CCPR S1 SUPPLEMENTARY COMPARISON

Spectral Radiance 220 to 2500 nm

Final Report

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1. ORGANISATION OF THE COMPARISON

1.1. INITIALISATION OF THE COMPARISON

The decision of carrying out an intercomparison of Spectral Radiance was taking first in 1994 at the meeting of CCPR.

The 1997 meeting of CCPR confirmed the previous decision and defined the level of this comparison as supplementary. At the same time VNIIOFI was chosen to act as a pilot laboratory. Two BIPM letters, dated 2 April 1997 and 20 October 1997, were send round to invite the CCPR members to participate in the comparison.

1.2. LIST OF PARTICIPANTS

The following five National metrological Institutes (NMI) took part in the comparison:

BNM-INM	Bureau National de Métrologie / Institut National de Métrologie, **France** Contact person: Bernard Rougié (bernard.rougie@cnam.fr)
NIST	National Institute of Standards and Technology, **USA** Contact person: Charles Gibson (cgibson@nist.gov)
NRC	National Research Council of Canada, **Canada** Contact person: Arnold A. Gaertner (arnold.gaertner@nrc-cnrc.gc.ca)
PTB	Physikalisch-Technische Bundesanstalt, Berlin, **Germany** Contact person: Rudiger Friedrich Dieter Taubert (dieter.taubert@ptb.de) – since 2006
VNIIOFI (The Pilot)	All-Russian Research Institute for Optical and Physical Measurements, **Russia** Contact person: Boris Khlevnoy (khlevnoy-m4@vniiofi.ru)

1.3. SPECTRAL RANGE AND ARTEFACTS

Tungsten strip lamps were used as the comparison artefacts.

Pilot suggested that each participant to prepare 6 (six) lamps divided in two groups to cover the spectral range 220 to 2500 nm in following way: three lamps to be used at the radiance temperature ($\lambda \approx$ 650nm) of about 2370 K in the spectral range 220 to 400 nm and other three lamps to be used at the radiance temperature of about 2270 K in the spectral range 300 to 2500 nm. Only NIST and PTB provided two groups and cover whole spectral range, but PTB used two lamps in each groups instead three. BNM-INM provided one group of three lamps to cover the range 300 to 2500 nm. NRC used one group of three identical lamps; spectral range of comparison was 400 to 800 nm. Details of the lamps and conditions of measurements are presented in Table 1.1.

Table 1.1. Lamps details and conditions of measurements.

	BNM-INM	NIST		NRC	PTB	
Type of Lamps	Polaron 24/G/UV	General Electric Model # 30/T24/13		General Electric Model # 30/T24/13	Osram Wi17/G	
Spectral Range, nm	300 – 2500	220-400	300-2500	400-800	220-400	300-2500
Number of Lamps	3	3	3	3	2	2
Radiance Temperature at 650 nm	2170 K	2370 K	2270 K	2300 K	2500 K	2300 K
Current	15.000 A	39 A	35 A	35 A	15 A	12.5 A
Strip size	1.7x34 mm	3x15 mm		3x15 mm	1.3x20 mm	
Target area size	0.5x0.5 mm	0.6x0.8 mm		circle of 0.6mm diameter	0.2x1.0 mm	
Solid angle	0.01 sr	0.125 rad in vertical and 0.0625 rad in horizontal		0.008 sr	0.01 sr	

Conditions of measurements at VNIIOFI (a Pilot laboratory) were made as close as possible to that used at the participant laboratories. For instance, VNIIOFI changed masks on the entrance slit and imaging optics to use proper target area size and solid angle.

1.4. SCHEME OF THE COMPARISON

The comparison was organised as a star comparison. The measurement sequence was

NMI – Pilot – NMI

Each participant carried out the **First Round** of measurements, then send lamps to VNIIOFI, where **Pilot Measurement** was done; then lamp were send back to the participant, and the participant made the **Second Round** of measurements.

Because each individual NMI had its own group of lamps, which was measured at this NMI and the pilot only (no other participants measured these lamps), the comparison was actually a number of bilateral comparisons between the pilot and individual NMIs.

1.5. TIMETABLE OF THE COMPARISON

The table shows the actual dates of the comparison steps.

	Round 1 of NMI	Lamps send to VNIIOFI	Pilot measurements	Lamps send back to NMI	Round 2 of NMI	NMI reported Results to Pilot
BNM-INM	Jan 1999	Feb 1999	Jan 2000	Feb 2000	May-June 2001	May 2002
NIST	Sept 1998	Oct 1998	July-Aug 1999	Dec 1999	Oct 2001	Mart 2004
NRC	Oct 1999	Nov 1999	April 2000	Sept 2000	Oct 2001	Feb. 2006
PTB	Feb 1999	May 1999	Nov-Dec 1999	March 2000	Aug-Sept 2000	Oct 2000

2. MEASUREMENTS AT THE PILOT LABORATORY (VNIIOFI)

2.1. SPECTRAL RADIANCE FACILITY DIAGRAM

Spectral Radiance measurement facility used for the comparison is shown on the diagram (Fig.2.1).

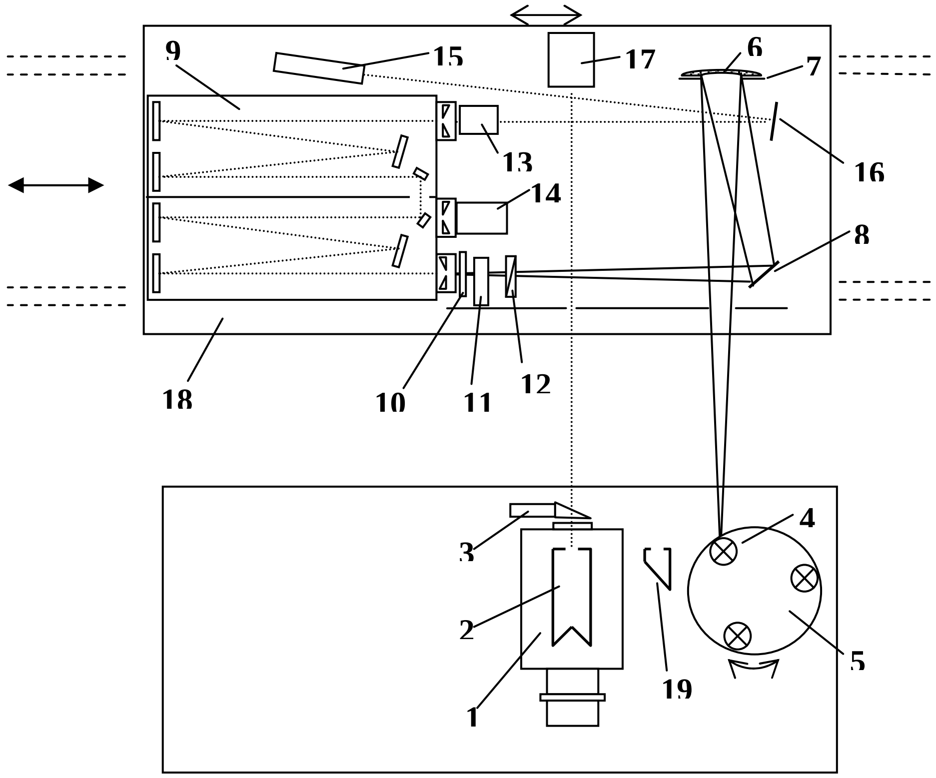

Fig.2.1. Spectral Radiance Facility of VNIIOFI

The facility was consists of the following elements:
1 – High-temperature blackbody of BB22p type;
2 – Radiating cavity of the blackbody;
3 – Feed-back optics for blackbody temperature stabilization system;
4 – Measuring lamp;
5 – Rotating table for the lamps;
6 – Focusing mirror;
7 – Mask of the focusing mirror;
8 – Flat mirror;
9 – Double grate monochromator;
10 – Set of cut-off filters for monochromator;
11 – Chopper for monochromator;
12 – Polarizer;
13 – Set of replacement detectors (photomultiplier or Si photodiode);
14 – PbS photoresistor;
15 – Alignment lasers;
16 – Flat mirror for alignment lasers;
17 – Pyrometer for blackbody temperature measurements;
18 – Translation stage;
19 – Black target for Dark signal measurement;

2.2. PRIMARY SCALE REALIZATION

Spectral Radiance scale was realized by using of a high-temperature blackbody (1 on the Figure 2.1). The blackbody was BB22p type [1-3] with a graphite radiator. Cylindrical cavity (2) of the BB22p has depth of 140 mm, diameter of 22 mm and opening diameter of 15 mm. The bottom of the cavity was a graphite cone of 140°. The BB22p was a windowless blackbody: no glass plate covered the radiation output hole. The BB22p was blown up with argon, which went out through the output hole. The effective emissivity estimated was about 0.999.

Feedback system was used for blackbody temperature stabilization. Feedback optics (3) was placed just in front of blackbody output. It consisted of flat mirror, lens, glass filter and Si photodiode. All elements were collected inside the temperature-stabilized water jacket. Part of the cavity bottom radiation was reflected by flat mirror and used for feedback purpose. The main part of the cavity radiation went through the large hole in the center of that mirror without any changes in the spectrum.

The Spectral Radiance realized by the blackbody was calculated as

$$L_{BB}(\lambda,T) = \varepsilon_{eff} \bullet \frac{C_1}{\pi\lambda^5 n^2} \bullet \frac{1}{exp\left(\frac{C_2}{\lambda T n}\right) - 1}, \qquad (2.1)$$

were
$C_1 = 3.74177 \cdot 10^{-16}$ W·m²;
$C_2 = 1.4388 \cdot 10^{-2}$ K·m;
λ - wavelength in vacuum;
T – temperature of the blackbody;
n = 1.000285 – air refraction index;
ε_{eff} = 0.999 – effective emissivity of the blackbody.

The temperature of the BB22p was varied from 1750 K to 2600 K in depends of spectral range to match spectral radiance of a tungsten strip lamp. For instance, for the range from 300 to 1050 nm the temperature of the blackbody was about 2300 K. The TSP-2 [4] type radiance thermometer (17 on the diagram) was used for measuring the BB22p temperature. The TSP-2 was based on the temperature-stabilized detector, which was combination of Si photodiode and interference filter with the central wavelength of 650 nm and band pass of 20 nm.

2.2.1. Scale realization uncertainties.

Accuracy of the BB temperature measurements gave the main contribution to the uncertainty of the VNIIOFI spectral radiance scale realization. TSP-2, which relative spectral responsivity was previously measured, was calibrated against a copper fixed-point blackbody and a set of temperature standard lamps. In October 2000 the TSP-2 took part in the international comparison of radiation temperature scales [5] and showed good agreement with NPL and PTB temperature scales. The uncertainty of the TSP-2 during the CCPR-S1 intercomparison was estimated to be 0.6 K (k=1) at the level of 2300 K (see Table 2.1). Other contributions were due to blackbody drift and non-uniformity, limits in estimating effective emissivity ε_{eff} and non-accurate knowledge of C_1, C_2 and n (equation 2.1). The budget of uncertainties of the spectral radiance realization is shown in Table 2.2.

Table 2.1. Uncertainty budget of the blackbody temperature measurement

Uncertainty Sources for the temperature at the level of 2300 K (k=1), K	
Cu blackbody realization	0.1
Relative Spectral responsivity	0.4
Size-of-source effect	0.2
Non-linearity and gain ratio	0.1
Stability	0.3
Alignment and focusing repeatability	0.2
Ambient temperature	0.1
Total	**0.6**

Table 2.2. Uncertainty budget of the Spectral Radiance scale realization

Wavelength, Nm	Relative Standard Uncertainties (k=1), %							
	n	C_1	C_2	ε_{eff}	T measure-ment	Blackbody Uniformity	Blackbody Drift	Total
220	0.06	0.01	0.12	0.15	0.74	0.19	0.10	**0.80**
230	0.06	0.01	0.11	0.15	0.59	0.18	0.09	**0.76**
240	0.05	0.01	0.11	0.15	0.68	0.17	0.09	**0.73**
250	0.05	0.01	0.10	0.10	0.65	0.16	0.09	**0.69**
260	0.05	0.01	0.10	0.10	0.63	0.16	0.08	**0.67**
270	0.05	0.01	0.09	0.10	0.61	0.15	0.08	**0.65**
280	0.05	0.01	0.09	0.10	0.58	0.15	0.08	**0.62**
290	0.04	0.01	0.09	0.10	0.56	0.14	0.08	**0.60**
300	0.04	0.01	0.09	0.10	0.55	0.14	0.07	**0.59**
325	0.04	0.01	0.08	0.10	0.50	0.13	0.07	**0.54**
350	0.04	0.01	0.07	0.10	0.47	0.12	0.06	**0.51**
375	0.04	0.01	0.07	0.05	0.44	0.11	0.06	**0.47**
400	0.04	0.01	0.07	0.05	0.41	0.10	0.05	**0.43**
450	0.03	0.01	0.06	0.05	0.36	0.09	0.05	**0.38**
500	0.03	0.01	0.06	0.05	0.33	0.08	0.04	**0.35**
550	0.02	0.01	0.05	0.05	0.30	0.07	0.04	**0.32**
600	0.02	0.01	0.05	0.05	0.27	0.07	0.04	**0.29**
656.3	0.02	0.01	0.04	0.05	0.25	0.06	0.03	**0.27**
700	0.02	0.01	0.04	0.05	0.23	0.06	0.03	**0.25**
800	0.02	0.01	0.04	0.05	0.20	0.05	0.03	**0.22**
900	0.01	0.01	0.03	0.05	0.18	0.05	0.02	**0.20**
1000	0.01	0.01	0.03	0.05	0.16	0.04	0.02	**0.18**
1050	0.01	0.01	0.03	0.05	0.16	0.04	0.02	**0.18**
1200	0.01	0.01	0.03	0.10	0.14	0.03	0.02	**0.18**
1550	0.01	0.01	0.02	0.10	0.11	0.03	0.01	**0.15**
1700	0.01	0.01	0.02	0.10	0.10	0.02	0.01	**0.14**
2100	0	0.01	0.02	0.10	0.08	0.02	0.01	**0.13**
2300	0	0.01	0.02	0.10	0.08	0.02	0.01	**0.13**
2400	0	0.01	0.02	0.10	0.07	0.02	0.01	**0.13**
2500	0	0.01	0.02	0.10	0.07	0.02	0.01	**0.13**

2.3. LAMPS MEASUREMENT

The lamps, took part in the intercomparison, were measured by direct comparing with BB22p. Therefore, there was no any transfer standards used for the intercomparison lamps measurements.

Measuring lamp position was next to the blackbody, at about 300 mm distance. Lamps were set up on the rotating table (5 in the Figure 2.1). This allowed aligning three lamps a priori. In between the lamp and blackbody in the source table there was a black target (19) for dark signal measurement.

The blackbody and lamp ware compared by using spectral comparator based on monochromator with a set of detectors and imaging optics. All elements of the spectral comparator were set up on the translation stage (18) just opposite to the source table. Therefore, the comparator could be moved along the source table as a whole thing. The translation of the stage was 500 mm, therefore not more than two sources could be compared (just one lamp and the blackbody) at once.

The monochromator (9) was a double grate one of JOBIN YVON HRD1 type. Three pairs of gratings (1200, 600 and 300 s/mm) were used to cover the whole spectral range from 220 to 2500 nm. A set of second order cut-off filters (10) was mounted in front of the entrance slit. The gratings cut-off filters were changed manually.

Three detectors were used: multi-alkali PMT, Si photodiode, and PbS photoresistor for the following spectral ranges: 220 to 350 nm, 350 to 1050 nm and 1200 to 2500 nm respectively. The PMT and Si were mounted in front of the main exit slit of the monochromator (position 13 on the diagram) alternatively, and were changed manually. The PbS (14) was mounded on the additional exit slit. In this case the monochromator was used as a single one. Optical chopper (11) was used together with PbS photoresistor.

Spectral bandpass of the monochromator was: 1 nm in the range 220 to 700 nm, 2 nm in the range 700 to 1050 nm and 8 nm in the range 1200 to 2500 nm.

The imaging optics was consisted of a toroidal mirror (6) and flat mirror (8). The toroidal mirror had diameter of 150 mm and focal length f = 600 mm. The distance from the mirror to the source was 1200 mm. Therefore, the image of the measuring source (strip of the lamp or opening of the blackbody) was focused on the entrance slit of the monochromator with magnification 1:1. A mask (7) was put in front of the toroidal mirror to form a solid angle of measuring source radiation.

The monochromator showed strong polarization dependence. Radiation of the strip lamps was, as a role, polarized by the level of up to a few percent. To avoid a systematic error associated with the polarization dependence of the monochromator a thing film polarizer (12) was used. The Lamp to BB ratio was measured for two orthogonal orientations of the polarizer and then averaged.

Wavelength setting, stage positioning and detectors signal reading were made automatically within several spectral ranges.

The procedure of the measurement was the following: the polarizer set in the orientation $\parallel$; wavelength set; stage moved at the black target position; dark signal read; stage moved at the lamp position; LAMP signal read; stage moved to the BB; BB signal read; ratio LAMP/BB calculated; the signals and ratio saved in the file; then measurements repeated so that four to six ratios measured for each wavelength with necessary stage movements. Then new wavelength set. Temperature of the blackbody was measured twice for each individual cycle of measurements: just before and immediately after. After that the polarizer orientation changed to the (⊥), which was orthogonal to the orientation (||), and then measurements were repeated in the same spectral range.

The spectral radiance of the lamp was calculated as following:

$$L_{lamp}(\lambda) = \frac{1}{2} \bullet (R_{\parallel}(\lambda) + R_{\perp}(\lambda)) \bullet L_{BB}(\lambda, T) \qquad (2.2)$$

were $R_{\parallel}(\lambda)$ and $R_{\perp}(\lambda)$ – the LAMP-to-BB signal ratios (inclusive of darks) for two orthogonal orientations of the polarizer.

Each lamp was measured at list tree times in all spectral range and the averages were assumed as final values of spectral radiance.

2.3.1. Lamps measurement uncertainties

Lamp current was set and measured with the relative standard uncertainty of *di/i*=0.006%, which corresponds to the radiance temperature uncertainty of about 0.07 K (*k*=1).

Wavelength accuracy of the monochromator was not worse that Δλ=0.2 nm. Associated spectral radiance uncertainty is $u_\lambda(\lambda)$= Δλ*∂*R*(λ)/∂λ, where *R*(λ) – Lamp-to-Blackbody signal ratio as a function of wavelength. Figure 5.2 shows the typical ratio spectrum for NIST's lamps. $u_\lambda(\lambda)$ slightly depended on the lamp type but did not exceed 0.1%.

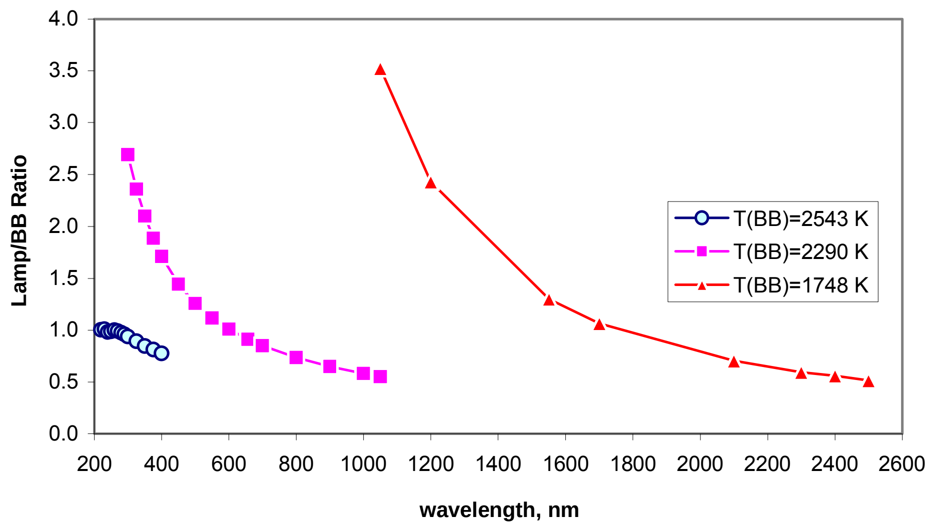

Figure 2.2. Typical ratio spectrum *R*(λ) for NIST's lamps.

