lamps that were used to transfer their measurements to the pilot laboratory. The intercomparison sequence began with the participant measurements, then the pilot measurements, followed by a second set of measurements by the participant laboratory. The measurements were carried out from 1998 to 2002, with the final report completed in 2008. This paper presents the descriptions of measurement facilities and uncertainties of the participants, as well as the comparison results that were analysed in accordance with the *Guidelines for CCPR Comparisons Report Preparation*, and a re-evaluation of the results taking into account the instability of some of the transfer lamps. Excluding a few wavelengths, all participants agree with each other within ±1.5%. The disagreement decreases to approximately ±1.0% when the anomalous data are excluded from the analysis.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Spectral radiance is one of the basic radiometric quantities. The present importance of remote Earth observations has generated an increased demand for accurate spectral radiance measurements. Very few international comparisons have been carried out to check the consistency of national spectral radiance measurements. The most recent comparison was a bilateral comparison between NIST and VNIIOFI in 1991 [1].

At the 1997 meeting of the Consultative Committee for Photometry and Radiometry (CCPR), the decision was made to undertake a supplementary international comparison of spectral radiance measurements, identified as CCPR-S1. VNIIOFI was chosen as the pilot laboratory.

The measurements were carried out in the period from 1998 to 2002. The final report was completed and published in 2008 [2, 3].

2. Organization of comparison

2.1. Participants

Five national metrology institutes (NMIs) took part in the comparison: BNM/INM (France), NIST (USA), NRC

(Canada), PTB (Germany) and VNIIOFI (Russia) as the pilot laboratory.

2.2. Spectral range and artefacts

Tungsten strip-filament lamps were used as the comparison transfer standards. Thirty wavelengths were chosen for the comparison: 220 nm, 230 nm, 240 nm, 250 nm, 260 nm, 270 nm, 280 nm, 290 nm, 300 nm, 325 nm, 350 nm, 375 nm, 400 nm, 450 nm, 500 nm, 550 nm, 600 nm, 656.3 nm, 700 nm, 800 nm, 900 nm, 1000 nm, 1050 nm, 1200 nm, 1550 nm, 1700 nm, 2100 nm, 2300 nm, 2400 nm, 2500 nm.

The original intent was that each participant would prepare six lamps divided into two groups to cover the spectral range from 220 nm to 2500 nm so that three lamps would operate at the radiance temperature (at $\lambda \approx 650$ nm) of approximately 2100 °C for use in the spectral range from 220 nm to 400 nm and the other three lamps would operate at a radiance temperature of 2000 °C for use in the spectral range from 300 nm to 2500 nm. However, only NIST and PTB provided two groups of lamps to cover the entire spectral range. PTB used two lamps in each group instead of three. BNM/INM and NRC each provided only one group of three lamps, which covered the range from 300 nm to 2500 nm and from 400 nm to 800 nm, respectively. The lamp types used were Polaron[6] 24/G/UV (BNM/INM), General Electric # 30/T24/13 (NIST and NRC) and Osram Wi17/G (PTB).

2.3. Scheme of the comparison

Each participant prepared their transfer lamps, performed their first round of measurements and then sent the lamps to VNIIOFI for pilot measurements. The lamps were then sent back to the participant for their second round of measurements.

Because each participant used its own group of lamps, which was measured only by that particular participant and the pilot, the comparison was actually a number of bilateral comparisons between the individual participants and the pilot laboratory.

3. Scales realization and measurement of lamps

All participants, except NRC, realized their spectral radiance scales independently using variable high-temperature blackbodies according to the Planck law:

$$L_{\mathrm{BB}}(\lambda, T) = \varepsilon_{\mathrm{eff}} \cdot \frac{c_1}{\pi \lambda^5 n^2} \cdot \frac{1}{\exp\left(\dfrac{c_2}{\lambda T n}\right) - 1}, \qquad (1)$$

where $L_{\mathrm{BB}}(\lambda, T)$ is the spectral radiance of the blackbody, $c_1 = 3.741\,77 \times 10^{-16}$ W m^2, $c_2 = 1.4388 \times 10^{-2}$ K m, λ is the wavelength in vacuum, T is the temperature of the blackbody, n is the air refractive index and $\varepsilon_{\mathrm{eff}}$ is the effective emissivity of the blackbody.

[6] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the NMIs, nor does it imply that the material or equipment are necessarily the best available for the purpose.

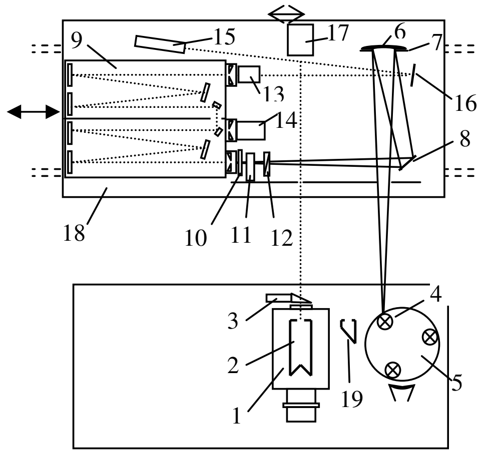

Figure 1. VNIIOFI Spectral radiance facility.

At each laboratory, the temperature determinations were based on fixed-point blackbodies: BNM/INM and VNIIOFI used a copper fixed point and NIST and PTB used a gold fixed point. The gold fixed-point temperature at NIST and at PTB was confirmed radiometrically with a scale derived from cryogenic radiometers.

NRC used three NIST-calibrated lamps as standards to calibrate the comparison transfer lamps.

To determine the spectral radiances of the lamps, all participants, except NRC, used spectral comparators based on double monochromators and mirror imaging optics with 1 : 1 magnification. The NRC spectral comparator was based on a double prism monochromator and imaging lens optics.

The measurement facility used in the pilot laboratory is shown in figure 1. The lamps were measured by a direct comparison with a high-temperature blackbody (1) of the BB22p type [4] with a graphite cavity radiator (2) with an emissivity of 0.999. A feedback system (3) enabled stabilization of the blackbody temperature within 0.1 K. The lamps (4) were set up next to the blackbody on a rotating table (5) which permitted alignment of three lamps. A black target (19) placed between the lamp and the blackbody was used for the measurement of dark signals. The temperature of the BB22p was varied from 1750 K to 2600 K to match the spectral radiance of the tungsten strip-filament lamp for each spectral range. A radiation thermometer (17) of the TSP-2 type [5] was used for measuring the BB22p temperature with a typical uncertainty of 0.6 K ($k = 1$) at 2300 K. The spectral comparator, based on a double grating monochromator (9) with a set of detectors (13, 14), cut-off filters (10), an optical chopper (11) and a thin film polarizer (12), was set up on a translation stage (18) opposite to the source. The imaging optics consisted of a toroidal (6) and a flat (8) mirror, a mask (7) which limited the solid angle of collecting radiation, as well as an alignment laser (15) and a mirror (16).

The radiation of the strip-filament lamps was polarized by up to a few per cent. To avoid a systematic error associated with the polarization, the lamp-to-blackbody ratio $R(\lambda)$ was measured for two orthogonal orientations of the polarizer and

Table 1. Reported uncertainties ($k = 1$) of lamp measurements and the cut-off values, as percentages.