One of the main uncertainty was that associated with **lamps alignment**. It was estimated as about 0.25% in visible, less than 0.2% in IR and more than 0.5% in UV.

Polarization effect was another source of uncertainty. We estimated is as 0.1% spectrally independent.

In the IR range there were two more uncertainty sources connected with **linearity** of the PlS plus Lock-in amplifier system **and cut-off filters**.

Lamp/BB ratio (Type A) was, as a rule, within 0.2% in the range from 300 to 1200 nm and increased toward the spectral range edges.

Table 2.3 shows the typical uncertainty budget.

Table 2.3. Uncertainty budget of lamps measurement

Wavelength, nm	Relative Standard Uncertainties (k=1), %								
	VNIIOFI SR Scale Realization	Lamp current	Lamp alignment	Wavelength accuracy	Polarization	Cut-off filters	Linearity	Lamp/BB Ratio	**Total**
220	0.80	0.09	0.51	0.04	0.10			0.60	**1.13**
230	0.76	0.08	0.49	0.04	0.10			0.40	**1.00**
240	0.73	0.08	0.47	0.04	0.10			0.27	**0.92**
250	0.69	0.08	0.45	0.04	0.10			0.23	**0.87**
260	0.67	0.07	0.44	0.04	0.10			0.20	**0.84**
270	0.65	0.07	0.42	0.04	0.10			0.18	**0.80**
280	0.62	0.07	0.41	0.04	0.10			0.18	**0.77**
290	0.60	0.07	0.39	0.04	0.10			0.17	**0.75**
300	0.59	0.06	0.38	0.04	0.10			0.17	**0.73**
325	0.54	0.06	0.36	0.04	0.10			0.15	**0.67**
350	0.51	0.05	0.33	0.04	0.10			0.15	**0.64**
375	0.47	0.05	0.31	0.04	0.10			0.13	**0.59**
400	0.43	0.05	0.30	0.04	0.10			0.13	**0.56**
450	0.38	0.04	0.27	0.05	0.10			0.13	**0.50**
500	0.35	0.04	0.25	0.04	0.10			0.12	**0.46**
550	0.32	0.03	0.23	0.04	0.10			0.12	**0.43**
600	0.29	0.03	0.22	0.03	0.10			0.10	**0.39**
656.3	0.27	0.03	0.20	0.03	0.10			0.10	**0.37**
700	0.25	0.03	0.20	0.03	0.10			0.09	**0.35**
800	0.22	0.02	0.18	0.02	0.10			0.09	**0.32**
900	0.20	0.02	0.17	0.02	0.10			0.10	**0.30**
1000	0.18	0.02	0.16	0.02	0.10			0.12	**0.29**
1050	0.18	0.02	0.16	0.03	0.10			0.17	**0.31**
1200	0.18	0.02	0.15	0.02	0.10	0.15	0.20	0.18	**0.40**
1550	0.15	0.01	0.14	0.02	0.10	0.15	0.20	0.22	**0.41**
1700	0.14	0.01	0.14	0.02	0.10	0.15	0.20	0.24	**0.41**
2100	0.13	0.01	0.13	0.02	0.10	0.15	0.20	0.25	**0.41**
2300	0.13	0.01	0.13	0.02	0.10	0.20	0.20	0.27	**0.44**
2400	0.13	0.01	0.13	0.02	0.10	0.20	0.20	0.27	**0.44**
2500	0.13	0.01	0.13	0.02	0.10	0.20	0.20	0.30	**0.46**

Table 2.4 shows the Reproducibility of the Pilot (VNIIOFI) measurements.

Table 2.4. Reproducibility of Pilot (VNIIOFI) measurements

Wavelength, nm	Reproducibility Components, %					**Total**
	TSP stability and repeatability	Lamp current	Lamp alignment	BB stability	Lamp/BB Ratio	
220	0.37	0.09	0.51	0.10	0.60	**0.88**
230	0.36	0.08	0.49	0.09	0.40	**0.73**
240	0.34	0.08	0.47	0.09	0.27	**0.65**
250	0.33	0.08	0.45	0.09	0.23	**0.61**
260	0.31	0.07	0.44	0.08	0.20	**0.58**
270	0.30	0.07	0.42	0.08	0.18	**0.56**
280	0.29	0.07	0.41	0.08	0.18	**0.54**
290	0.28	0.07	0.39	0.08	0.17	**0.52**
300	0.27	0.06	0.38	0.07	0.17	**0.51**
325	0.25	0.06	0.36	0.07	0.15	**0.47**
350	0.23	0.05	0.33	0.06	0.15	**0.44**
375	0.22	0.05	0.31	0.06	0.13	**0.41**
400	0.20	0.05	0.30	0.05	0.13	**0.39**
450	0.18	0.04	0.27	0.05	0.13	**0.36**
500	0.16	0.04	0.25	0.04	0.12	**0.33**
550	0.15	0.03	0.23	0.04	0.12	**0.30**
600	0.14	0.03	0.22	0.04	0.10	**0.28**
656.3	0.12	0.03	0.20	0.03	0.10	**0.26**
700	0.12	0.03	0.20	0.03	0.09	**0.25**
800	0.10	0.02	0.18	0.03	0.09	**0.23**
900	0.09	0.02	0.17	0.02	0.10	**0.22**
1000	0.08	0.02	0.16	0.02	0.12	**0.22**
1050	0.08	0.02	0.16	0.02	0.17	**0.25**
1200	0.07	0.02	0.15	0.02	0.18	**0.25**
1550	0.05	0.01	0.14	0.01	0.22	**0.27**
1700	0.05	0.01	0.14	0.01	0.24	**0.28**
2100	0.04	0.01	0.13	0.01	0.25	**0.29**
2300	0.04	0.01	0.13	0.01	0.27	**0.30**
2400	0.04	0.01	0.13	0.01	0.27	**0.30**
2500	0.04	0.01	0.13	0.01	0.30	**0.33**

2.4. REFERENCES

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3. BNM / INM – VNIIOFI BILATERAL COMPARISON

The present Part of the document is based on the Report of BNM-INM submitted to the pilot by e-mail in May 2002.

3.1. BNM-INM LAMPS AND SPECTRAL RANGE

For the comparison BNM-INM used one set of three lamps of Polaron 24/G/UV type. All three lamps were measured in identical conditions to cover the spectral range of 300 to 2500 nm. The main characteristics of the lamps and the measuring conditions are listed in the Table 3.1.

Table 3.1. Characteristics of theBNM-INM lamps and the measuring conditions

Type of lamps	Polaron 24/G/UV
Number of lamps	3
Spectral Range	300 – 2500 nm
Radiance temperature t_r(650 nm)	2170 K;
Current	15.000 A
Strip size	1.7x34 mm
Target area size	0.5x0.5 mm
Solid angle	0.01 sr

The lamps were marked with the following numbers: 145, 146 and 148.

For the first round of BNM-INM measurement, which was done in 1999, the setting of lamps temperature was wrong. Therefore, BNM-INM presented, as the first round, the results of the measurement, which was done in **1996** for two lamps (145 and 146) and for the range from 300 to 1050 nm only.

The second round is achieved in the whole spectrum range from 300 nm to 2500 nm for all three lamps (145, 146 and 148) for the same temperature. The second round measurements were done on March and May 2001. Other checking measurements were done in June and September 2001. In April 2002 BNM-INM measured the radiance in the same conditions than 1999’s one in order to estimate more accurately the lamps drift.

3.2. REALISATION OF RADIANCE STANDARD

The radiance is derived from the blackbody radiator whose temperature is referred to the copper fixed point. The temperature of the blackbody is directly measured by comparison to a fixed point blackbody in the higher part of the spectrum or compared to a pyrometric transfer lamp in the lower part of the spectrum.

The spectrum is divided in two parts with two different apparatuses and almost similar process differing by the standard of temperature.

On the spectroradiometric bench :

From 300 nm to 1050 nm we use a pyrometric standard lamp (Lpyr) for measuring the temperature of a Variable Temperature Blackbody (VTBB) with the spectro radiometric bench operating at 654 nm. A filter pyrometer operating at 654 nm is also used for monitoring the VTBB temperature.

The radiance of this blackbody is compared to the one of the lamps by the mean of the spectro-radiometric bench.

On a the infrared radiance comparator:

From 950 nm to 2500 nm we use a copper fixed point blackbody (CuBB) as temperature standard for measuring the temperature of a VTBB by the mean of a so called 'radiance comparator' operating at 950 nm.

The radiance of the VTBB is compared to the one of the lamps through this same radiance comparator in the infrared spectrum range (950 nm- 2500 nm).

The pyrometric standard lamp used in the first part of the spectrum is calibrated with the radiance comparator using the CuBB as reference at 650 nm and 654 nm.

Table 3.2. Optical characteristics of spectro-radiometric bench and radiance comparator

	Spectro-radiometric bench	Radiance comparator
Optical entrance	1 toroidal mirror R=1600 mm 1 plane mirror	1 concave mirror R=1000 mm 1 convex mirror R=5000 mm
Magnification	1	1
Alignment	Laser Direct observation of source image on field stop	Laser Reflex device and CCD camera
Aperture stop	50 mm placed at 650 mm from source	40 mm placed at 500 mm from source
Field stop	□ 0,5 mm	Φ 0,5 mm
Spectral selection	Double grating monochromator $\Delta\lambda = 1$ nm	Simple grating monochromator $\Delta\lambda = 6$ nm
Detector	Photo multiplier Silicon photo diode	Silicon photo diode Lead sulphide detector

3.3. MEASURING PROCESS

3.3.1. Spectrum range 300 nm-1050 nm

3.3.1.1. VTTB temperature

Some reason such as photo multiplier stability or saving burning time of pyrometric standard, lead us to use a filter pyrometer for monitoring the temperature of the VTBB.

For avoiding an accurate characterisation of this pyrometer we check its temperature sensitivity by measuring the VTBB temperature with pyrometer and spectro-radiometric bench at the same time. Then we calculate the sensitivity factor of the pyrometer.

3.3.1.2. Radiance comparison

At each wavelength setting we measure in a symmetrical cycle, photo currents corresponding to the radiance of:

→Lamp →VTBB →Room temperature black surface →VTBB as measured by pyrometer

The 300 nm-1050 nm range is divided in two parts. Grating and detector are changed to be adapted to the wavelength.

3.3.2. Spectrum range 950 nm-2500 nm

3.3.2.1. VTTB temperature

In this experimental device the stability of radiance comparator and VTBB temperature avoid to use an additional pyrometer.

The 950 nm radiance comparator response with its silicon photodiode detector is calibrated twice a day by observing the melting and freezing plateau of the copper fixed point. This is the pyrometric calibration of the radiance comparator.

A pyrometric measurement of the VTBB is performed with a 15 minutes time interval during the radiance calibration of each lamp by measuring its 950 nm response. The VTBB temperature reproducibility is better than 25 mK

3.3.2.2. Radiance comparison

At each wavelength setting we measure in a symmetrical cycle, photo currents corresponding to the radiance of:

→Lamp →VTBB →Room temperature black surface →VTBB pyrometric measurement

For radiance comparison the signal is issued from the lead sulphide detector of the comparator. The detectors in the comparator are automatically changed in a few seconds.

3.3.3. Summary of measuring process

A first round of radiance measurement has been made in 1999 with a temperature of lamps which did not fit with the pilot laboratory requirements. So we have chosen to present the one having been done previously in 1996 as our first measurement round. The lamps have not been used in this period excepted for the comparison reported here.

Table 3.3. Summary of measuring process

	300-550	1050-2500
1st round 1996	Spectro radiometric bench Lamps 145 and 146	Not measured
2nd round 2001	Spectro radiometric bench Lamps 145 146 and 148	Infrared radiance comparator Lamps 145, 146 and 148
Low current 1999 (drift control)	Spectro radiometric bench Lamps 145 146 and 148	
Low current 2002 (drift control)	Spectro radiometric bench Lamps 145 146 and 148	

3.4. RADIANCE CALCULATION AND CORRECTIONS

3.4.1. VTBB temperature

The temperature value of VTBB is calculated from the radiance ratio of reference and VTBB sources using the Wienn approximation of Planck law. The error induced is neglected but it is lower than 10mK in all cases.

$$\frac{1}{T_{VTBB}}=\frac{1}{T_{BBCu}}-\frac{n\cdot\lambda}{C2}\cdot Ln\left(\frac{R_{VTBB}}{R_{BBCu}}\right) \text{ or } \frac{1}{T_{VTBB}}=\frac{1}{T_{Lpyr}}-\frac{n\cdot\lambda}{C2}\cdot Ln\left(\frac{R_{VTBB}}{R_{Lpyr}}\right)$$

depending on temperature reference.

- R_{VTBB}, R_{BBCu} and R_{Lpyr}, or T_{VTBB}, T_{BBCu} and T_{Lpyr}, are the radiance responses or the radiance temperature of the sources VTBB, BBCu and Lpyr, respectively.
- n, is the refractive index of air and λ is the air value of wavelength.
- C2 is the second constant of radiation : 0.014387752 mK.

3.4.2. Correction factors and their associated uncertainty

3.4.2.1. Lamp current adjustment

As the measured value of current does not exactly match the calibrated value we correct the radiance temperature according to the (dT/dI) coefficient of the pyrometric lamp. This correction is not applied to the 950 nm to 2500 nm range because pyrometric lamp is not used.

The correction been very small its uncertainty is neglected but the uncertainty attached to the current measurement remains.

3.4.2.2. Size of source effect

Due to a non null sensitivity of radiance measurement device outside the target field we must subtract from the signal the amount of flux coming from the surrounding part of the source.

This correction is neglected in the range 300 nm to 650 nm because is this case the temperature reference and the radiance lamp have the same emitting area. The error affecting the temperature measurement compensates the error affecting the radiance measurement. Furthermore the size of the VTBB emitting area is small, reducing the effect of the source size.

This correction is applied in the second case in the 1050 nm to 2500 nm range because a blackbody with a large emitting area is used as a reference of temperature. The correction is applied in a first step to the VTBB temperature measurement and in a second step to the radiance comparison of the lamp against the VTBB.

The uncertainty of this correction is 30% of the correction itself.

3.4.2.3. ‘Out of band correction’ : ‘Blocking’.

The transmittance, outside the transfer function, is not exactly null. Hence, the flux is affected for a small part by the entire spectrum of the source.

In the 300 nm to 1050 nm range the double grating monochromator insures a very good spectral selection so that the correction is null.

In the 950 nm to 2500 nm the temperature is measured at the 950 nm wavelength where the correction is negligible. It is not either applied to radiance comparison because the combination of the decreasing radiance with wavelength and high pass filters reduces the effect of ‘out of band’ transmittance.

This effect is corrected in pyrometric lamp calibration at 650 nm which is not reported here.

3.4.2.4. Wavelength adjustment

There is no need to correct it because the monochromator wavelength can be adjusted to any suitable value. The uncertainty of wavelength setting is 0.2 nm in the 300 nm to 1050 nm range and 0.025 nm in the 950 nm to 2500 nm range. The temperature uncertainty is computed by using Planck law.

3.4.2.5. Detector non linearity

Photo multiplier and silicon detector works far from their limit of linearity but the lead sulphide detector is running near its limit. Corrections of non linearity are not applied because the lightning conditions of detector in radiance measurement and in linearity measurement are not similar. The uncertainty is taken equal to the value of non linearity correction itself.

3.4.2.6. Lamps drift

As a consequence of the use of too low current settings (~10 A) in 1999 these measurements have not been used as our measurement round and replaced by previous measurements made in 1996 (=15 A). It is the reason why our first and second measurement rounds are 5 years far one from the other (1996 and 2001).

Results of first and second round presented below show a significant drift of the lamps.

In order to diminish or explain the influence of such a large time interval on lamp drift we have decided to perform a second comparison in 2002 at the same current settings than the 1999 measurement (~10 A). This comparison has been limited to the 350 nm to 650 nm part of the spectrum, the only one giving an uncertainty suiting to this comparison. Results of the comparison performed at the low current are not used for the CCPR S1 intercomparison.

Table 3.4. Low current radiance results : used as lamp drift control

	Lamp 145 (10.55 A)		Lamp 146 (10.30 A)		Lamp 148 (10.38 A)		Relative uncertainty	
	1999	2002	1999	2002	1999	2002	1999	2002
350	2.279E+06	2.352E+06	2.313E+06	2.357E+06	2.445E+06	2.543E+06	2.2%	2.0%
375	7.051E+06	7.289E+06	7.169E+06	1.871E+12	7.567E+06	7.742E+06	1.5%	1.4%
400	1.858E+07	1.915E+07	1.884E+07	1.919E+07	1.980E+07	2.013E+07	0.9%	0.7%
450	8.789E+07	9.040E+07	8.920E+07	9.052E+07	9.319E+07	9.449E+07	0.8%	0.6%
500	2.869E+08	2.943E+08	2.906E+08	2.945E+08	3.023E+08	3.060E+08	0.7%	0.5%
550	7.213E+08	7.383E+08	7.299E+08	7.380E+08	7.556E+08	7.650E+08	0.6%	0.5%
600	1.494E+09	1.520E+09	1.507E+09	1.520E+09	1.558E+09	1.574E+09	0.5%	0.4%
650	2.667E+09	2.713E+09	2.690E+09	2.712E+09	2.772E+09	2.800E+09	0.5%	0.4%

The Table 3.5 shows the variations of the lamps observed between the first and the second round with the ~10 A current and the normal 15 A current. We give here a mean value at the 500 nm wavelength.

Table 3.5. Radiance variation observed between the 1st and 2nd round

	L145		L146		L148	
	10.55 A	15.000 A	10.300 A	15.000A	10.380 A	15.000 A
Relative variation ($2^{nd}-1^{st}$)round	+2.5%	+2.5%	+1.3%	+0.6%	+1.2%	-

3.5. UNCERTAINTY

We describe the other sources of uncertainty then we give two uncertainty budgets :

The first one giving the temperature uncertainty of the blackbody and the second one giving the radiance uncertainty of the lamps referring to the effects due the comparison between lamps and blackbody.

The three lamps are not so different we need to distinguish their uncertainties.

3.5.1. Blackbody temperature uncertainty

The uncertainties are given as their standard deviation. A percentage means that it is the relative value of uncertainty.

Table 3.6. Uncertainty of the variable temperature blackbody

	Spectro radiometric bench	Kelvin	Radiance comparator	Kelvin
Temperature reference	Lamp at 1910 K		Fixed point BB at 1357 K	
Reference		0.25		0.025
Control pyrometer calibration	0.15 %	0.24	-	-
Blocking	0	0	0	0
Wavelength	0.2 nm	0.05	0.01 nm	0.01
Size of source effect	0	0	0.08 %	0.14
Lamp current : resistor and voltmeter calibration	0,005 %	0.05	-	-
Non linearity	0.01 %	0.02	0.01 %	0.02
Alignment	0.10 %	0.16	0	0.00
Final uncertainty		0.39		0.14

3.5.2. Spectral radiance uncertainty

Uncertainty represented by relative standard deviation is given for typical wavelengths. If applied, the parameter uncertainty is given in the second column.

Table 3.7. Uncertainty budget of lamps measurements

Description of uncertainty parameter and its value		300	325	500	850	1050	1050	1550	2200	2500
VTBB temperature 1st round 300-1050 nm	1,2 K	1,61%	1,48%	0,96%	0,57%	0,46%	-	-	-	-
VTBB temperature 2nd round 300-1050 nm	0,39 K	0,52%	0,48%	0,31%	0,18%	0,15%	-	-	-	-
VTBB temperature 2nd round 950-2500 nm	0,14 K	-	-	-	-	-	0,07%	0,05%	0,04%	0,03%
Photo current		1,50%	0,60%	0,18%	0,09%	0,09%	0,37%	0,13%	0,34%	0,34%
Blocking	0	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Wavelength 300-1050 nm	0,2 nm	0,34%	0,29%	0,12%	0,04%	0,03%	-	-	-	-
Wavelength 950-2500 nm	0,025 nm	-	-	-	-	-	0,01%	0,00%	0,00%	0,00%
Size of source	0,30%	-	-	-	-	-	0,30%	0,30%	0,30%	0,30%
Non linearity		0,01%	0,01%	0,01%	0,01%	0,01%	0,20%	0,20%	0,20%	0,20%
Alignment	0,10%	0,22%	0,20%	0,13%	0,08%	0,06%	0,06%	0,04%	0,03%	0,03%
global uncertainty 1st round		2,23%	1,64%	1,00%	0,58%	0,47%	-	-	-	-
global uncertainty 2nd round		1,64%	0,84%	0,40%	0,22%	0,19%	0,53%	0,39%	0,50%	0,50%

3.6. BNM-INM RESULTS

The values of measured spectral radiance of the lamps and their uncertainties are shown in Table 3.8. The unit of spectral radiance is $W/m^3/sr$. The wavelength is given in nm. The coverage factor of uncertainty is 1

Table 3.8. BNM-INM results: Spectral Radiance ($W/m^3/sr$) and relative Uncertainties

Wavelength, nm	Lamp 145		Lamp 146		Lamp 148		Uncertainty (*k*=1)	
	1st round	2nd round	1st round	2nd round	1st round	2nd round	1st round	2nd round
300	3.224E+07	3.329E+07	4.574E+07	4.493E+07	-	4.300E+07	2.23%	1.64%
325	1.038E+08	1.067E+08	1.399E+08	1.424E+08	-	1.354E+08	1.64%	0.84%
350	2.734E+08	2.823E+08	3.672E+08	3.671E+08	-	3.510E+08	1.37%	0.76%
375	6.175E+08	6.319E+08	8.074E+08	8.125E+08	-	7.786E+08	1.37%	0.76%
400	1.221E+09	1.257E+09	1.577E+09	1.586E+09	-	1.523E+09	1.25%	0.51%
450	3.627E+09	3.729E+09	4.548E+09	4.577E+09	-	4.421E+09	1.25%	0.51%
500	8.135E+09	8.327E+09	9.977E+09	1.001E+10	-	9.714E+09	1.00%	0.40%
550	1.501E+10	1.541E+10	1.804E+10	1.821E+10	-	1.772E+10	1.00%	0.40%
600	2.400E+10	2.455E+10	2.846E+10	2.860E+10	-	2.790E+10	1.00%	0.40%
656.3	3.587E+10	3.599E+10	4.183E+10	4.204E+10	-	4.111E+10	0.60%	0.28%
700	4.544E+10	4.649E+10	5.242E+10	5.283E+10	-	5.179E+10	0.60%	0.28%
800	6.612E+10	6.742E+10	7.490E+10	7.537E+10	-	7.406E+10	0.60%	0.28%
900	8.166E+10	8.269E+10	9.103E+10	9.126E+10	-	8.986E+10	0.58%	0.22%
1000	9.014E+10	9.116E+10	9.909E+10	1.010E+11	-	9.845E+10	0.58%	0.22%
1050	9.173E+10	9.322E+10	1.006E+11	1.017E+11	-	1.003E+11	-	0.53%
1200	-	9.123E+10	-	9.926E+10	-	9.728E+10	-	0.53%
1550	-	6.726E+10	-	7.181E+10	-	7.085E+10	-	0.39%
1700	-	5.623E+10	-	5.978E+10	-	5.904E+10	-	0.39%
2100	-	3.332E+10	-	3.515E+10	-	3.477E+10	-	0.39%
2300	-	2.495E+10	-	2.630E+10	-	2.605E+10	-	0.50%
2400	-	2.226E+10	-	2.339E+10	-	2.316E+10	-	0.50%
2500	-	1.885E+10	-	2.008E+10	-	1.967E+10	-	0.50%

3.7. VNIIOFI RESULTS

Table 3.9 presents the values of Spectral Radiance of the BNM-INM lamps measured at VNIIOFI and their uncertainties.

Table 3.9. VNIIOFI results of the BNM-INM lamps: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp 145	Lamp 146	Lamp 148	Uncertainty (k=1)
300	3,332E+07	4,665E+07	4,343E+07	0,73%
325	1,073E+08	1,459E+08	1,366E+08	0,67%
350	2,821E+08	3,760E+08	3,535E+08	0,64%
375	6,345E+08	8,296E+08	7,826E+08	0,59%
400	1,256E+09	1,618E+09	1,532E+09	0,56%
450	3,712E+09	4,654E+09	4,434E+09	0,50%
500	8,321E+09	1,019E+10	9,762E+09	0,46%
550	1,534E+10	1,843E+10	1,773E+10	0,43%
600	2,449E+10	2,896E+10	2,796E+10	0,39%
656.3	3,653E+10	4,256E+10	4,122E+10	0,37%
700	4,635E+10	5,347E+10	5,193E+10	0,35%
800	6,741E+10	7,637E+10	7,438E+10	0,32%
900	8,282E+10	9,254E+10	9,043E+10	0,30%
1000	9,124E+10	1,008E+11	9,879E+10	0,29%
1050	9,296E+10	1,022E+11	1,002E+11	0,31%
1200	9,083E+10	9,875E+10	9,718E+10	0,40%
1550	6,711E+10	7,179E+10	7,087E+10	0,41%
1700	5,614E+10	5,980E+10	5,906E+10	0,41%
2100	3,342E+10	3,537E+10	3,498E+10	0,41%
2300	2,523E+10	2,661E+10	2,637E+10	0,44%
2400	2,249E+10	2,370E+10	2,347E+10	0,44%
2500	1,915E+10	2,015E+10	2,002E+10	0,46%

3.8. BNM-INM TO VNIIOFI DIFFERENCE.

The percentage differences between BNM-INM measurements, reported for individual rounds, and VNIIOFI measurements are calculated as

$$\Delta_{BNM,j,r} = \left(\frac{L_{BNM,j,r}}{L^P_{BNM,j}} - 1 \right) \cdot 100\% , \qquad (3.8.1)$$

and their uncertainties are calculated as

$$u_{rel}\left(\Delta_{BNM,j,r}\right) = \sqrt{u^2_{rel,BNM,r} + u^2_{rel,VNIIOFI}} , \qquad (3.8.2)$$

where

$L_{BNM,j,r}$ Spectral Radiance of lamp j of BNM-INM, measured by the BNM-INM in round r (=1 to 2);

$L^P_{BNM,j}$ Spectral Radiance of lamp j of BNM-INM, measured by the pilot (VNIIOFI);

$u_{rel,BNM,r}$ Total relative uncertainty reported by BNM-INM for round r;

$u_{rel,VNIIOFI}$ Total relative uncertainty reported by VNIIOFI.

Fig. 3.8.1 and Fig. 3.8.2 show differences $\Delta_{BNM,j,1}$ and $\Delta_{BNM,j,2}$ respectively and their uncertainties.

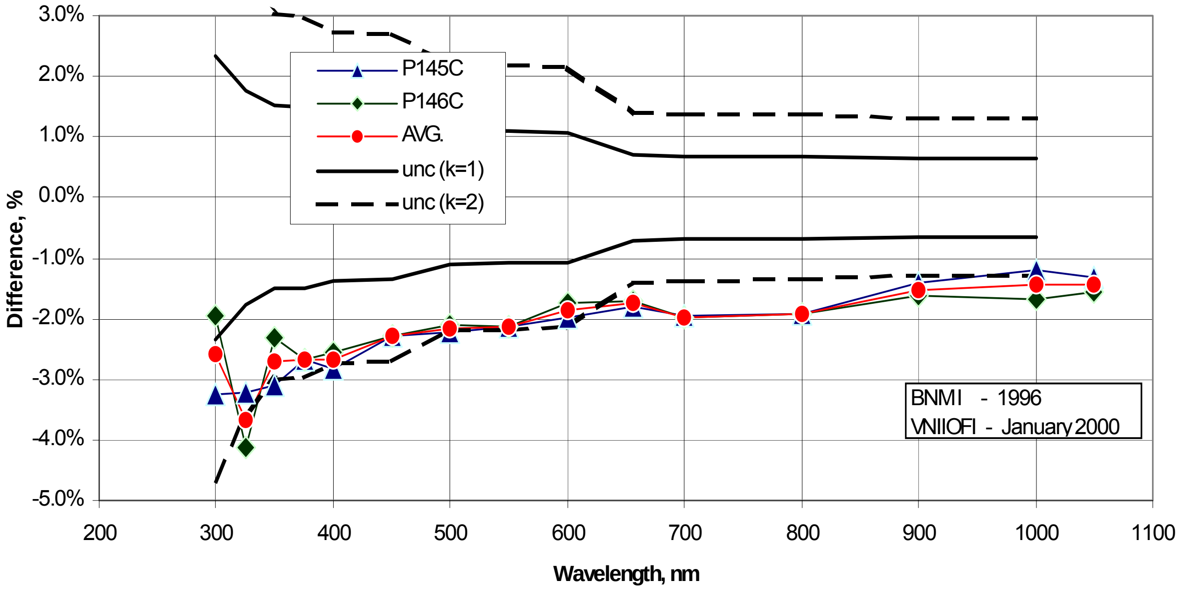

Figure 3.8.1. Difference $\Delta_{BNM,j,1}$ between 1st round of BNM and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (3.8.2) and unc(k=2) = unc(k=1)*2.

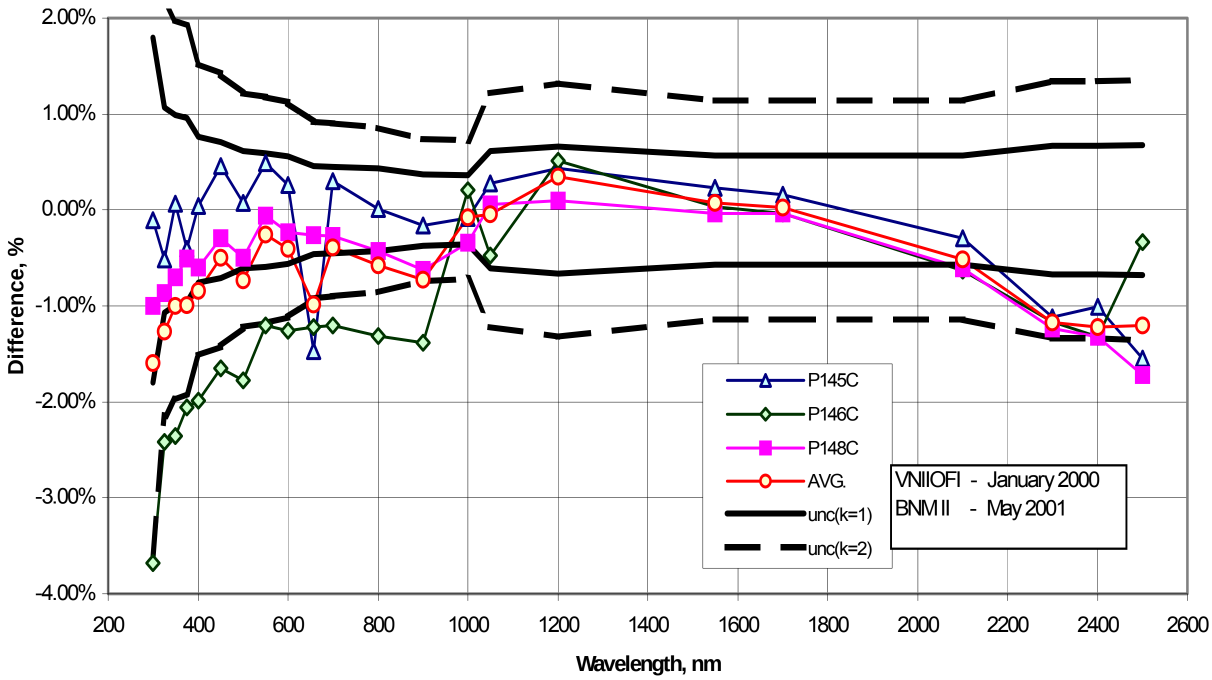

Figure 3.8.2. Difference $\Delta_{BNM,j,2}$ between 2nd round of BNM and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (3.8.2) and unc(k=2) = unc(k=1)*2.

Fig. 3.8.3 shows the BNM to VNIIOFI differences averaged by two rounds. The differences are calculated as

$$\Delta_{BNM,j} = \left(\frac{\overline{L}_{BNM,j}}{L^{P}_{BNM,j}} - 1 \right) \cdot 100\% , \qquad (3.8.3)$$

where $\overline{L}_{BNM,j} = \frac{1}{2} \sum_{r=1}^{2} L_{BNM,j,r}$.

The uncertainties of $\Delta_{BNM,j}$ are calculated as

$$u_{rel}(\Delta_{BNM}) = \sqrt{u^2_{rel,BNM} + u^2_{rel,VNIIOFI}} , \qquad (3.8.4)$$

where $u_{rel,BNM} = \frac{1}{2} \sum_{r=1}^{2} u_{rel,BNM,r}$

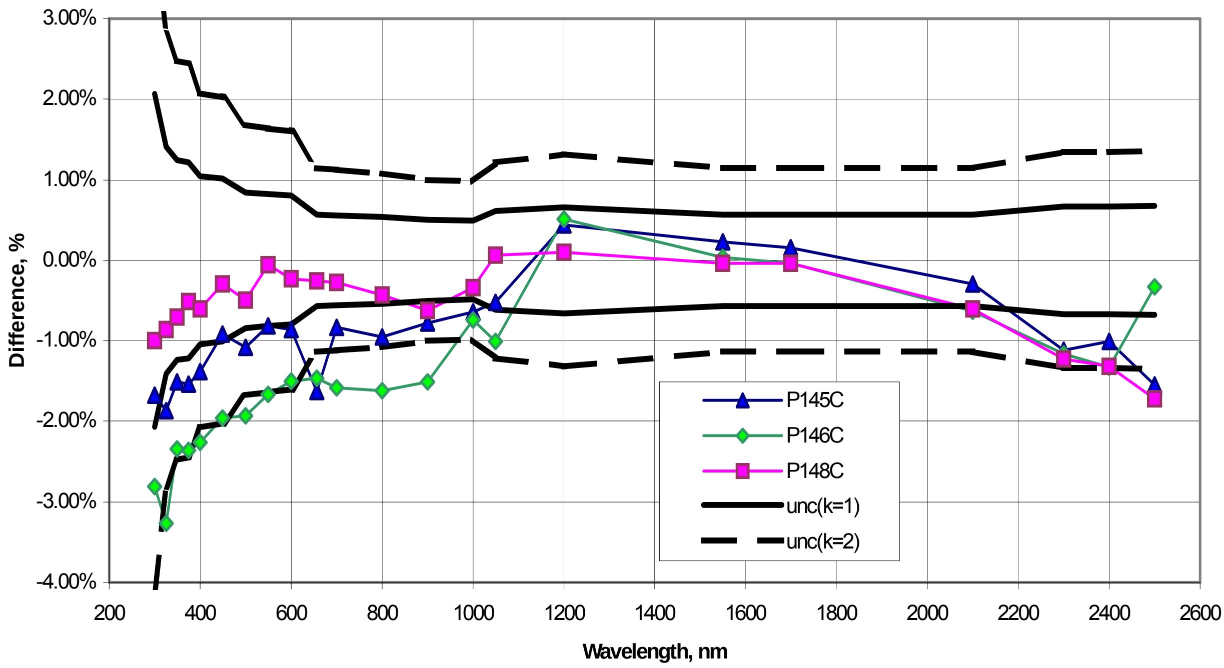

Figure 3.8.3. Difference $\Delta_{BNM,j}$ BNM and VNIIOFI measurements, averaged by two rounds. Uncertainties unc(k=1) calculated by (3.8.4) and unc(k=2) = unc(k=1)*2.

Fig. 3.8.4 shows the total average difference between BNM-INM and VNIIOFI calculated as

$$\Delta_{BNM} = \frac{1}{3} \sum_{j=1}^{3} \Delta_{BNM,j} \qquad (3.8.5)$$

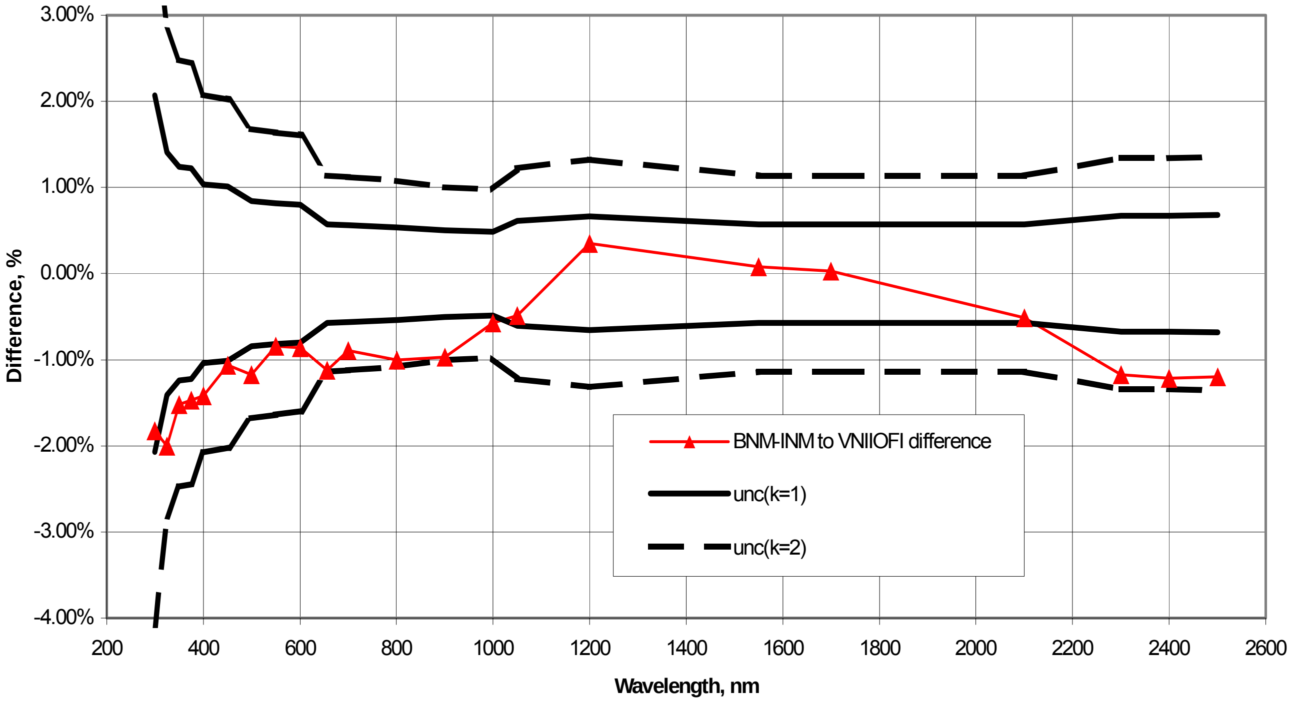

Figure 3.8.4. Difference Δ_{BNM} BNM and VNIIOFI measurements, averaged by two rounds and three lamps. Uncertainties unc(k=1) calculated by (3.8.4) and unc(k=2) = unc(k=1)*2.

4. NIST – VNIIOFI BILATERAL COMPARISON

This Part presents the NIST Report Dated 22 March 2004 combined with the Comparison Questionnaire response.

4.1. INTRODUCTION

NIST prepared six tungsten strip lamps for the comparison. Preparation of the lamps included measurements to determine the lamp stability, spatial uniformity, and polarization. NIST measured the lamps in October 1998 and then hand-carried the lamps to VNIIOFI for measurements. The lamps were returned to NIST in December 2000 and NIST completed the second measurement of the lamps in October 2001.

4.2. SCALE REALIZATION

A full description of the NIST spectral radiance scale and the measurement facility are given Ref [1] and summarized in Ref [2]. The freezing point of gold (GBPP) (1337.33 K) was determined by measurements with an electrical substitution radiometer (ECR) (primary standard). The gold-point blackbody (reference standard) and the Planck radiation equation were used to realize and disseminate the 1990 NIST Radiance Temperature Scale. In the following steps, the FASCAL spectroradiometer was the transfer device used to compare sources. The radiance temperature of the gold-point transfer standard (GPTS), a high stability vacuum lamp operated at approximately 1337.33 K, was determined by comparison to the gold-point blackbody. The radiance temperature of the working standard (WS), a high stability vacuum lamp operated at approximately 1528 K, was determined by comparison to the gold-point transfer standard. The radiance temperature of the variable-temperature blackbody (VTBB) was determined by comparison to the working standard. Finally, the spectral radiance of the comparison lamps was determined by comparison to the variable-temperature blackbody. A flow chart illustrating the sequence of measurements to realize the NIST spectral radiance scale and to transfer the scale to the comparison lamps is shown in Figure 4.1.