λ/nm	BNM/INM	NIST	NRC	PTB	VNIIOFI	Cut-off
220	—	**0.89**	—	2.14	**1.13**	1.01
250	—	**0.61**	—	1.08	**0.87**	0.74
300	1.94	**0.51**	3.70	**0.88**	**0.73**	0.71
400	0.88	**0.44**	2.17	**0.63**	**0.56**	0.54
600	0.70	**0.37**	1.69	**0.42**	**0.39**	0.39
800	0.44	**0.26**	1.51	**0.33**	**0.32**	0.30
1000	0.40	0.61	—	**0.27**	**0.29**	0.28
1550	**0.39**	0.62	—	**0.23**	0.41	0.31
2100	**0.39**	0.65	—	**0.24**	0.41	0.32
2500	0.50	0.69	—	**0.29**	**0.46**	0.38

the lamp spectral radiance was calculated as follows:

$$L_{\rm lamp}(\lambda) = \tfrac{1}{2}(R_{\parallel}(\lambda) + R_{\perp}(\lambda)) \cdot L_{\rm BB}(\lambda, T). \qquad (2)$$

The measurement conditions at the participant laboratories differed in the target area, the solid angle and the alignment procedure. The pilot tried to duplicate the conditions as closely as possible to those of the participant laboratories. For lamps from a participant laboratory, VNIIOFI changed masks on the entrance slit and the imaging optics to match the target areas and solid angles used at the participant laboratory.

More details concerning the measuring facilities and procedures can be obtained from [2, 6–8].

The typical uncertainties for the lamp measurements are presented in table 1.

4. Data analysis

When all data were collected, the pilot analysed the measurements according to the *Guidelines for CCPR Comparisons Report Preparation* [9]. The aim of the analysis is the determination of the comparison reference value (CRV) and the differences between participants' values and the CRV.

First, the differences $\Delta_{i,j}$ between each participant i and pilot measurements for each lamp j were determined. As an example, figure 2 presents the differences between NIST and VNIIOFI. The uncertainties are calculated as

$$u_{\rm rel}(\Delta_{{\rm NIST},j,r}) = \sqrt{u^2_{\rm rel,NIST} + u^2_{\rm rel,VNIIOFI}}, \qquad (3)$$

where $u_{\rm rel,NIST}$ and $u_{\rm rel,VNIIOFI}$ are the total relative uncertainties ($k = 1$) reported by NIST and VNIIOFI, respectively.

Then the differences Δ_i between participant i and pilot scales were found as an average of $\Delta_{i,j}$ for all lamps and measurement rounds. The CRV were calculated as a weighted mean with a cut-off. The *cut-off* values are calculated based on the reported uncertainties $u_{{\rm rel},i}$ by

$$u_{\text{cut-off}} = \text{average}\{u_{{\rm rel},i}\} \quad \text{for } u_{{\rm rel},i} \leqslant \text{median}\{u_{{\rm rel},i}\};$$

$$i = 0 \text{ to } 4 \qquad i = 0 \text{ corresponds to the pilot}. \qquad (4)$$

Table 1 presents the reported uncertainties and the calculated cut-off values for a selection of the wavelengths. Bold entries are the uncertainties used for calculating the cut-off.

Next the reported uncertainty $u_{{\rm rel},i}$ of each NMI i was adjusted by the cut-off:

$$u_{{\rm rel,adj},i} = u_{{\rm rel},i} \qquad \text{for } u_{{\rm rel},i} \geqslant u_{\text{cut-off}}, \qquad (5)$$

$$u_{{\rm rel,adj},i} = u_{\text{cut-off}} \qquad \text{for } u_{{\rm rel},i} < u_{\text{cut-off}}.$$

The uncertainty of Δ_i after applying the cut-off is given by

$$u_{\rm adj}(\Delta_i) = \sqrt{u^2_{{\rm rel,adj},i} + u^2_{\rm rel,PR}}, \qquad (6)$$

where $u_{\rm rel,PR}$ is the reproducibility of the pilot measurements, including the stability of the scale during the comparison and the repeatability of the transfer lamp.