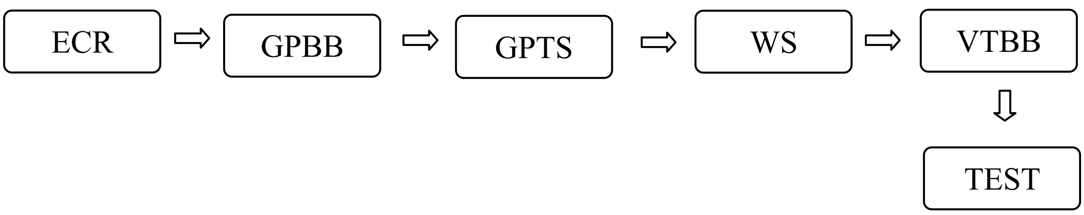

Figure 4.1. Flow chart of NIST spectral radiance scale realization

4.3. FASCAL FACILITY

The Facility for Automated Spectroradiometric Calibrations (FASCAL) spectroradiometer used to transfer spectral radiance units from VTBB to comparison lamps. The block diagram of the FASCAL facility is showed in Figure 4.2.

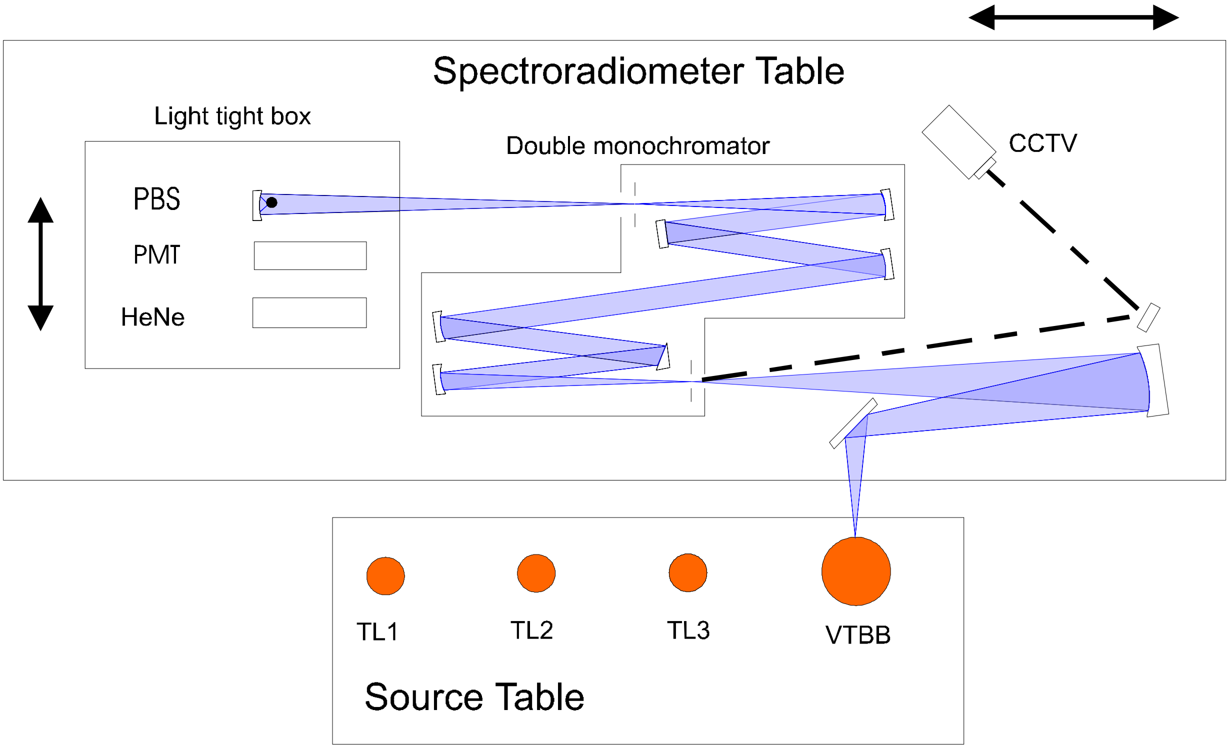

Figure 4.2. Facility for Automated Spectroradiometric Calibrations (FASCAL).

The FASCAL spectroradiometer is based on the prism-grating double monochromator of Cary 14 type with effective spectral bandpass varied from 1 nm at 220 nm to 3 nm at 2500 nm . Two detectors (see table 4.1.) were used for the measurements: PMT for spectral range 220 to 900 nm and PbS for the range 800 to 2500 nm. During the second round of the NIST measurements InGaAs detector was used in IR range instead PbS.

Table 4.1. Detectors characteristics

Detector type	S-20 PMT	PBS
Spectral range (nm)	200 to 900	800 to 2500
Measuring mode	DC	AC
Thermoelectric cooling temperature	-15 °C	-25 °C

Entrance optics focuses sources images to the entrance clit of the monocromator with magnification 1:1. The entrance aperture of the focusing mirror is rectangular in shape, with the vertical angle of 0.125 radian and the horizontal angle of 0.0625 radian. The target spot size is a 0.6 mm wide by 0.8 mm tall rectangle.

4.4. LAMP PREPARATION

NIST provided six General Electric Model 30/T24/13 gas-filled tungsten strip lamps for the comparison. The Lamps had a mogul bi-post base and fused silica window. Size of the lamp strip was 3 mm width and 15 mm height.

The lamps had the following serial numbers: Q123, Q124, Q124, Q129, Q130 and Q133. The serial number was located on the rear of the lamp envelope opposite the side viewed by the spectroradiometer

The lamp was operated on direct current with the longer filament support at positive potential. Three lamps (Q129, Q130 and Q133) were operated at approximately 2270 K and used for the spectral range 220 to 400 nm. Other tree had radiance temperuture of about 2370 K and were calibrated in the spectral range 220 to 400 nm. The measurements that NIST performed to prepare these lamps for use in this comparison are described below.

4.4.1. Aging

In July 1998, the lamps were aged to increase the temporal stability. All six lamps were operated at 2620 K (44 A) for 2 hours. The lamp current was reduced to 35 A for the first set of three lamps and operated at 2270 K for 96 hours. The current for the second set of three lamps was reduced to 38.5 A and operated at 2370 K for 96 hours.

4.4.2. Stability

In September 1998, the stability measurements were performed before the spectral radiance measurements. The spectral radiance of the lamp was measured initially and again after 20 h or 24 h. The stability results at 654.6 nm are shown in Table 4.2.

Table 4.2. Stability results at 654.6 nm

Lamp number	Change in spectral radiance
Q123	-0.08 % in 20 h
Q124	+0.23 % in 20 h
Q125	-0.21 % in 20 h
Q129	-0.26 % in 20 h
Q130	-0.74 % in 20 h
Q133	-0.28 % in 24 h

The relative change in spectral radiance at other wavelengths is expected to be approximately inversely proportional to the wavelength as given by Eq (4.1).

$$\Delta L_{\lambda} = \Delta L_{654.6} \times 654.6 / \lambda \qquad (4.1)$$

where λ is the wavelength in nm, ΔL_{λ} is the change in spectral radiance at λ, and $\Delta L_{654.6}$ is the change in spectral radiance at 654.6 nm.

4.4.3. Polarization

The polarization measurements performed in September 1998 are described in Ref. [1]. Table 4.3 gives the results of the polarization measurements at 654.6 nm. The direction of polarization of the larger component for all the lamps was counter clockwise from the horizontal when viewed from the spectroradiometer.

Table 4.3. Polarization results at 654.6 nm

Lamp number	Degree of polarization	Direction of polarization / °
Q123	0.0045	84.4
Q124	0.0036	83.4
Q125	0.0027	74.4
Q129	0.0070	23.8
Q130	0.0044	52.0
Q133	0.0174	80.1

4.4.4. Spatial uniformity

The difference in spectral radiance from the center position was determined for each lamp at 350 nm and 654.6 nm using a 0.6 mm wide by 0.8 mm tall target area. The lamps were scanned vertically ± 0.6mm along the length of the filament and horizontally ± 0.4 mm across the width of the filament.

4.4.5. Alignment procedure

The lamp orientation chosen minimizes the variation in lamp output while maintaining the optical axis of the measuring instrument approximately normal to the lamp filament. This orientation is determined with the lamp operating at approximately 1970 K. An arrow is etched onto the rear surface of the lamp envelope to allow reproducible alignment of this orientation. The alignment is performed with the lamp operating base down, the filament vertical, and the optical axis of the spectroradiometer passing through the lamp envelope and intersecting the center of the filament at the height of the notch. The sides of the target area, area 0.6 mm wide by 0.8 mm high, are approximately parallel to the sides of the lamp filament. The center of the target area is located at the intersection of two orthogonal lines on the filament surface. One line bisects the filament lengthwise, and the other passes through the point centered at the mouth of the notch. The lamp is positioned so that the etched arrow on the lamp envelope is to the rear, as viewed from the spectroradiometer. The center of the target area is viewed along the optical axis of the spectroradiometer. A plumb line is used to make the notch side of the filament vertical. The image of the lamp filament is focused onto the monochromator slit to within 2.5 mm. The lamp is then successively rotated about the horizontal and vertical centerlines through the target area until the tip of the arrowhead is centered at the mouth of the notch.

4.5. COMPARISON MEASUREMENTS

4.5.1. Lamp operating conditions

Table 4.4 gives the lamp currents, the lamp voltages at the end of the first NIST measurement in 1998 and second NIST measurement in 2001, the spectral range of the spectral radiance measurements, and the nominal radiance temperature that corresponds to the lamp current.

Table 4.4. Lamp operation conditions

Lamp number	Current /A	1998 Voltage / V	2001 Voltage / V	Range / nm	Temperature / K
Q123	38.8	4.64	4.36	220 - 400	2370
Q124	38.5	5.02	4.63	220 - 400	2370
Q125	38.5	4.65	4.73	220 - 400	2370
Q129	34.8	4.08	4.11	300 - 2500	2270
Q130*	35.3	4.37	4.49	300 - 2500	2270
Q130**	35.8	N/a	4.61	300 - 2500	2270
Q133	34.6	4.53	4.50	300 - 2500	2270

* Q130 was first measured at 35.3 A. VNIIOFI was given the incorrect current of 35.8 A. The lamp was first measured at 35.8A then at 35.3 A then at 35.8 A and finally at 35.3 A.
** This is the lamp current that VNIIOFI used for lamp Q130.

4.5.2. Details of the first-round NIST measurement are listed below:

1. The measurements were conducted between Oct. 5, 1998 and Oct. 15, 1998.
2. Six comparison lamps and three check standard lamps were spectrally compared to the VTBB using the FASCAL spectroradiometer.
3. The comparison lamps were Q123, Q124, Q125, Q129, Q130, and Q133.
4. The check standard lamps were Q104, Q106, and Q109.
5. The point-by-point method was used to transfer the spectral radiance from the VTBB to the comparison lamps.
6. Three comparison lamps were operated at the same time. The VTBB temperature and spectral radiance were determined for one wavelength. The spectral radiance at the one wavelength was transferred to the comparison lamps.
7. The previous step was repeated until all wavelengths were measured.
8. The PbS detector was used for measurements from 800 nm to 2500 nm.

4.5.3. Details of the second-round NIST measurement are listed below:

1. The measurements were conducted between Sept. 20, 2001 and Sept. 28, 2001.
2. Six comparison lamps and three check standard lamps were spectrally compared to the VTBB using the FASCAL spectroradiometer.
3. The comparison lamps were Q123, Q124, Q125, Q129, Q130, and Q133.
4. The check standard lamps were Q104, Q106, and Q109.
5. The scanning method was used to transfer the spectral radiance from the VTBB to the comparison lamps.
6. One lamp was operated at any one time. The VTBB temperature was determined and spectral radiances were determined for a wavelength region from the single temperature measurement. The spectral radiances for the wavelength region are transferred to the comparison lamps.
7. The previous step was repeated until all the wavelength regions were measured.
8. The InGaAs detector was used for measurements from 800 nm to 2500 nm.

4.6. UNCERTAINTY BUDGET

Table 4.5. NIST Spectral Radiance Uncertainty

			Relative Expanded Uncertainties (k = 2) [%]								
	Source of Uncertainty	Type	220 nm	250 nm	350 nm	550 nm	656.3 nm	900 nm	1000 nm	1550 nm	2500 nm
1	Blackbody quality	B	0.19	0.16	0.09	0.02	0.00	0.03	0.04	0.06	0.07
2	Calibration of the reference radiance temperature lamp relative to the 1990 NIST Radiance Temperature Scale	B	0.47	0.42	0.30	0.20	0.16	0.11	0.10	0.07	0.05
3	Temperature determination of blackbody and transfer of blackbody spectral radiance to test lamp	A	1.48	0.84	0.67	0.71	0.52	0.40	0.39	0.48	0.78
4	Lamp drift correction	B	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
5	Polarization effects	B	0.01	0.01	0.02	0.03	0.03	0.04	0.06	0.11	0.17
6	Current measurement	B	0.07	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.01
7	Wavelength measurement	B	0.16	0.15	0.11	0.06	0.05	0.04	0.03	0.02	0.01
8	1990 NIST Radiance Temperature Scale (1990 NIST)	B	0.81	0.73	0.52	0.33	0.28	0.20	0.19	0.12	0.07
9	Lock-in amplifier linearity	B	-	-	-	-	-	-	0.50	0.50	0.50
10	Lock-in amplifier gain factor	B	-	-	-	-	-	-	1.00	1.00	1.00
	Overall uncertainty of test with respect to SI units		**1.77**	**1.22**	**0.92**	**0.82**	**0.62**	**0.48**	**1.21**	**1.24**	**1.38**

4.7. DISCUSSION

NIST provided VNIIOFI with an incorrect lamp current for Lamp Q130. The error was not discovered until after VNIIOFI returned the lamps to NIST. During the second NIST measurement in 2001, Lamp Q130 was measured at 35.8 A as reported to VNIIOFI. NIST is only submitting data for the second measurement in 2001 at 35.8 A.

Figures 4.3 and 4.4 summary the difference between two rounds of NIST measurements.

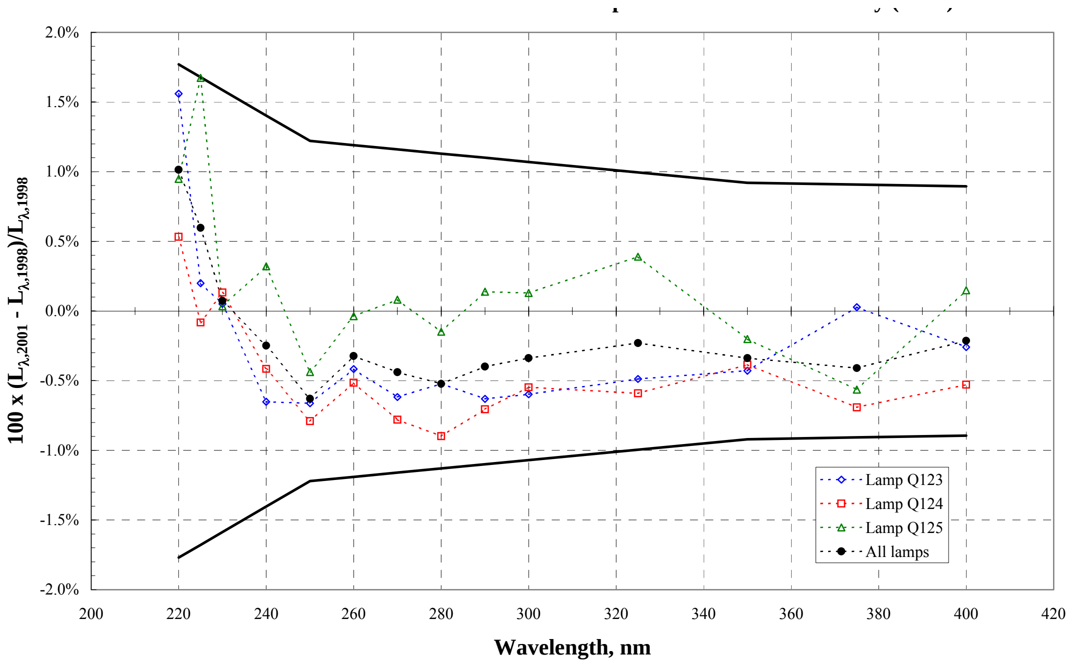

Figure 4.3. The percent difference between the measurements in1998 and 2001. The solid line is the NIST spectral radiance uncertainty (k=2).

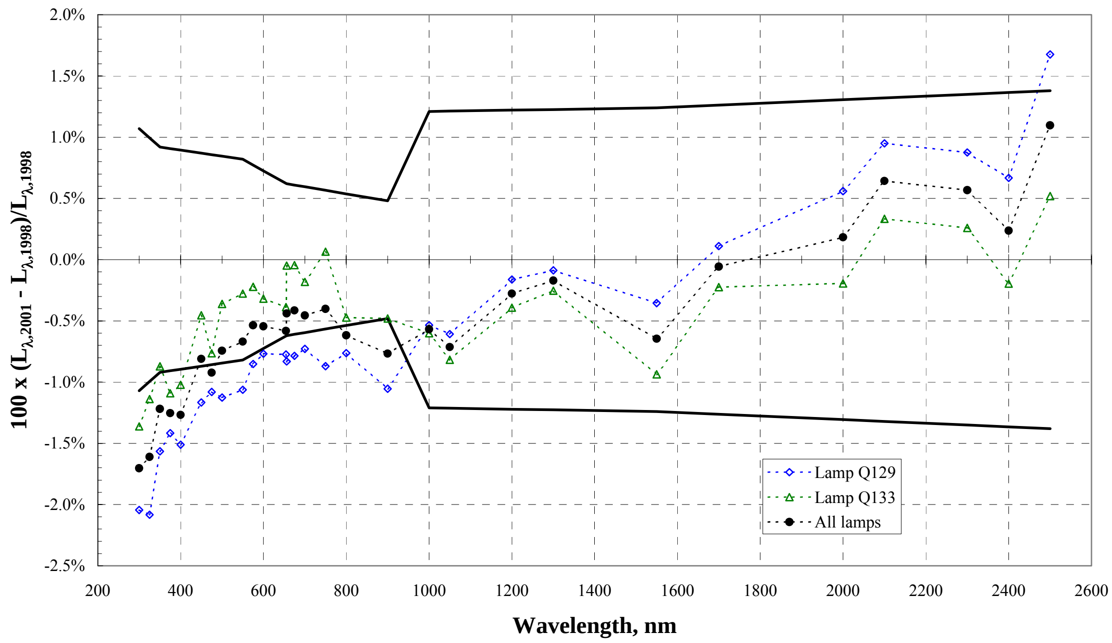

Figure 4.4. The percent difference between the measurements in1998 and 2001. The solid line is the NIST spectral radiance uncertainty (k=2).

The differences for the UV comparison lamps in Fig. 4.3 are within the total uncertainties (k = 2). The differences between the UV-VIS-IR comparison lamps in 1998 and 2001 are attributed to drift due to burning hours during the comparison. Because of lamp drift, the differences for Lamp Q129 are slightly larger than the total uncertainties from 300 nm to 900 nm. The 0.7 % increase in the total uncertainty between 900 nm and 1000 nm is due to use of very conservative estimations of the uncertainty for the lock-in amplifier gain and linearity components.

4.8. REFERENCES

[1] J. H. Walker, R.D. Saunders, and A. T. Hattenburg, "Spectral Radiance Calibrations," *NBS Special Publication* **250-1** (1987).

[2] CCPR Spectral Radiance Intercomparison Questionnaire [NIST CCPR Rad. Questionnaire response.doc]

[3] Excel Spreadsheet of Results [NIST CCPR-S1 Results 3-22-04.xls].

[1]Any mention of commercial products within this document is for information only; it does not imply recommendation or endorsement by NIST.

4.9. NIST RESULTS

The NIST results of the spectral radiance measurements and their uncertainties (k=1) are presented in Table 4.9.a and Table 4.9.b The unit of spectral radiance is W/m^3/sr.

Table 4.9.a NIST results for the lamps measured in the spectral range 220 to 400 nm: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp Q123		Lamp Q124		Lamp Q125		Uncertainty (k=1)
	1st round	2nd round	1st round	2nd round	1st round	2nd round	
220	1.539E+06	1.563E+06	1.504E+06	1.512E+06	1.160E+06	1.171E+06	0.89%
230	3.890E+06	3.892E+06	3.786E+06	3.791E+06	2.889E+06	2.890E+06	0.76%
240	8.589E+06	8.533E+06	8.424E+06	8.389E+06	6.539E+06	6.560E+06	0.67%
250	1.814E+07	1.802E+07	1.772E+07	1.758E+07	1.370E+07	1.364E+07	0.61%
260	3.603E+07	3.588E+07	3.495E+07	3.477E+07	2.686E+07	2.685E+07	0.58%
270	6.637E+07	6.596E+07	6.409E+07	6.359E+07	4.952E+07	4.956E+07	0.56%
280	1.151E+08	1.145E+08	1.114E+08	1.104E+08	8.692E+07	8.679E+07	0.54%
290	1.903E+08	1.891E+08	1.844E+08	1.831E+08	1.447E+08	1.449E+08	0.52%
300	3.014E+08	2.996E+08	2.922E+08	2.906E+08	2.313E+08	2.316E+08	0.51%
325	8.191E+08	8.151E+08	7.961E+08	7.914E+08	6.413E+08	6.438E+08	0.48%
350	1.867E+09	1.859E+09	1.817E+09	1.810E+09	1.487E+09	1.484E+09	0.46%
375	3.699E+09	3.700E+09	3.616E+09	3.591E+09	3.012E+09	2.995E+09	0.45%
400	6.579E+09	6.562E+09	6.427E+09	6.393E+09	5.384E+09	5.392E+09	0.44%

Table 4.9.b NIST results for the lamps measured in the spectral range 300 to 2500 nm: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp Q129		Lamp Q130		Lamp Q133		Uncertainty (k=1)
	1st round	2nd round	1st round	2nd round	1st round	2nd round	
300	1.075E+08	1.053E+08	-	1.288E+08	1.006E+08	9.923E+07	0.51%
325	3.166E+08	3.100E+08	-	3.748E+08	2.986E+08	2.952E+08	0.48%
350	7.718E+08	7.597E+08	-	9.050E+08	7.351E+08	7.287E+08	0.46%
375	1.622E+09	1.599E+09	-	1.880E+09	1.557E+09	1.540E+09	0.45%
400	3.038E+09	2.992E+09	-	3.497E+09	2.933E+09	2.903E+09	0.44%
450	8.127E+09	8.032E+09	-	9.256E+09	7.919E+09	7.883E+09	0.43%
500	1.685E+10	1.666E+10	-	1.896E+10	1.657E+10	1.651E+10	0.42%
550	2.913E+10	2.882E+10	-	3.250E+10	2.885E+10	2.877E+10	0.41%
600	4.407E+10	4.373E+10	-	4.874E+10	4.391E+10	4.377E+10	0.37%
656.3	6.247E+10	6.195E+10	-	6.856E+10	6.247E+10	6.244E+10	0.31%
700	7.670E+10	7.614E+10	-	8.366E+10	7.703E+10	7.689E+10	0.29%
800	1.046E+11	1.038E+11	-	1.129E+11	1.059E+11	1.054E+11	0.26%
900	1.229E+11	1.216E+11	-	1.315E+11	1.250E+11	1.244E+11	0.24%
1000	1.306E+11	1.299E+11	-	1.389E+11	1.332E+11	1.324E+11	0.61%
1050	1.310E+11	1.302E+11	-	1.391E+11	1.346E+11	1.335E+11	0.61%
1200	1.233E+11	1.231E+11	-	1.305E+11	1.277E+11	1.272E+11	0.62%
1550	8.718E+10	8.687E+10	-	9.133E+10	9.181E+10	9.095E+10	0.62%
1700	7.175E+10	7.183E+10	-	7.539E+10	7.587E+10	7.570E+10	0.63%
2100	4.178E+10	4.217E+10	-	4.406E+10	4.491E+10	4.506E+10	0.65%
2300	3.175E+10	3.203E+10	-	3.330E+10	3.468E+10	3.477E+10	0.66%
2400	2.822E+10	2.841E+10	-	2.960E+10	3.076E+10	3.070E+10	0.67%
2500	2.427E+10	2.468E+10	-	2.545E+10	2.694E+10	2.708E+10	0.69%

4.10. VNIIOFI RESULTS

Table 4.10.a. VNIIOFI results of the NIST lamps measured in the spectral range 220 to 400 nm: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp Q123	Lamp Q124	Lamp Q125	Uncertainty (*k*=1)
220	1.589E+06	1.546E+06	1.192E+06	1.13%
230	3.920E+06	3.825E+06	2.916E+06	1.00%
240	8.575E+06	8.447E+06	6.549E+06	0.92%
250	1.810E+07	1.770E+07	1.373E+07	0.87%
260	3.588E+07	3.481E+07	2.683E+07	0.84%
270	6.605E+07	6.393E+07	4.952E+07	0.80%
280	1.145E+08	1.109E+08	8.667E+07	0.77%
290	1.892E+08	1.836E+08	1.445E+08	0.75%
300	2.993E+08	2.909E+08	2.318E+08	0.73%
325	8.155E+08	7.921E+08	6.416E+08	0.67%
350	1.848E+09	1.809E+09	1.486E+09	0.64%
375	3.680E+09	3.597E+09	2.992E+09	0.59%
400	6.538E+09	6.398E+09	5.383E+09	0.56%

Table 4.10.b. VNIIOFI results of the NIST lamps measured in the spectral range 300 to 2500 nm: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp Q129	Lamp Q130	Lamp Q133	Uncertainty (*k*=1)
300	1.064E+08	1.249E+08	9.856E+07	0.73%
325	3.131E+08	3.636E+08	2.934E+08	0.67%
350	7.645E+08	8.785E+08	7.230E+08	0.64%
375	1.608E+09	1.834E+09	1.535E+09	0.59%
400	3.011E+09	3.408E+09	2.893E+09	0.56%
450	8.080E+09	9.040E+09	7.852E+09	0.50%
500	1.678E+10	1.855E+10	1.642E+10	0.46%
550	2.897E+10	3.179E+10	2.860E+10	0.43%
600	4.381E+10	4.777E+10	4.357E+10	0.39%
656.3	6.205E+10	6.726E+10	6.212E+10	0.37%
700	7.616E+10	8.222E+10	7.654E+10	0.35%
800	1.045E+11	1.113E+11	1.053E+11	0.32%
900	1.224E+11	1.297E+11	1.245E+11	0.30%
1000	1.300E+11	1.371E+11	1.332E+11	0.29%
1050	1.303E+11	1.374E+11	1.340E+11	0.31%
1200	1.225E+11	1.288E+11	1.272E+11	0.40%
1550	8.614E+10	9.001E+10	9.093E+10	0.41%
1700	7.119E+10	7.431E+10	7.569E+10	0.41%
2100	4.164E+10	4.335E+10	4.513E+10	0.41%
2300	3.163E+10	3.273E+10	3.474E+10	0.44%
2400	2.804E+10	2.905E+10	3.064E+10	0.44%
2500	2.426E+10	2.493E+10	2.693E+10	0.46%

4.11. NIST TO VNIIOFI DIFFERENCE.

The percentage differences between NIST measurements, reported for individual rounds, and VNIIOFI measurements are calculated as

$$\Delta_{NIST,j,r} = \left(\frac{L_{NIST,j,r}}{L^P_{NIST,j}} - 1 \right) \cdot 100\%, \qquad (4.8.1)$$

and their uncertainties are calculated as

$$u_{rel}\left(\Delta_{NIST,j,r}\right) = \sqrt{u^2_{rel,NIST} + u^2_{rel,VNIIOFI}}, \qquad (4.8.2)$$

where

$L_{NIST,j,r}$ Spectral Radiance of lamp *j* of NIST, measured by the NIST in round *r* (=1 to 2);

$L^P_{NIST,j}$ Spectral Radiance of lamp *j* of NIST, measured by the pilot (VNIIOFI);

$u_{rel,NIST}$ Total relative uncertainty reported by NIST;

$u_{rel,VNIIOFI}$ Total relative uncertainty reported by VNIIOFI.

Fig. 4.8.1 and Fig. 4.8.2 show differences $\Delta_{NIST,j,1}$ and $\Delta_{NIST,j,2}$ respectively and their uncertainties. Fig. 4.8.3 shows the NIST to VNIIOFI differences averaged by two rounds calculated as

$$\Delta_{NIST,j} = \left(\frac{\overline{L}_{NIST,j}}{L^P_{NIST,j}} - 1 \right) \cdot 100\%, \qquad (4.8.3)$$

where $\overline{L}_{NIST,j} = \frac{1}{2}\sum_{r=1}^{2} L_{NIST,j,r}$

Fig. 4.8.4 shows the total average difference between NIST and VNIIOFI calculated as

$$\Delta_{NIST} = \frac{1}{3}\sum_{j=1}^{3} \Delta_{NIST,j} \qquad (4.8.5)$$

Total average values Δ_{NIST} are calculated independently for two groups of lamps. Lamps Q123, Q124 and Q125, measured in UV range, form one group. Lamps Q129, Q130 and Q133, measured in the range 300 to 2500nm, form another group.

Lamp Q130 was not measured during Round 1 at NIST. The results for Round 2 (see Fig. 4.8.2.) show that the NIST-VNIIOFI difference for the lamp Q130 exceed the expended (k=2) uncertainty of the bilateral comparison for almost all wavelengths, while other two lamps (Q129 and Q133) differences are totally within the expanded uncertainty and, moreover, are mostly within the standard (k=1) uncertainty. In the previouse version of the Draft A report it was supposed that there was, perhaps, some problem with the Q130 lamp during the comparison, such as instability or other. For that reason two versions of Δ_{NIST} values were calculated in Draft A for spectral range 300 to 2500 nm: the first – as an average for all three lamps Q129, Q130 and Q133; and the second – for two lamps Q129 and Q133 only. After analysis of the Draft A the NIST experts confirm that the Q130 lamp was not really stable, which is illustrated by the Table 4.2: the change of the spectral radiance of the Q130 lamp at 654.6 nm during 20 h was 0.74 % that is about three times larger than any of the other lamps. The Pilot suggested and the NIST agreed that the lamp Q130 should be excluded from the further analysis. However, this suggestion was not supported by other participants as well as the CCPR WG-KC because it was made after Draft A report. Although the Fig. 4.8.4 shows two curves of NIST-VNIIOFI difference in 300 to 2500 nm range, only that based on all three lamps (Q129, Q130 and Q133) is represented the Δ_{NIST} values. The second curve based on two lamps only lamps (Q129 and Q133) was used for alternative analysis presented in Appendix A.

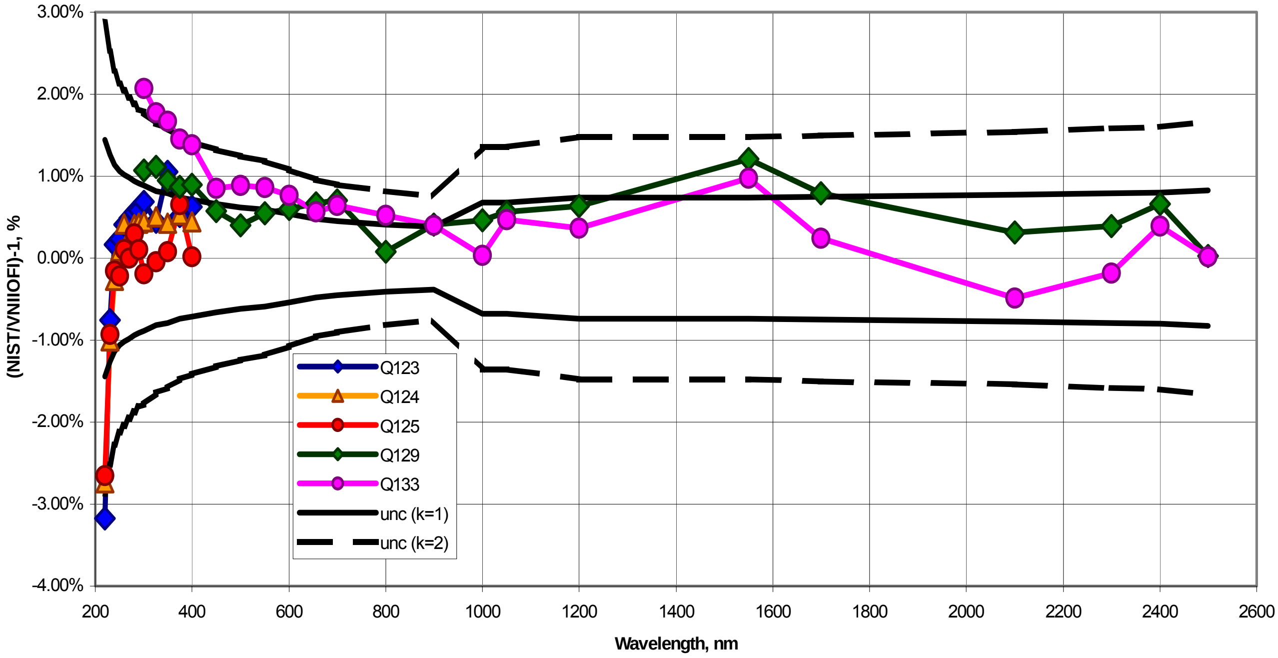

Figure 4.8.1. Difference $\Delta_{NIST,j,1}$ between 1st round of NIST and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (4.8.2) and unc(k=2) = unc(k=1)*2.

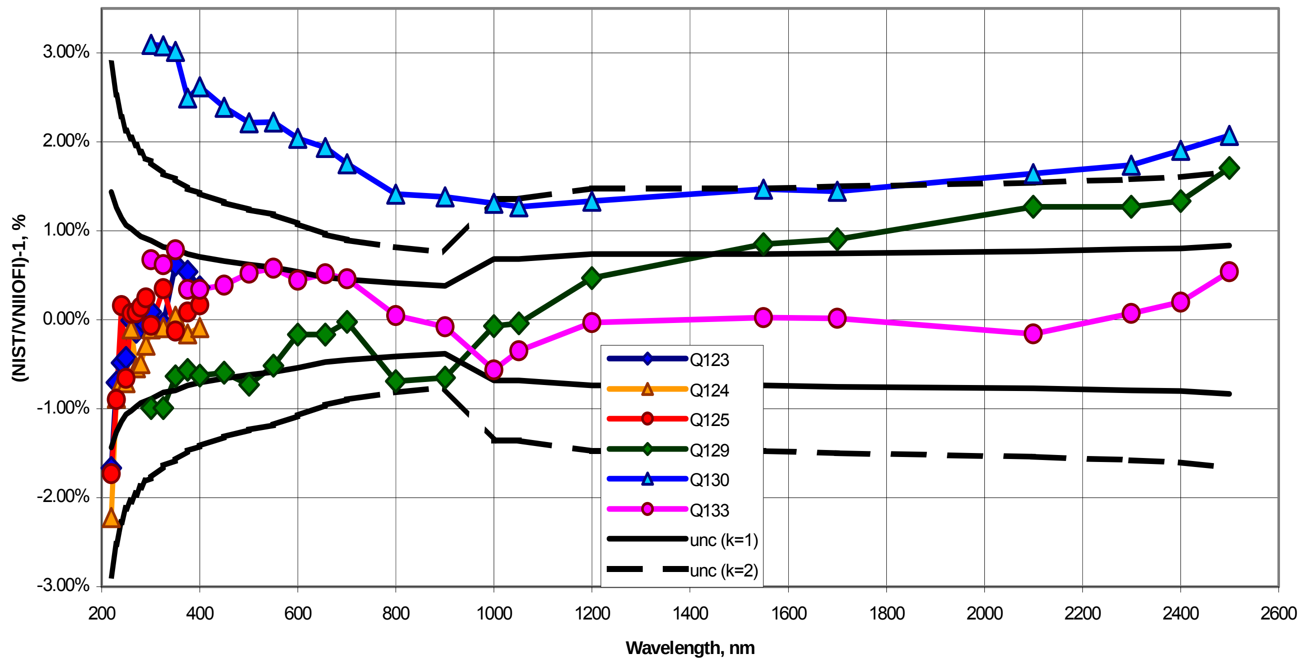

Figure 4.8.2. Difference $\Delta_{NIST,j,2}$ between 2nd round of NIST and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (4.8.2) and unc(k=2) = unc(k=1)*2.

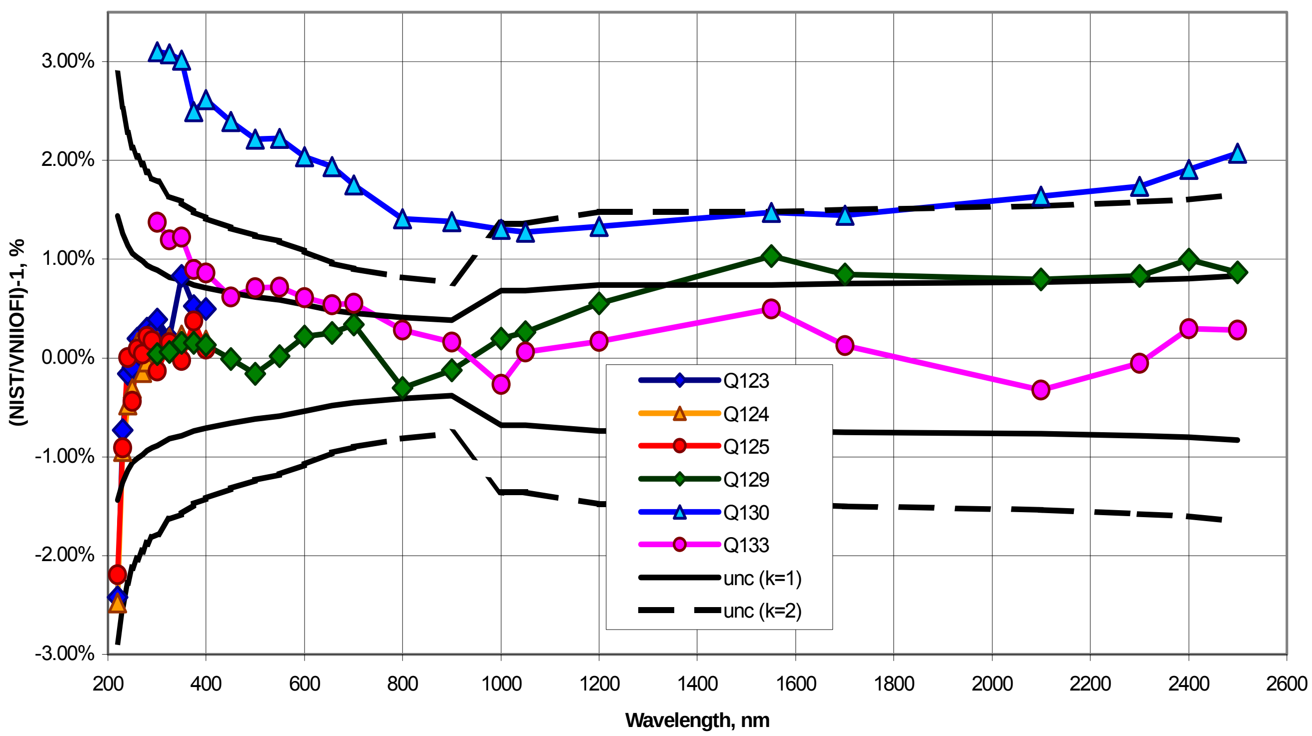

Figure 4.8.3. Difference $\Delta_{NIST,j}$ between NIST and VNIIOFI measurements, averaged by two rounds. Uncertainties unc(k=1) calculated by (4.8.4) and unc(k=2) = unc(k=1)*2.