Then the weights w_i for participant i are determined by

$$w_i = u^{-2}_{\rm adj}(\Delta_i) \Big/ \sum_{i=0}^{N} u^{-2}_{\rm adj}(\Delta_i) \qquad (7)$$

and the CRV are determined by

$$\Delta_{\rm CRV} = \sum w_i \Delta_i. \qquad (8)$$

Thus, the CRV values $\Delta_{\rm CRV}$ represent the average scale of the comparison. One can see that a large reported uncertainty results in a smaller influence of that participant on the average scale due to the weighting function in equation (7). For instance, the contribution of NIST to the CRV at a wavelength of 600 nm was 29% while the NRC contribution was 2%.

Finally, differences between the measurements of each participant and the CRV, and their expanded uncertainties, were calculated by

$$D_i = \Delta_i - \Delta_{\rm CRV}, \qquad (9)$$

$$U_i = k\sqrt{u^2(\Delta_i) + u^2(\Delta_{\rm CRV}) - 2\left(\frac{u^2(\Delta_i)}{u^2_{\rm adj}(\Delta_i)} \Big/ \sum_{i=0}^{N} u^{-2}_{\rm adj}(\Delta_i)\right)}, \qquad (10)$$

where $k = 2$, $u(\Delta_i) = \sqrt{u^2_{{\rm rel},i} + u^2_{\rm rel,PR}}$ and

$$u(\Delta_{\rm CRV}) = \sqrt{\sum_{i=0}^{N} \frac{u^2(\Delta_i)}{u^2_{\rm adj}(\Delta_i)}} \Big/ \sum_{i=0}^{N} u^{-2}_{\rm adj}(\Delta_i).$$

5. Results

The differences from the CRV, and their expanded uncertainties, calculated by (9) and (10) separately for two spectral ranges are presented in tables 2 and 3 and shown in figure 3. These values are the official results on the comparison presented in the final report [2, 3] and are based on the data from all participating lamps, excluding the second round measurement of the PTB UV-region lamp 915.

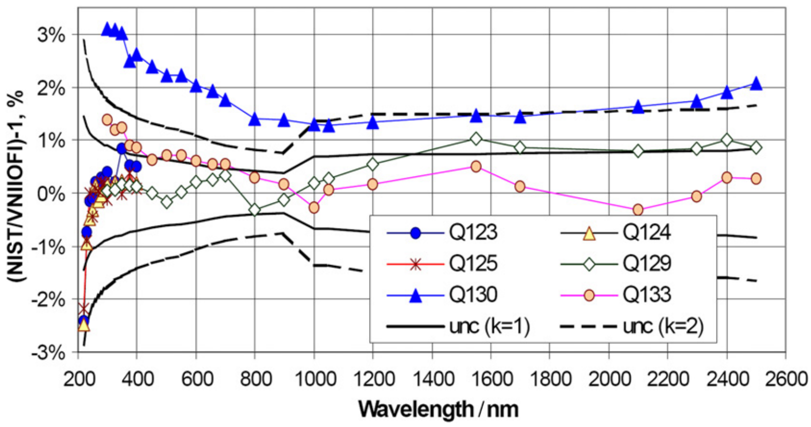

Figure 2. Differences $\Delta_{\mathrm{NIST},j}$ between NIST and VNIIOFI measurements, averaged over two rounds. Uncertainties unc($k = 1$) calculated by (3), unc($k = 2$) = 2 · unc($k = 1$).

Table 2. Differences from the CRV and uncertainties ($k = 2$) for the spectral range from 220 nm to 400 nm.