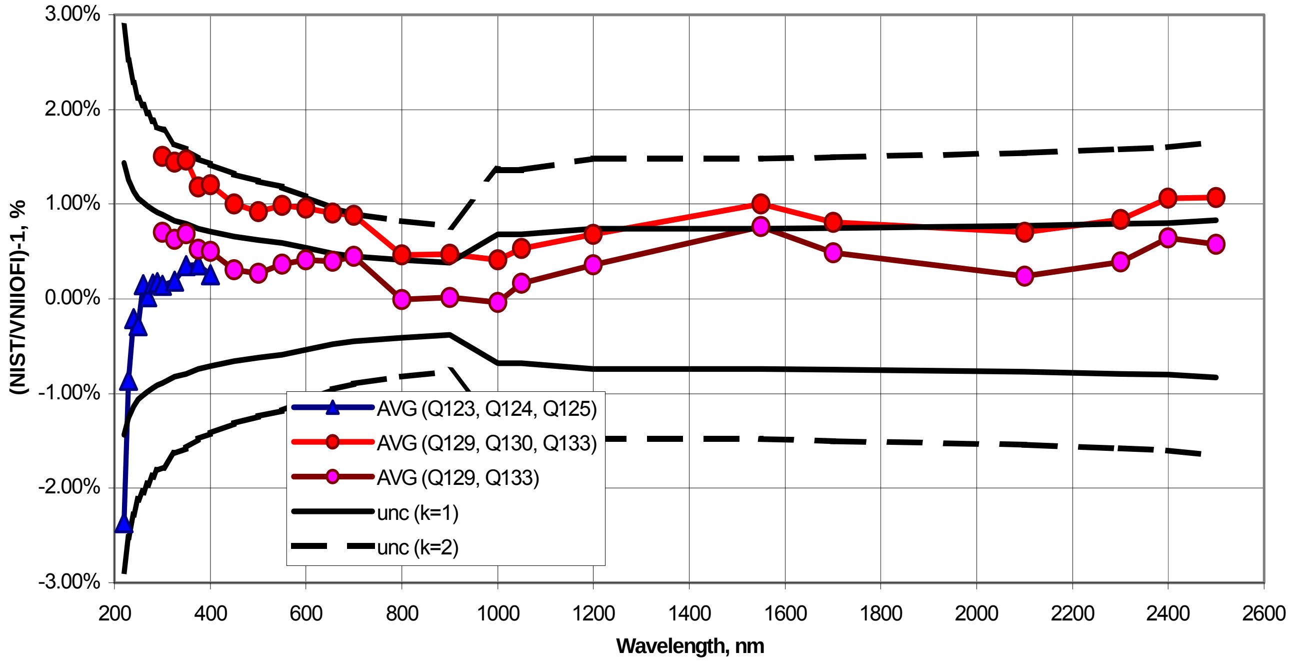

Figure 4.8.4. Difference Δ_{NIST} NIST and VNIIOFI measurements, averaged by two rounds and three lamps. Uncertainties unc(k=1) calculated by (4.8.4) and unc(k=2) = unc(k=1)*2.

5. NRC – VNIIOFI BILATERAL COMPARISON

Sections 5.1 – 5.7 of the present document are based on the NRC Report submitted to the pilot by e-mail in January 2006.

5.1. NRC LAMPS AND SPECTRAL RANGE.

Originally the pilot was informed that NRC was going to measure the comparison lamps in the spectral range of 400 to 1650 nm. Therefore, the pilot measured the NRC lamps exactly in this range (400-1650 nm). Actually NRC covered another spectral range: 300 to 800 nm. Unfortunately, the pilot knew this too late, when the lamps were already sent back to the participant. As a result, the actual spectral range of the NRC-VNIIOFI bilateral comparison was 400 to 800 nm.

The three NRC lamps were tungsten strip filament lamps of type GE 30A/3.5V. The markings on the lamps also indicated "Ultraviolet Spectrum, Base Down". The lamps were identified as: SR01, SR02 and SR03.

5.1.1. Lamp Aging

Each of the three lamps was aged at approximately 40 amps dc before calibration. The radiance temperature at this operating current was measured with a Leeds and Northrup optical pyrometer. The aging parameters are summarized in Table 5.1.

Table 5.1. Parameters for the aging of the three NRC spectral radiance lamps. Lamp aging current of 40 amps dc.

Lamp	Aging Time hrs	Radiance Temperature K
SR01	66	2510
SR02	72	2505
SR03	81	2495

The current and voltage of the lamp, as well as the light output of the lamp, were monitored during the aging process. The light output was measured using a photometer. The photometric measurements indicated that the output of each lamp was decreasing at approximately 0.01%-hr^{-1} during the last 20 hrs of aging.

After aging, the electrical current through each lamp was set such that the operating radiance temperature of each lamp was approximately 2300 K at 650 nm. The resulting electrical operating parameters for the lamps are given in Table 5.2.

Table 5.2. Electrical operating parameters for NRC spectral radiance lamps. Radiance temperature of 2300K at 650 nm. Lamps operated at constant current.

Lamp	Operating Current Amperes dc	Lamp Voltage Volts dc
SR01	34.702	4.345
SR02	34.676	4.136
SR03	35.202	4.253

5.1.2. Lamp Measurements

The first set of NRC spectral radiance measurements were performed on the three lamps during August to November 1999. A copper-freezing-point blackbody radiator was used with filter radiometers to calibrate directly the three lamps, using the techniques discussed in Reference [1]. Due to the difficulties encountered (Reference [1]) in the measurements and analysis of the data, we have decided not to use the results of these measurements for this comparison.
The lamps were shipped to VNIIOFI on 1999-November-24.
The lamps were received from VNIIOFI on 2000-October-26.
The second set of NRC spectral radiance measurements was performed on the three lamps during 2001-January-29 to 2001-February-06. These calibrations were carried out using NRC standard lamps of spectral radiance to calibrate the three CCPR lamps. The remainder of this report will describe the procedures and results of this second set of measurements only.

5.2. NRC LAMP STANDARDS

Three calibrated standard lamps of spectral radiance were used to calibrate the NRC spectroradiometer. All three are gas-filled General Electric type 30/T24/13 ribbon filament lamps supplied and calibrated by the National Bureau of Standards (NBS) of the USA (References [2,3,4]). The lamps are designated Q34, Q85, and Q86. The spectral radiance values for each lamp are supplied for 34 wavelengths between 225 nm and 2400 nm.

5.3. MEASUREMENT FACILITY

A schematic of the measurement facility used for the spectroradiometric measurements is given in Fig. 5.1. The spectroradiometer is composed of the monochromator and reference lamp assembly, the detector, and the input optics for the lamps to be measured.

5.3.1. Monochromator and Reference Lamp

The monochromator was a Hilger and Watts Model D300 double monochromator with quartz prisms. The collimating mirrors are of focal length 670 mm. The spectroradiometer was designed to operate using a reference lamp to monitor the operation and stability of the monochromator and detector. The basic operation of this configuration is described in Reference [5]. We were only able to operate this monochromator between the wavelengths from 300 nm to 800 nm at 5 nm steps.

The slit widths used were approximately 0.5 mm, which gives a bandwidth that varies from approximately 0.4 nm at 300 nm, to approximately 6.3 nm at 800 nm.

5.3.2. Detector

The detector used was a Hamamatsu R6872 photomultiplier operating at a temperature of –12°C provided by a thermoelectric cooler.

5.3.3. Input Optics and Lamp Alignment

All three of the NRC Lamp Standards are operated in the same geometrical configuration. Therefore we measured the three NRC-CCPR transfer standard lamps in this same geometrical configuration.

The physical area of the strip filament, the direction normal to the strip filament, and the solid angle of the radiation to be measured are all defined in the calibration reports (References [2,3,4]). The optical setup we used is shown in Figure One. The lens nearest the monochromator (lens L2) was a quartz/LiF doublet (focal length ~260 mm) and the lens nearest the lamp (lens L1) was a quartz plano-convex lens (focal length ~300 mm).

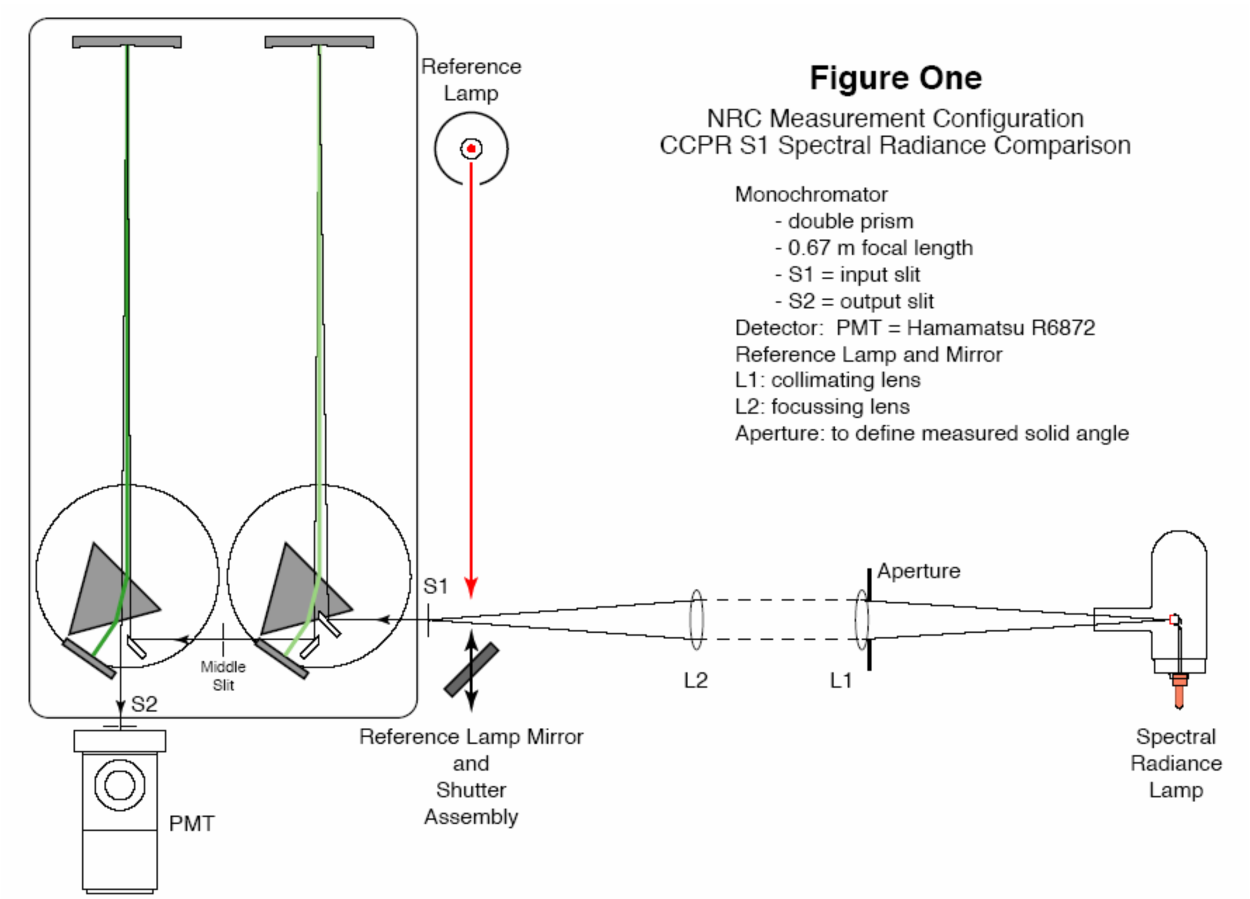

Figure 5.1. Schematic of NRC facility for spectroradiometric measurements.

The input slits to the monochromator were adjusted in height and width until the image of the slits at the lamp filament was the required rectangular target area of 0.8 mm in height and 0.6 mm in width. The position of this target area on the lamp filament is determined by two imaginary perpendicular lines located on the filament surface, one line bisecting the filament along its length, and the other passing though the point centered at the mouth of the V-notch in the filament. The lamp position is adjusted until the centroid of the target area is at the intersection of these two imaginary lines.

The angular orientation of the strip filament of the NRC-CCPR lamps to the optical axis of the spectroradiometer is set using a plumb bob and the laser beam that passes along the optical axis. The angular orientation of the lamp about the optical axis, and the angular orientation about the horizontal axis perpendicular to the optical axis, are set such that the lamp envelope is parallel to the plumb bob. The angular orientation about the vertical axis perpendicular to the optical axis is set such that the black dot on the lamp envelope and the centroid of the target area are on the optical axis.

The required rectangular solid angle (a rectangular pyramid with vertex angles of 0.125 radians (7.16°) in the vertical direction, and 0.0625 radians (3.58°) in the horizontal direction) was set by adjusting the size of the rectangular aperture placed near lens L1, between the lamp and the first lens as shown in Figure One.

These target areas and solid angles are slightly different from the original sizes used for our first set of measurements (before shipping the lamps to the pilot laboratory). The original target area was a circle of diameter 0.6 mm, and the solid angle used was circular of approximately 0.008 sr. Depending on the geometrical configuration used by the pilot laboratory, this difference may affect the spectral radiance values measured by the pilot and our second set of measurements described in this report.

5.4. MEASUREMENT PROCEDURE

The basic procedure used is a sequential method: Each lamp was measured completely through the complete wavelength range before installing another lamp onto the optical axis to repeat the process. The spectroradiometer system was calibrated by measuring one or two NRC standard lamps during each measurement day. The measurement sequence and wavelength range was fixed for this spectroradiometer. The wavelength range was from 800 nm to 300 nm in 5 nm steps. The sequence of four measurements at each wavelength was Reference lamp signal / zero signal (shutter closed) / Test lamp signal / zero signal (shutter closed).

Each of the six lamps (three standard and three transfer lamps) was measured three times over a period of six days. The sequence of measurements is given in Table 5.3.

Table 5.3. Measurement Sequence for Spectral Radiance Lamps

Date	Lamp Sequence
2001-January-29	Q85, SR02
2001-January-30	Q86, SR03, Q34, SR01
2001-January-31	Q85, SR02, Q86, SR03
2001-February-01	SR03, Q34, SR01, Q85
2001-February-05	Q34, SR01
2001-February-06	SR02, Q86

The electrical supply to the lamps was derived from a high-stability (Kepco) DC power supply. The current supplied to the lamps was measured using a calibrated standard resistor (0.01-ohm) in the standard 4-terminal measuring configuration. The voltage at the lamps was measured at the lamp socket.

5.5. DATA ANALYSIS

The measurements taken permit three possible means of analysis of the data:

1. It could be assumed that the spectroradiometer remained stable over the six days during which the data was taken.
2. It could be assumed that the spectroradiometer remained stable only during each day in which measurements were taken.
3. It could be assumed that the reference lamp remained stable during each day during which measurements were taken.

All three methods were used and the final results will be given for method 3, which assumes the reference lamp is stable during each day of measurements. Each transfer lamp is thus compared via the reference lamp to each standard lamp on each day. This method provided the most self-consistent results for the calibration of each of the three transfer lamps. As can be seen from Table 5.3, this method results in five calibration datasets for lamp SR01, four calibration datasets for SR02, and six for lamp SR03. These datasets were averaged for each lamp to give the final results presented below in Table 5.7. The data point at 656.3 nm was obtained from a cubic spline fit to the original dataset, which consisted of data taken at 5-nm intervals. This data, together with the uncertainties, is also available in the Excel data file CCPRS1NRC.xls.

5.6. UNCERTAINTIES

The estimated uncertainties are presented in two sections: those pertaining to the calibration of the spectroradiometer, which are common to all transfer lamps (Table 5.5.), and those specific to each transfer lamp (Table 5.6.). The uncertainties given are for one standard deviation (coverage factor k=1).

5.6.1. Uncertainties in the calibration of the spectroradiometer (Table 5.5.)

These uncertainties are also composed of two parts, those pertaining to the use of the standard lamps, and those pertaining to the calibration of the spectroradiometer by the standard lamps.

Table 5.5. Common uncertainties for the calibration of all lamps. Values given are fractional uncertainty in spectral radiance. Coverage Factor k=1.

TYPE:	B	B	B	A	B	B	Quadrature Sum
Wavelength	Standard Lamps			SpectroRadiometer			
nm	Calibration	Alignment	Electrical	Calibration	Wavelength	Detector Linearity	
300.00	0.0052	0.0060	0.0020	0.0154	0.0015	0.0010	0.0176
325.00	0.0045	0.0060	0.0020	0.0125	0.0015	0.0010	0.0148
350.00	0.0039	0.0060	0.0020	0.0152	0.0015	0.0010	0.0170
375.00	0.0037	0.0060	0.0020	0.0180	0.0015	0.0010	0.0195
400.00	0.0035	0.0060	0.0020	0.0146	0.0015	0.0010	0.0164
450.00	0.0033	0.0060	0.0020	0.0141	0.0015	0.0010	0.0159
500.00	0.0030	0.0060	0.0020	0.0148	0.0015	0.0010	0.0165
550.00	0.0027	0.0060	0.0020	0.0117	0.0015	0.0010	0.0137
600.00	0.0024	0.0060	0.0020	0.0117	0.0015	0.0010	0.0136
656.30	0.0022	0.0060	0.0020	0.0102	0.0015	0.0010	0.0124
700.00	0.0020	0.0060	0.0020	0.0109	0.0015	0.0010	0.0129
800.00	0.0019	0.0060	0.0020	0.0085	0.0015	0.0010	0.0109

Standard Lamps – calibration: this is the average uncertainty given in the calibration reports [2,3,4] for the three standard lamps.

Standard Lamps – alignment: this is the uncertainty derived from estimated alignment uncertainties using the variation of spectral radiance due to these uncertainties as given in the standard lamp calibration reports [2,3,4]. It was assumed a possible uncertainty of 0.2 mm in each of the two linear axes for the position of the measured spot on the surface of the filament, and an uncertainty of one degree in each of the three possible angular alignments. The final uncertainty given is the square root of the sum of the squares of these five uncertainties.

Standard Lamps – electrical: this is the estimated uncertainty due to an estimated uncertainty of 10 ma in the operating current of the standard lamps.

Spectroradiometer – calibration: it was assumed for the data analysis presented above that the reference lamp was stable during each day of operation. An estimate of the validity of this assumption and the transfer of the calibration from the standard lamps to this reference lamp can be obtained from the fractional standard deviation of all the calibrations of the reference lamp during five of the six measurement days (the data from 2001-January-29 could not be used for this calculation since the reference lamp had been set at a different electrical operating point from that of the following five days). The fractional standard deviation of the resulting eight reference lamp calibration datasets is presented as the uncertainty of the calibration and operation of the spectroradiometer.

Spectroradiometer – wavelength: The wavelength accuracy and reproducibility of the monochromator was estimated to be approximately 0.2 nm. The estimated uncertainty in the transfer of the spectral radiance calibration from the standard lamps to the CCPR lamps due to this uncertainty in the wavelength accuracy was estimated to be approximately 0.1%. The uncertainty in our measurements due to the wavelength reproducibility is reduced by the use of the reference lamp at each measurement point. The uncertainty in our spectral radiance measurements due to the wavelength reproducibility is also estimated to be 0.1%. These two uncertainties were added in quadrature to give an estimated uncertainty of 0.15% in our spectral radiance measurements due to wavelength uncertainties.

Spectroradiometer – detector linearity: These figures are derived from measurements in our laboratory for similar detectors to the ones used in these measurements. They represent upper limits of uncertainty that can be expected.

5.6.2. Uncertainties in the calibration of the transfer lamps (Table 5.6.)

The uncertainties given in the column for the calibration of the transfer lamps is the fractional standard deviation of all the calibration datasets for each lamp. As indicated above, this is five calibration datasets for lamp SR01, four calibration datasets for SR02, and six for lamp SR03. The values given are the standard deviations of the calibration datasets, not of the mean. The final uncertainties for each lamp are the quadrature sum of the uncertainties in the calibration column and the uncertainties from Table 5.5.

Table 5.6. Uncertainties for the calibration of the NRC transfer lamps. Values given are fractional uncertainties in the spectral radiance of the lamps. Coverage factor k=1.

	Lamp SR01		Lamp SR02		Lamp SR03	
	TYPE A	Quadrature Sum	TYPE A	Quadrature Sum	TYPE A	Quadrature Sum
Wavelength nm	Calibration	FINAL	Calibration	FINAL	Calibration	FINAL
300.00	0.0330	0.0374	0.0386	0.0424	0.0257	0.0311
325.00	0.0108	0.0184	0.0319	0.0352	0.0165	0.0222
350.00	0.0079	0.0187	0.0178	0.0246	0.0204	0.0266
375.00	0.0113	0.0225	0.0221	0.0295	0.0176	0.0263
400.00	0.0098	0.0191	0.0172	0.0237	0.0151	0.0223
450.00	0.0077	0.0176	0.0180	0.0240	0.0154	0.0221
500.00	0.0104	0.0195	0.0162	0.0231	0.0146	0.0220
550.00	0.0064	0.0152	0.0155	0.0207	0.0103	0.0172
600.00	0.0058	0.0148	0.0129	0.0187	0.0107	0.0173
656.30	0.0053	0.0135	0.0119	0.0172	0.0085	0.0150
700.00	0.0069	0.0146	0.0116	0.0173	0.0088	0.0156
800.00	0.0044	0.0117	0.0108	0.0153	0.0148	0.0183

5.7. REFERENCES

[1] A.A. Gaertner and C.K. Ma, *Experimental Investigation on the Establishment of a Spectral Radiance Scale Based on a Copper-Freezing-Point Black-Body Radiator*, Metrologia **37**, 535-538 (2000).

[2] NBS Report of Calibration – Special Calibration of Tungsten Ribbon Filament Lamp, NBS Test Number 211491, dated April 23, 1975.

[3] NBS Report of Calibration – Lamp Standard of Spectral Radiance, NBS Test Number 534/231206-1, dated May 01, 1984.

[4] NBS Report of Calibration – Lamp Standard of Spectral Radiance, NBS Test Number 534/231206-2, dated May 01, 1984.

[5] C.L. Sanders and W. Gaw, *A Versatile Spectroradiometer and Its Applications,* Applied Optics **6**, 1639–1647 (1967).

5.8. NRC RESULTS

NRC results of the measurements and their uncertainties (*k*=1) are shown in Table 5.7.

Table 5.7. NRC results: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp SR01			Lamp SR02			Lamp SR03		
	1st round	2nd round	Uncertainty (k=1)	1st round	2nd round	Uncertainty (k=1)	1st round	2nd round	Uncertainty (k=1)
300	-	1.496E+08	3.74%	-	1.578E+08	4.24%	-	1.571E+08	3.11%
325	-	4.399E+08	1.84%	-	4.325E+08	3.52%	-	4.384E+08	2.22%
350	-	1.048E+09	1.87%	-	1.022E+09	2.46%	-	1.038E+09	2.66%
375	-	2.153E+09	2.25%	-	2.112E+09	2.95%	-	2.141E+09	2.63%
400	-	3.958E+09	1.91%	-	3.883E+09	2.37%	-	3.929E+09	2.23%
450	-	1.035E+10	1.76%	-	1.016E+10	2.40%	-	1.029E+10	2.21%
500	-	2.089E+10	1.95%	-	2.050E+10	2.31%	-	2.074E+10	2.20%
550	-	3.535E+10	1.52%	-	3.480E+10	2.07%	-	3.525E+10	1.72%
600	-	5.298E+10	1.48%	-	5.189E+10	1.87%	-	5.256E+10	1.73%
656.3	-	7.369E+10	1.35%	-	7.234E+10	1.72%	-	7.308E+10	1.50%
700	-	8.950E+10	1.46%	-	8.779E+10	1.73%	-	8.865E+10	1.56%
800	-	1.196E+11	1.17%	-	1.178E+11	1.53%	-	1.189E+11	1.83%
900	-	-	-	-	-	-	-	-	-
1650	-	-	-	-	-	-	-	-	-

5.9. VNIIOFI RESULTS

VNIIOFI results of the measurements of the NRC lamps are presented in the Table 5.8.

Table 5.8. VNIIOFI results of the NRC lamps: Spectral Radiance (W/m^3/sr) and relative Uncertainties

Wavelength, nm	Lamp SR01	Lamp SR02	Lamp SR03	Uncertainty (*k*=1)
300	-	-	-	-
375	-	-	-	-
400	3.953E+09	3.889E+09	3.860E+09	0.56%
450	1.029E+10	1.013E+10	1.007E+10	0.50%
500	2.081E+10	2.050E+10	2.036E+10	0.46%
550	3.527E+10	3.473E+10	3.451E+10	0.43%
600	5.249E+10	5.172E+10	5.139E+10	0.39%
656.3	7.311E+10	7.214E+10	7.168E+10	0.37%
700	8.887E+10	8.764E+10	8.696E+10	0.35%
800	1.190E+11	1.173E+11	1.165E+11	0.32%
900	1.374E+11	1.356E+11	1.351E+11	0.30%
1000	1.442E+11	1.423E+11	1.420E+11	0.29%
1050	1.441E+11	1.421E+11	1.417E+11	0.31%
1200	1.342E+11	1.324E+11	1.318E+11	0.40%
1550	9.215E+10	9.080E+10	9.154E+10	0.41%
1650	8.111E+10	7.964E+10	8.058E+10	0.46%

5.10. NRC TO VNIIOFI DIFFERENCE.

The percentage differences between NRC measurements, reported for rounds 2 (data for round 1 were not reported), and VNIIOFI measurements are calculated as

$$\Delta_{NRC,j,2} = \left(\frac{L_{NRC,j,2}}{L^P_{NRC,j}} - 1 \right) \cdot 100\% \, , \qquad (5.1)$$

and their uncertainties are calculated as

$$u_{rel}\left(\Delta_{NRC,j,2}\right) = \sqrt{u^2_{rel,NRC,j} + u^2_{rel,VNIIOFI}} \, , \qquad (5.2)$$

where

$L_{NRC,j,2}$	Spectral Radiance of lamp *j* of NRC, measured by the NRC in the round 2;
$L^P_{NRC,j}$	Spectral Radiance of lamp *j* of NRC, measured by the pilot (VNIIOFI);
$u_{rel,NRC,j}$	Total relative uncertainty reported by NRC for lamp *j*;
$u_{rel,VNIIOFI}$	Total relative uncertainty reported by VNIIOFI.

Fig. 5.2 shows differences $\Delta_{NRC,j,2}$ and the uncertainties for lamp SR03 (the differences for the lamps SR01 and SR02 are notably less than their uncertainty).

Fig. 5.3 shows the total average difference between NRC and VNIIOFI calculated as an average for all lamps :

$$\Delta_{NRC} = \frac{1}{3} \sum_{j=1}^{3} \Delta_{NRC,j,2} \qquad (5.3)$$

The uncertainties of the Δ_{NRC} are calculated as an average of $u_{rel}\left(\Delta_{NRC,j,2}\right)$ for all three lamps:

$$u_{rel}\left(\Delta_{NRC}\right) = \frac{1}{3} \sum_{j=1}^{3} u_{rel}\left(\Delta_{NRC,j,2}\right) \qquad (5.4)$$

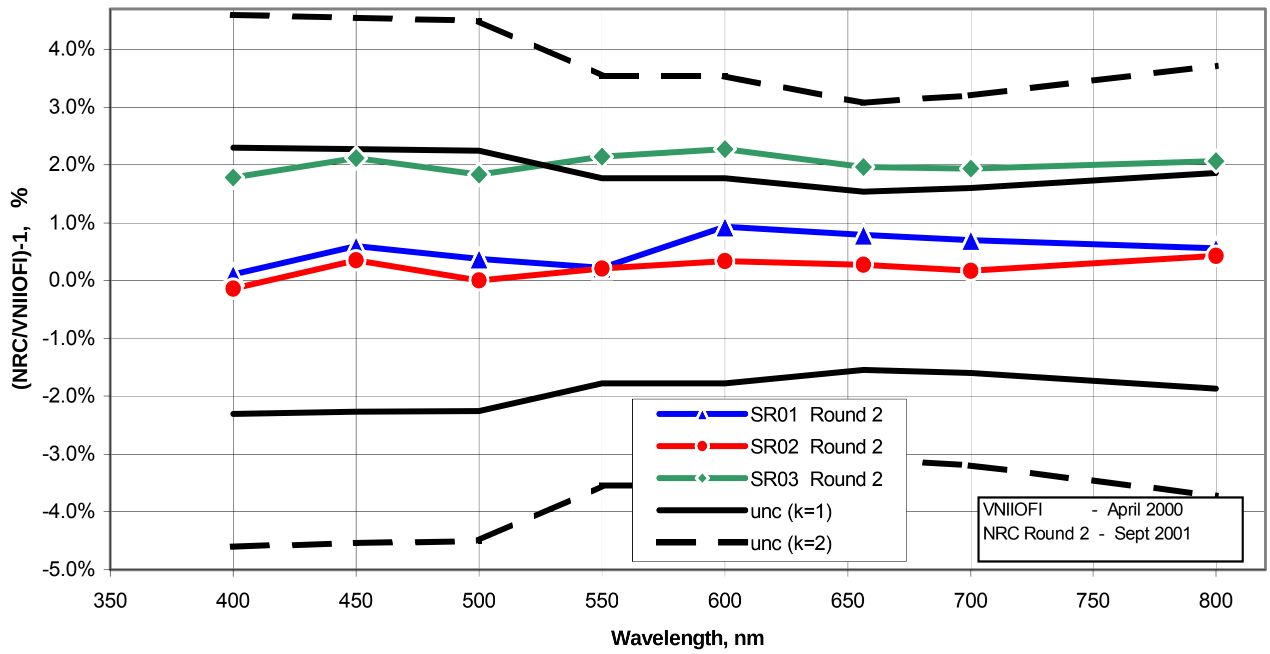

Figure 5.2. Difference $\Delta_{NRC,j,2}$ between 2nd round of NRC and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (5.2) for the lamp SR03 (the differences $\Delta_{NRC,j,2}$ for the lamps SR01 and SR02 are notably less than their uncertainties). unc(k=2) = unc(k=1)*2.

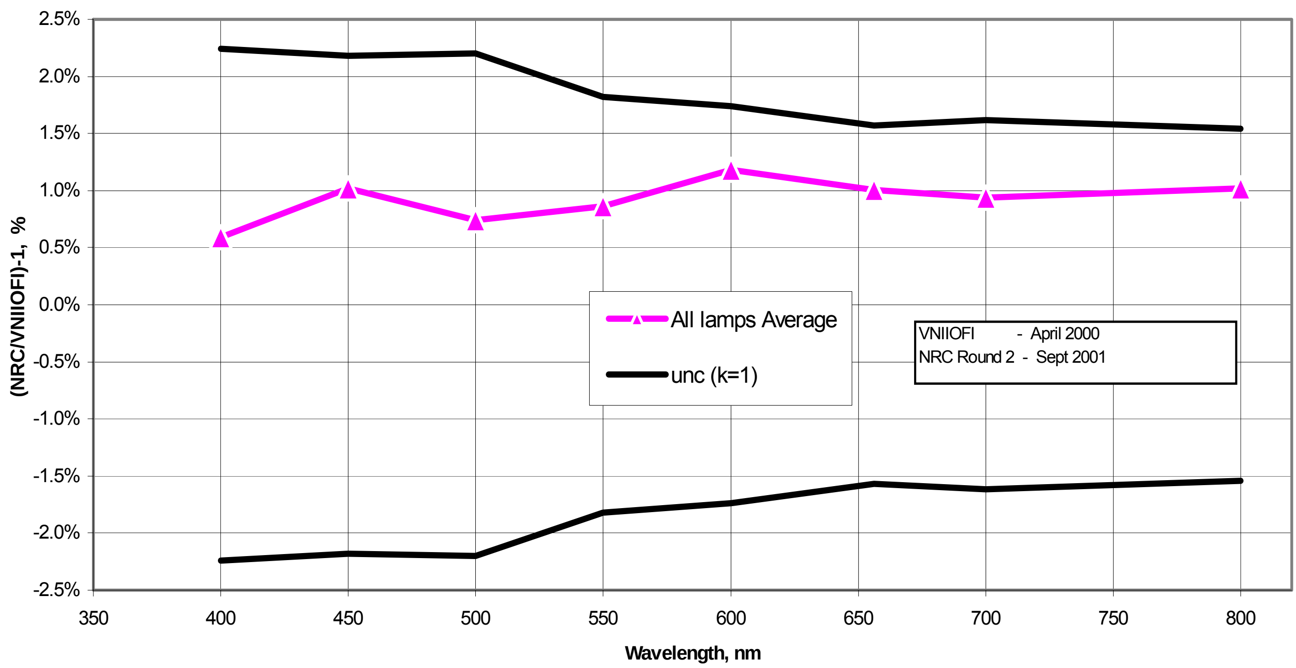

Figure 5.3. Difference Δ_{NRC} between NRC and VNIIOFI measurements, averaged for all lamps. Uncertainties unc(k=1) calculated by (5.4)

6. PTB – VNIIOFI BILATERAL COMPARISON

The sections 6.1 – 6.9 are based on the PTB Report dated by 20 September 1999.

6.1. PTB LAMPS AND SPECTRAL RANGE

The PTB (Radiation Temperature Section) took part in the CCPR-S1 comparison with four gas-filled lamps of Osram Wi17/G type. The lamps had the following identification numbers: 408, 915, 1101 and X1032. Two of them, 408 and 915, were used for spectral region 220 nm to 400 nm at the level of radiance temperature T_s(650 nm) of about 2500 K. The other two, 1101 and X1032, were used for the range 300 nm to 2500 nm with radiance temperature of about 2300 K. Each lamp had its individual fixed measuring base. The first round of the lamps calibrations was performed at the PTB in February 1999. Then the lamps were sent to the pilot laboratory, and then returned to the PTB for a second round of calibrations which were performed in July/August 2000.

6.2. STANDARDS OF THE PTB

A high temperature blackbody (HTBB) developed at the VNIIOFI (Moscow) [1] was used as the calibration source. Its temperature was determined by monochromatic radiation thermometry at 650 nm relative to the freezing point of gold according to the ITS-90. Additionally the temperature was confirmed by absolute radiometry using filter radiometers calibrated against a cryogenic radiometer (RTCR) [2]. In this report only the temperature determination according to the ITS-90 is considered.

6.3. MEASURING EQUIPMENT

Figure 6.1 shows the schematic layout of the used spectral radiance comparator. The radiating area of the sources is imaged on the entrance slit of the monochromator. The imaging ratio is 1:1, a mirror optics with 600 mm focal length and a f-number 1:4.3 is used. The monochromator is a 0.25 m grating double monochromator in the additive configuration with four automatically exchangeable gratings for a wavelength range from 220 nm to 13 μm. Table 6.1 gives the data of the gratings. The exit slit image is demagnified (1:0.75) with an aspherical mirror optics onto detectors. The detectors are mounted on a translation stage (800 mm travelling range), and are automatically exchangeable. The different detectors make it possible to measure in the whole wavelength range. For special applications it is also possible to use additional detectors. A survey of the detectors is given in table 6.2. Two filter wheels in front of the monochromator hold the necessary order sorting filters. The filter wheels are tilted at an angle of about 8° to avoid back reflections. The lateral shift of the image was measured for each filter and is automatically corrected during the measurement. A chopper wheel allows to measure also modulated signals. A polarizer (Glan prism) in front of the filter wheels enables to measure in *s*- and *p*-direction. The whole detection facility (imaging optics, double grating monochromator, detectors, filter radiometers) is mounted on a 3 m air bearing translation stage. The translation stage can be moved with a speed of 250 mm/s and with a reproducibility of 10 μm. In front of the translation stage are mounted the lamps under test, a radiator at room temperature, the standard lamp (T_s(650nm) = 1800 K), a spectral lamp, the high temperature blackbody (HTBB) and a laser for alignment. The detection facility can be moved in a very short time in front of the source under test. The fixed stage for the sources is equipped with mounting and positioning units for 6 transfer standard lamps.

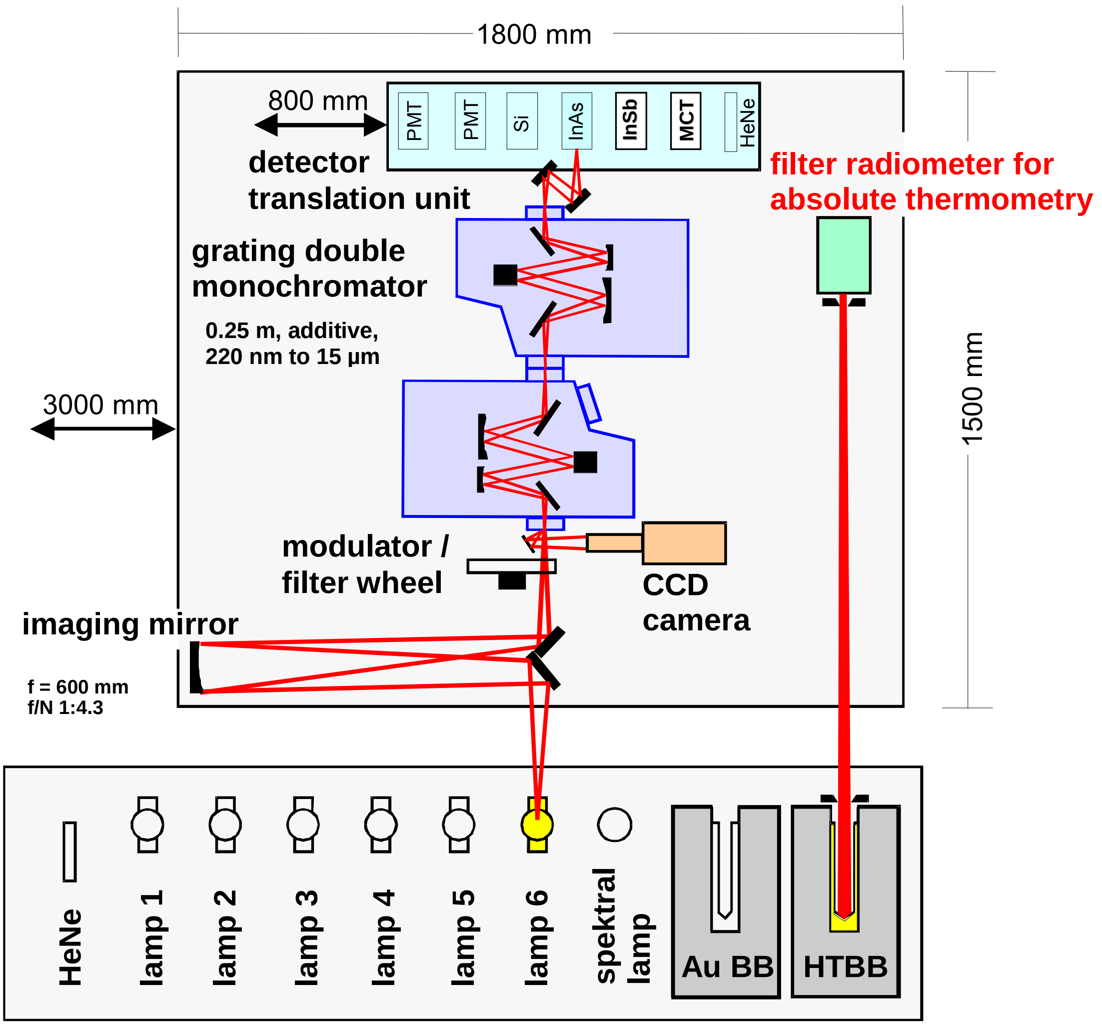

Figure 6.1. PTB spectral radiance Facility used for the comparasion

Table 6.1. Gratings of the monochromator with the used wavelength range.

grating	lines/mm	blaze/nm	wavelength range/nm	
			as used for the CCPR-S1 comparison	operational
1	**2400**	**250**	**220-450**	200-700
2	**1200**	**750**	**450-1300**	450-1400
3	**300**	**2000**	**1300-2500**	1100-3400
4	100	5180		3200-13000

Table 6.2. Detectors with the used wavelength range

detector	type	area/mm	wavelength range/nm	
			as used for the CCPR-S1 comparison	operational
Photo-multiplier	**Hamamatsu R166**	**8x24**	**220- 300**	160- 320
Photo-multiplier	**EMI 9558 QB**	**Ø 44**	**290- 700**	185- 800
Si-diode	**Hamam. S1337-33BQ**	**2.4x2.4**	**650-1100**	190-1100
InGaAs-diode	**LMS InGaAs-3D**	**Ø 3**	**1050-1600**	850-1700
InAs-diode	**J12TE2-HSA2-R02M**	**Ø 2**	**1500-2500**	1000-3800
InSb-diode	J10D-M200-R02M	Ø 2		1-5.5 µm
MCT-photocond	J15D16-M200-S02M	2 x 2		2-26 µm

6.4. SIZE OF SOURCE EFFECT

If we compare radiation sources of different geometrical dimensions, we have to take into account the size of source effect, that means the different part of the signal arising from the radiating field outside the nominal area of measurement. A black strip in the dimensions of the lamp strip (1.3 mm x 20 mm) was mounted on a frosted glass illuminated from the back side. The relative signal of this black strip was measured in dependence of the diameter of the outer radiating field ranging from 10 mm to 40 mm. For the aperture of the HTBB of 26 mm, the SSE correction was determined to 1.00184, a special accurate measuring aperture of 20 mm diameter in front of the HTBB reduces the correction to 1.00173.