	NIST		PTB		VNIIOFI	
Wavelength/nm	D	$U(D)$	D	$U(D)$	D	$U(D)$
220	−1.11%	1.91%	0.01%	4.24%	1.26%	2.18%
230	−0.26%	1.69%	−0.41%	2.44%	0.61%	1.98%
240	0.05%	1.49%	−0.44%	2.26%	0.26%	1.80%
250	0.01%	1.38%	−0.42%	2.12%	0.29%	1.69%
260	0.31%	1.32%	−0.73%	2.00%	0.16%	1.63%
270	0.23%	1.28%	−0.64%	1.89%	0.21%	1.57%
280	0.28%	1.23%	−0.59%	1.77%	0.13%	1.52%
290	0.23%	1.19%	−0.41%	1.69%	0.06%	1.47%
300	0.17%	1.17%	−0.27%	1.62%	0.02%	1.44%
325	0.09%	1.09%	−0.01%	1.46%	−0.10%	1.33%
350	0.12%	1.04%	0.09%	1.34%	−0.23%	1.25%
375	0.10%	0.99%	0.16%	1.23%	−0.26%	1.17%
400	−0.01%	0.96%	0.28%	1.15%	−0.26%	1.10%

Table 3. Differences from the CRV and uncertainties ($k = 2$) for the spectral range from 300 nm to 2500 nm.

	BNM-INM		NIST		NRC		PTB		VNIIOFI	
Wavelength/nm	D	$U(D)$	D	$U(D)$	D	$U(D)$	D	$U(D)$	D	$U(D)$
300	−2.53%	3.85%	0.80%	1.26%			0.48%	1.72%	−0.70%	1.42%
325	−2.29%	2.47%	1.16%	1.18%			−0.05%	1.59%	−0.29%	1.33%
350	−1.76%	2.13%	**1.23%**	**1.11%**			−0.33%	1.46%	−0.24%	1.27%
375	−1.64%	2.13%	1.01%	1.06%			−0.29%	1.34%	−0.17%	1.18%
400	−1.60%	1.77%	1.02%	1.03%	0.41%	4.34%	−0.14%	1.28%	−0.18%	1.13%
450	−1.35%	1.77%	0.71%	0.96%	0.73%	4.25%	0.08%	1.12%	−0.29%	1.03%
500	−1.41%	1.42%	0.68%	0.92%	0.50%	4.31%	0.32%	1.03%	−0.24%	0.95%
550	−1.18%	1.41%	0.65%	0.87%	0.53%	3.55%	0.20%	0.92%	−0.33%	0.88%
600	−1.20%	1.41%	0.62%	0.79%	0.84%	3.38%	0.16%	0.86%	−0.34%	0.81%
656.3	**−1.25%**	**0.91%**	**0.78%**	**0.71%**	0.88%	3.05%	0.22%	0.79%	−0.13%	0.77%
700	**−1.07%**	**0.91%**	**0.71%**	**0.67%**	0.77%	3.17%	0.14%	0.75%	−0.17%	0.73%
800	**−1.11%**	**0.90%**	0.35%	0.60%	0.90%	3.03%	0.40%	0.69%	−0.11%	0.66%
900	**−1.19%**	**0.82%**	0.26%	0.56%			**0.72%**	**0.63%**	−0.21%	0.63%
1000	**−0.99%**	**0.81%**	0.00%	1.23%			**1.00%**	**0.57%**	−0.41%	0.59%
1050	**−1.10%**	**1.07%**	−0.08%	1.23%			**1.06%**	**0.59%**	−0.61%	0.64%
1200	−0.55%	1.04%	−0.22%	1.23%			**1.03%**	**0.59%**	**−0.90%**	**0.78%**
1550	−0.42%	0.80%	0.50%	1.25%			0.48%	0.60%	−0.50%	0.83%
1700	−0.41%	0.81%	0.37%	1.28%			0.47%	0.62%	−0.43%	0.85%
2100	**−0.94%**	**0.82%**	0.27%	1.32%			**0.94%**	**0.64%**	−0.43%	0.86%
2300	**−1.52%**	**1.01%**	0.49%	1.33%			**1.02%**	**0.68%**	−0.35%	0.90%
2400	**−1.49%**	**1.01%**	0.80%	1.35%			**0.83%**	**0.68%**	−0.27%	0.90%
2500	**−1.53%**	**1.03%**	0.75%	1.40%			**1.00%**	**0.75%**	−0.33%	0.96%

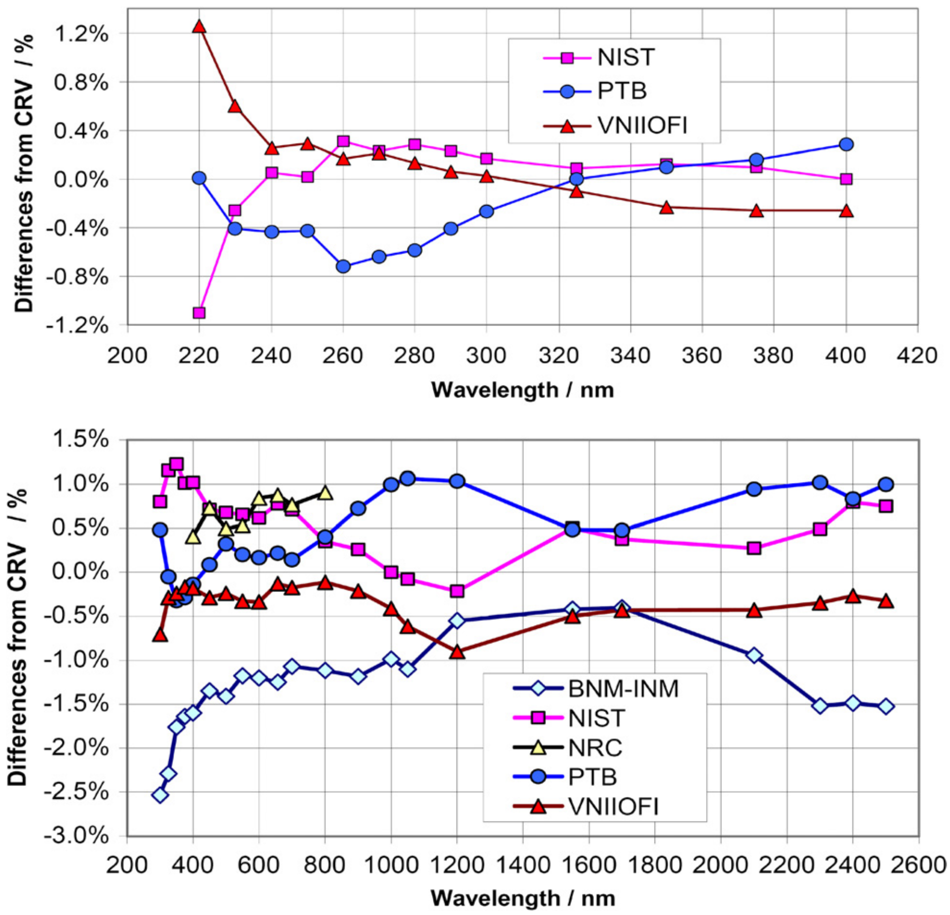

Figure 3. Differences from the CRV.

6. Stability of the lamps and alternative results

Although the tungsten strip-filament lamps are specially designed to be used as radiometric lamps, their temporal stability is often not adequate. Possible causes of the observed changes are due to the relatively high working temperature and the long burning hours, both of which are necessary to cover a wide spectral range in this intercomparison.

During this comparison the final results were influenced by some lamps which were determined to be temporally unstable. In this section we re-evaluate the results of the comparison by eliminating from the analyses the unstable lamps as well as anomalous data.

6.1. Unstable lamps

As mentioned in section 5, the PTB lamp number 915 demonstrated significant instability and was excluded from the analyses. However, two more lamps that were not excluded from the results presented in the previous section were also determined to be less stable than the others.

6.1.1. NIST lamp Q130. As one can see from figure 2, the lamp Q130 shows percentage differences between NIST and VNIIOFI measurements that are quite different spectrally from the other two NIST lamps. An examination of the lamp stability test measurements for Q130, carried out at NIST in 1998, showed that the change in the spectral radiance (at $\lambda = 654.6$ nm) of the lamp Q130 was at least three times greater than other NIST lamps [2].

6.1.2. PTB lamp X1032. PTB lamp X1032 showed odd behaviour in the range from 1000 nm to 1700 nm: the second round data differed from the first round data by up to 2%, whereas the other PTB lamp demonstrated good agreement between the rounds and with the VNIIOFI measurement. In addition, the first round of X1032 also agreed well with VNIIOFI. PTB investigated the history of the lamp and found that in 1999 it had already demonstrated instability of approximately 3% for half a year.

According to the *Guidelines* [9], the lamps Q130 and X1032 were taken into account for the CRV calculation because their instability was not realized until after the Draft A report. However, it was agreed that the lamp Q130 data and the second round of X1032 data are not representative of the laboratory capabilities. Therefore, the comparison results without these data were also evaluated and included in the final report in an appendix (see figure 4).

6.2. BNM-INM first round data

For the first round of BNM-INM measurements in 1999, the operating current of the lamps was set incorrectly. Therefore,

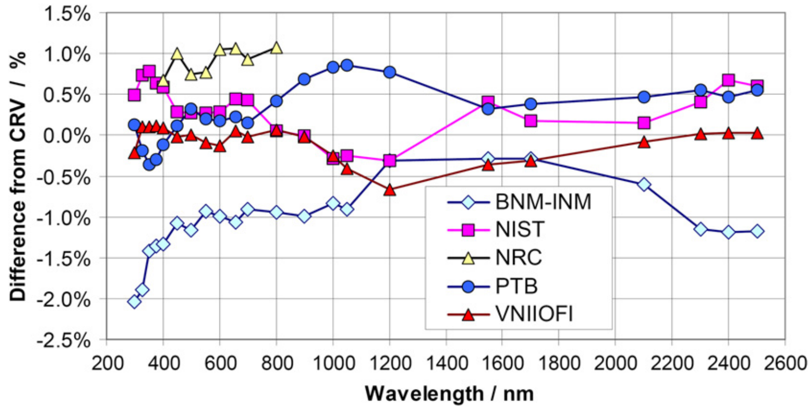

Figure 4. Alternative differences from the CRV for the range from 300 nm to 2500 nm. Data from Q130 lamp and the second round of X1032 lamp are not taken into account.

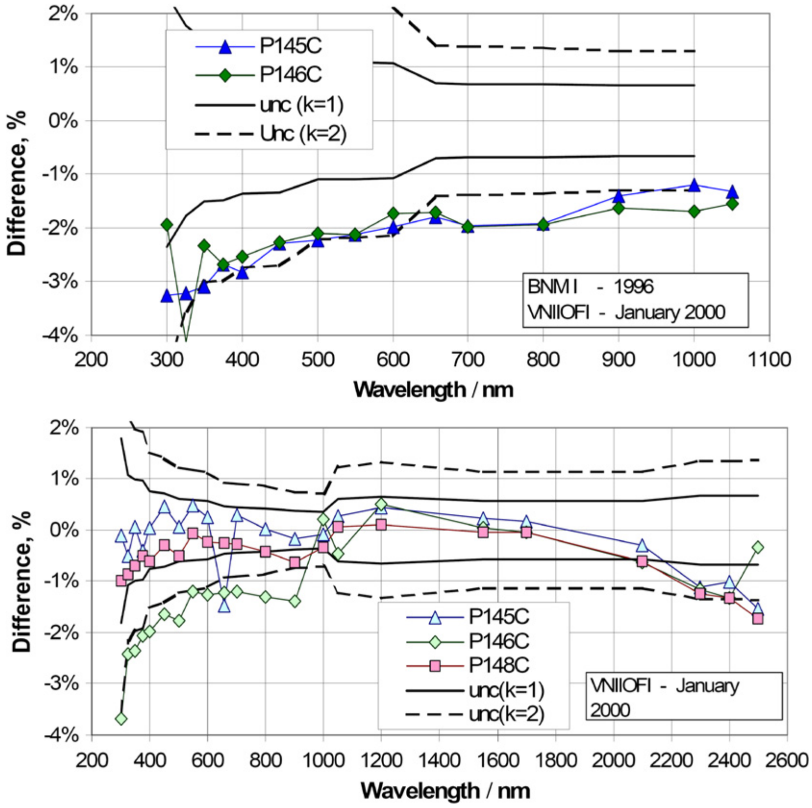

Figure 5. BNM-INM to VNIIOFI differences for the first (upper) and second (lower) round.

BNM-INM presented, as the first round data, the data of measurements that were made in 1996 for two lamps and for the range from 300 nm to 1050 nm only. The second round covered the whole spectrum range from 300 nm to 2500 nm for all three lamps using the correct lamp current.

Figure 5 shows a significant difference in the first round data from the second round data and from the VNIIOFI data. This fact entitles us to suppose that either the lamps drifted since 1996 or the 1996 measurements did not represent the actual scale of BNM-INM at the time of the comparison.

Consequently, with the additional exclusion of the anomalous BNM-INM first round data, we obtain the result shown in figure 6.

7. Conclusions

Five laboratories have demonstrated good agreement of their spectral radiance scales. Excluding BNM-INM results, the differences from the CRV, taking into account all lamps in the comparison, are within approximately ±1.0%. The corresponding BNM-INM differences are within approximately ±1.5% at most wavelengths. Except for a few wavelengths, the differences between all participants are within the expanded uncertainties ($k = 2$).

However, in the spectral range from 300 nm to 2500 nm the differences from CRV exceed their expanded uncertainties ($k = 2$), calculated by (9), at 24% of the measured spectral

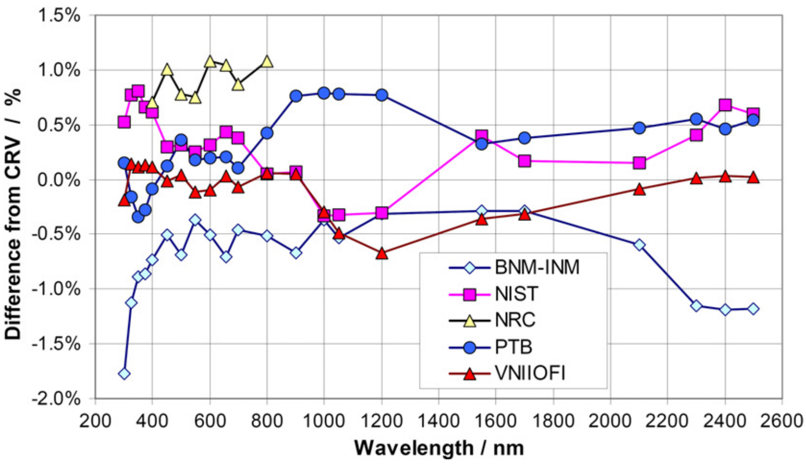

Figure 6. Alternative differences from the CRV for the range from 300 nm to 2500 nm. Data from Q130 lamp, the second round of X1032 lamp and the first round of BNM-INM are not taken into account.

points. The reason for this could be the instability of some lamps.

If anomalous data are excluded from the analyses, namely the NIST lamp Q130, the second round of the PTB lamp X1032 and the first round of the BNM-INM measurements, then the agreement in the range 300 nm to 2500 nm between the participants' scales is much better, with 93% of all points within the expanded uncertainties ($k = 2$).

In the UV range (from 220 nm to 400 nm) spectral radiances of NIST, PTB and VNIIOFI showed agreement within the standard uncertainties ($k = 1$), and the differences from CRV were less than 0.5% at most wavelengths.

Acknowledgments

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