6.5. MEASURING POSITION, ALIGNMENT AND CURRENT OF THE LAMPS

The target area used in the measurements was 0.2 mm x 1.0 mm. The lamps are aligned so that the measured strip area is perpendicular to the optical axis. The target position in the horizontal direction is in the centre of the strip. A vertical scan was made to find the best target position in the vertical direction. The reference point is a notch of the strip; a positive coordinate y indicates a position above the notch and a negative – below it. At the determined vertical target position additionally a horizontal scan was recorded. Vertical and horizontal distributions both were measured at a wavelength of 650 nm.

A laser beam, going through the monochromator, was used for alignment of the lamps. Each lamp was aligned in such a way that the laser beam hits the target position of the lamp. Then the reflection of the laser beam from the front window of the lamp was observed on a screen to align the tilt respective the rotation angle of the lamp. The distance from the window to the screen was 220 mm. Each lamp has its specific coordinates on the screen. Table 6.3 summarises the lamp currents, the target positions and the reflection coordinates of the lamps. Positive values of coordinates indicate that the reflection goes to the right respectively to the upward direction, as seen from the lamp to the reflection screen.

Table 6.3. Data of lamps

lamp No	Current i/A	wavelength range λ/nm	target pos. y/mm	window reflection x_r/mm	y_r/mm
408	15.031	220-400	0	-37.5	+7.5
915	15.167	220-400	+2.5	+2.0	-5.0
X1032	12.567	300-2500	-2.0	+10.0	-3.0
1101	12.525	300-2500	+0.8	-45.0	-28.0

6.6. POLARISATION

The radiance of an unknown radiator is measured as the ratio Q of the photo-currents of the unknown radiator and the standard radiator:

$$L_{\lambda L}(\lambda)=Q(\lambda)L_{\lambda N}(\lambda) \qquad (6.1)$$

A grating monochromator works as a partial polarizer depending on the wavelength. Due to the fact that the radiation of a tungsten strip lamp is partially polarized, the polarisation has to be taken into account. To achieve this, the polarizer in front of the entrance slit of the monochromator was used during the calibration. All measurements were made in *s*- and *p*-direction and the spectral radiance was calculated according to:

$$L_{\lambda L}(\lambda)(1+P)=Q_p(\lambda)L_{\lambda N}(\lambda) \qquad L_{\lambda L}(\lambda)(1-P)=Q_s(\lambda)L_{\lambda N}(\lambda) \qquad (6.2)$$

where $L_{\lambda L}(\lambda)$ – spectral radiance of the lamp; $L_{\lambda N}(\lambda)$ – spectral radiance of the standard radiator (HTBB); P – degree of polarisation of the lamp; $Q_s(\lambda)$ – ratio of photo-currents measured in *s*-direction and $Q_p(\lambda)$ – ratio of photo-currents measured in *p*-direction. Finally the spectral radiance of the lamp was calculated as

$$L_{\lambda L}(\lambda)=\frac{Q_s(\lambda)+Q_p(\lambda)}{2}L_{\lambda N}(\lambda) \qquad (6.3)$$

6.7. BUDGET OF UNCERTAINTIES

The following contributions to the uncertainty of the spectral radiances of the lamps are taken into account. Unless otherwise stated all uncertainties are given as relative standard uncertainties.

6.7.1. Blackbody temperature

The uncertainty u_1 is caused by the temperature determination of the HTBB. The temperature of the HTBB (2600 K or 2800 K) is measured against a vacuum tungsten strip lamp with a radiance temperature T_s(650nm)=1800 K. The standard uncertainty of the temperature of the standard lamp calibrated against the gold fixed point is 0.14 K [3]. Recalculating for 2600 K or 2800 K one gets:

u_L = 0.14 K (2600 K/1800 K)^2 = 0.292 K and (6.4)
u_L = 0.14 K (2800 K/1800 K)^2 = 0.339 K

This uncertainty in temperature corresponds to the relative standard uncertainty of the spectral radiance:

$u_1 = u_L.c_2 / (\lambda T^2)$, i.e. u_1 (2600) = 0.621/(λ/nm) and u_1 (2800 K) = 0.622/(λ/nm) (6.5)

6.7.2. Blackbody stability

The temporal stability of the HTBB during a few hours is within ±0.3 K. This results in a relative standard uncertainty:

$$u_2 = 0.3 \cdot c_2 / (\lambda \cdot T^2) / \sqrt{3}, \quad (6.6)$$

i.e. u_2 (2600 K) = 0.369/(λ/nm) and u_2 (2800 K) = 0.318/(λ/nm)

6.7.3. Blackbody temperature distribution non-uniformity

A non-isothermal deviation of the blackbody results from the non-uniformity of the temperature distribution in the walls and in the bottom of the cavity of the HTBB. Therefore the radiation is not Planck radiation for a certain temperature, but a mixture of radiation, which was calculated as a superposition of Planck's radiation for different temperatures weighted accordingly. We assume, that the parts of the radiation result meanly from a temperature range T±20 K. The resulting relative standard uncertainty u_3 is given in table 6.4.

Table 6.4. Estimation of the uncertainty due to a non-isothermal cavity of the HTBB

λ / nm	u_3•10^3	λ / nm	u_3•10^3
220	6.27	750	0.23
230	5.88	1000	0.52
240	5.49	1250	0.65
250	5.10	1500	0.72
300	3.28	1750	0.77
400	1.46	2000	0.79
500	0.61	2250	0.81
600	0.16	2500	0.83
650	0.00		

6.7.4. Lamp-to-HTBBB comparison

The comparison of the spectral radiance of the unknown lamp and the HTBB is performed within an uncertainty of $\Delta L_\lambda / L_\lambda$ = 1.5•10^{-3}. As the comparison is to be made in s- and p-direction, the uncertainty increases by the factor $\sqrt{2}$. The resulting standard uncertainty u_4 is

$$u_4 = 1.5 \cdot 10^{-3} \cdot \sqrt{2} / \sqrt{3} = 1.22 \cdot 10^{-3} \quad (6.7)$$

6.7.5. Lamp current setting

The setting of the current of the tungsten strip lamp gives a standard uncertainty, which results from two parts: uncertainty in the voltage measurement $1.3 \cdot 10^{-5}$ and uncertainty in the current measurement $1 \cdot 10^{-5}$, quadratic addition gives

$$u(\Delta i/i) = 1.64 \cdot 10^{-5} \qquad (6.8)$$

The current sensitivity of the strip temperature is approximately 1 K / 0.015 A for this type of tungsten strip lamp. Therefore at the current level of 15 A the temperature uncertainty of the lamp is:

$$u_c = 1.64 \cdot 10^{-5} \cdot 15\ \text{A} \cdot 1\ \text{K}/0.015\ \text{A} = 1.64 \cdot 10^{-2}\ \text{K} \qquad (6.9)$$

The relative standard uncertainty of the spectral radiance u_5 results in:

$$u_5 = u_c \cdot c_2/(\lambda T^2); \qquad (6.10)$$

u_5 (2300 K) = $4.461 \cdot 10^{-2}/(\lambda/\text{nm})$ and u_5 (2500 K) = $3.775 \cdot 10^{-2}/(\lambda/\text{nm})$

6.7.6. Polarisation filter – to – entrance slit interreflection

The measurement of the radiance ratios in s- and p-direction gives an additional uncertainty for the temperature. The main reason is that interreflections between the polarisation filter and the entrance slit of the monochromator could not be completely avoided. By the first measurements we took no precautions against interreflections and we have to take into account an additional temperature uncertainty of 1.5 K. The resulting standard deviation of the spectral radiance u_6 is:

$$u_6 = 1.5\ \text{K} \cdot c_2 / \left(\lambda T^2\right) / \sqrt{3} \qquad (6.11)$$

u_6 (2800 K) = $1.59/(\lambda/\text{nm})$ and u_6 (2600 K) = $1.84/(\lambda/\text{nm})$

6.7.7. Detector noise and non-linearity

The relative standard uncertainty of the spectral radiance resulting from noise and non-linearity of the detectors u_7 is estimated as given in table 6.5.

Table 6.5. Uncertainty estimation of the detectors (noise and non-linearity)

λ / nm	$u_7 \cdot 10^3$	λ / nm	$u_7 \cdot 10^3$
220	17.80	750	0.25
230	4.97	1000	0.24
240	4.32	1250	0.66
250	3.68	1500	0.97
300	1.43	1750	1.17
400	0.49	2000	1.35
500	0.24	2250	1.76
600	0.23	2500	2.28
650	0.22		

6.7.8. Wavelength setting

The uncertainty in wavelength depends on the precision of the wavelength calibration and on the precision of the actual wavelength setting of the monochromator. If we assume for each grating one step of the stepping motor as standard uncertainty we get an uncertainty of the wavelength u_λ as given in table 6.6.

Table6.6. Uncertainty of the monochromator wavelength setting

λ / nm	u_λ /nm
220-600	0.025
600-1200	0.050
1200-2500	0.200

The resulting relative standard uncertainty is the product of u_λ and the wavelength dependence of the radiance ratio Q of the lamp under test and the HTBB.

$$Q = L_\lambda(\lambda, T_s(\lambda))/L_\lambda(\lambda, T) \qquad (6.12)$$

where $T_s(\lambda)$ – radiance temperature of the lamp: T_s(650nm) ≈ 2300 K or T_s(650nm) ≈ 2500 K ;
T – temperature of the HTBB: T ≈ 2600 K or T ≈ 2800 K

Differentiation with respect to λ results:

$$\frac{1}{Q}\frac{\partial Q}{\partial \lambda} = \frac{1}{T_s} / \left(1 - e^{-\frac{c_2}{\lambda T_s}}\right) - \frac{1}{T} / \left(1 - e^{-\frac{c_2}{\lambda T}}\right) \qquad (6.13)$$

The relative standard uncertainty of the spectral radiance u_8 is

$$u_8 = u_\lambda \bullet Q^{-1} \bullet \partial Q / \partial \lambda \qquad (6.14)$$

In dependence of the wavelength we get the values given in tables 6.7 and 6.8.

Table 6.7. Spectral radiance uncertainty u_8 resulting from the wavelength for HTBB-temperature of T = 2800 K and lamp radiance temperature of T_s(650nm) ≈ 2500 K

λ/nm	$Q^{-1} \bullet \partial Q/\partial\lambda$/nm^{-1}	u_λ /nm	$u_8 \bullet 10^3$
220	$5.64 \bullet 10^{-3}$	0.025	0.141
230	$5.11 \bullet 10^{-3}$	0.025	0.128
240	$4.70 \bullet 10^{-3}$	0.025	0.118
250	$4.37 \bullet 10^{-3}$	0.025	0.109
300	$3.27 \bullet 10^{-3}$	0.025	0.082
400	$2.33 \bullet 10^{-3}$	0.025	0.058
650	$1.53 \bullet 10^{-3}$	0.050	0.076

Table 6.8. Spectral radiance uncertainty u_8 resulting from the wavelength for HTBB-temperature of T = 2600 K and lamp radiance temperature of T_s(650nm) ≈ 2300 K

λ/nm	$Q^{-1}\bullet\partial Q/\partial\lambda$/nm^{-1}	u_λ /nm	$u_8\bullet 10^3$
300	$4.37\bullet 10^{-3}$	0.025	0.109
400	$3.02\bullet 10^{-3}$	0.025	0.076
500	$2.34\bullet 10^{-3}$	0.025	0.058
600	$1.93\bullet 10^{-3}$	0.025	0.048
650	$1.78\bullet 10^{-3}$	0.050	0.089
750	$1.56\bullet 10^{-3}$	0.050	0.078
1000	$1.23\bullet 10^{-3}$	0.050	0.061
1250	$1.04\bullet 10^{-3}$	0.200	0.208
1500	$9.14\bullet 10^{-4}$	0.200	0.183
1750	$8.10\bullet 10^{-4}$	0.200	0.162
2000	$0.73\bullet 10^{-4}$	0.200	0.146
2250	$0.66\bullet 10^{-4}$	0.200	0.132
2500	$0.60\bullet 10^{-4}$	0.200	0.120

6.7.9. Lamp short term instability

The short term stability for gas-filled tungsten strip lamps leads from our experience to a maximal variation of the temperature within ±1 K at the level of T_s(650nm) ≈ 2500 K. The resulting relative standard uncertainty of the spectral radiance u_9 is:

$$u_9 = \left(1/\sqrt{3}\right)\cdot c_2 / \left(\lambda \cdot T_s^2\right) = 1.329 / \left(\lambda / \mathrm{nm}\right) \qquad (6.15)$$

6.7.10. Total uncertainty

The quadratic addition of all contributions u_1 up to u_9 yields the total relative uncertainty of the spectral radiance u, given in table 6.9 for lamps with T_s(650nm) ≈ 2500 K and in table 6.10 for lamps with T_s(650nm) ≈ 2300 K.

Table 6.9. Total relative uncertainty (k=1) for lamps with T_s(650nm) ≈ 2500 K and HTBB-temperature of T = 2800 K

λ/nm	$u\bullet 10^3$	λ/nm	$u\bullet 10^3$
220	21.4	350	6.8
230	12.3	375	6.2
240	11.5	400	5.8
250	10.8	450	5.1
260	10.2	500	4.6
270	9.6	550	4.2
280	9.0	600	3.9
290	8.6	650	3.6
300	8.2	656.3	3.6
325	7.4		

Table 6.10. Total relative uncertainty (k=1) for lamps with T_s(650nm) ≈ 2300 K and HTBB-temperature of T = 2600 K

λ/nm	u•10^3	λ/nm	u•10^3
300	8.8	1050	2.7
325	8.0	1100	2.6
350	7.3	1200	2.5
375	6.7	1300	2.4
400	6.3	1400	2.4
450	5.5	1500	2.3
500	5.0	1550	2.3
550	4.5	1600	2.3
600	4.2	1700	2.3
650	3.9	1800	2.3
656.3	3.8	1900	2.3
700	3.6	2000	2.3
750	3.4	2100	2.4
800	3.3	2200	2.5
850	3.1	2300	2.6
900	3.0	2400	2.7
950	2.8	2500	2.9
1000	2.7		

6.8. REFERENCES

[1] Sapritsky V.I., Black-body radiometry, *Metrologia*, 1996, 32, pp. 411-417.

[2] Fu L., Fischer J., Charakterisation of photodiodes in the visible spectral range based on cryogenic radiometry, *Metrologia*, 1993, **30**, pp. 297-303.

[3] Fischer J., Hartmann J., Calibration of tungsten strip lamps as transfer standards for temperature*, Proceedings of Tempmeko 99*.

6.9. PTB RESULTS

Values of spectral radiance measured at PTB and their uncertainties are presented in Table 6.11.a and Table 6.11.b The unit of spectral radiance is W/m^3/sr. The wavelength is given in nm. The coverage factor of the uncertainties is 1.

Table 6.11.a PTB results for the lamps measured in the spectral range 220 to 400 nm: Spectral Radiance (W/m³/sr) and relative Uncertainties

Wavelength, nm	Lamp 408		Lamp 915		Uncertainty (k=1)
	1st round	2nd round	1st round	2nd round	
220	5.145E+06	5.163E+06	4.757E+06	4.233E+06	2.14%
230	1.195E+07	1.185E+07	1.121E+07	1.000E+07	1.23%
240	2.552E+07	2.511E+07	2.418E+07	2.172E+07	1.15%
250	5.074E+07	4.972E+07	4.839E+07	4.375E+07	1.08%
260	9.467E+07	9.259E+07	9.071E+07	8.240E+07	1.02%
270	1.671E+08	1.633E+08	1.606E+08	1.467E+08	0.96%
280	2.806E+08	2.747E+08	2.703E+08	2.480E+08	0.90%
290	4.511E+08	4.424E+08	4.352E+08	4.008E+08	0.86%
300	6.973E+08	6.858E+08	6.733E+08	6.229E+08	0.82%
325	1.790E+09	1.774E+09	1.729E+09	1.613E+09	0.74%
350	3.881E+09	3.875E+09	3.743E+09	3.522E+09	0.68%
375	7.370E+09	7.404E+09	7.099E+09	6.726E+09	0.62%
400	1.261E+10	1.272E+10	1.210E+10	1.156E+10	0.58%
656.3	1.502E+11	1.500E+11	1.442E+11	1.409E+11	0.36%

Table 6.11.b PTB results for the lamps measured in the spectral range 300 to 2500 nm: Spectral Radiance (W/m³/sr) and relative Uncertainties

Wavelength, nm	Lamp 1101		Lamp x1032		Uncertainty (k=1)
	1st round	2nd round	1st round	2nd round	
300	1.378E+08	1.414E+08	1.374E+08	1.420E+08	0.88%
325	3.976E+08	4.027E+08	3.953E+08	4.038E+08	0.80%
350	9.546E+08	9.598E+08	9.481E+08	9.622E+08	0.73%
375	1.984E+09	1.986E+09	1.970E+09	1.993E+09	0.67%
400	3.675E+09	3.670E+09	3.649E+09	3.686E+09	0.63%
450	9.682E+09	9.663E+09	9.624E+09	9.717E+09	0.55%
500	1.974E+10	1.972E+10	1.964E+10	1.983E+10	0.50%
550	3.358E+10	3.360E+10	3.345E+10	3.376E+10	0.45%
600	5.013E+10	5.019E+10	4.997E+10	5.039E+10	0.42%
656.3	7.012E+10	7.022E+10	6.998E+10	7.047E+10	0.38%
700	8.532E+10	8.543E+10	8.526E+10	8.576E+10	0.36%
800	1.148E+11	1.149E+11	1.151E+11	1.158E+11	0.33%
900	1.334E+11	1.334E+11	1.342E+11	1.353E+11	0.30%
1000	1.407E+11	1.407E+11	1.420E+11	1.438E+11	0.27%
1050	1.408E+11	1.409E+11	1.423E+11	1.445E+11	0.27%
1200	1.314E+11	1.318E+11	1.331E+11	1.357E+11	0.25%
1550	9.053E+10	9.100E+10	9.134E+10	9.240E+10	0.23%
1700	7.448E+10	7.493E+10	7.510E+10	7.575E+10	0.23%
2100	4.307E+10	4.391E+10	4.326E+10	4.468E+10	0.24%
2300	3.291E+10	3.353E+10	3.294E+10	3.403E+10	0.26%
2400	2.888E+10	2.938E+10	2.895E+10	2.973E+10	0.27%
2500	2.518E+10	2.597E+10	2.528E+10	2.606E+10	0.29%

6.10. VNIIOFI RESULTS

The VNIIOFI results of the PTB lamps measurement are presented in the Tables 6.12a and 6.12b.

Table 6.12.a. VNIIOFI results of the PTB lamps measured in the spectral range 220 to 400 nm: Spectral Radiance (W/m³/sr) and relative Uncertainties

Wavelength, nm	Lamp 408	Lamp 915	Uncertainty (*k*=1)
220	5.201E+06	4.834E+06	1.13%
230	1.206E+07	1.129E+07	1.00%
240	2.572E+07	2.413E+07	0.92%
250	5.118E+07	4.819E+07	0.87%
260	9.556E+07	9.049E+07	0.84%
270	1.685E+08	1.602E+08	0.80%
280	2.828E+08	2.693E+08	0.77%
290	4.538E+08	4.325E+08	0.75%
300	7.009E+08	6.683E+08	0.73%
325	1.798E+09	1.711E+09	0.67%
350	3.898E+09	3.700E+09	0.64%
375	7.410E+09	7.018E+09	0.59%
400	1.267E+10	1.197E+10	0.56%
656.3	1.506E+11	1.426E+11	0.37%

Table 6.12.b. VNIIOFI results of the PTB lamps measured in the spectral range 300 to 2500 nm: Spectral Radiance (W/m³/sr) and relative Uncertainties

Wavelength, nm	Lamp 1101	Lamp x1032	Uncertainty (*k*=1)
300	1.377E+08	1.383E+08	0.73%
325	3.984E+08	3.994E+08	0.67%
350	9.560E+08	9.580E+08	0.64%
375	1.983E+09	1.988E+09	0.59%
400	3.662E+09	3.675E+09	0.56%
450	9.624E+09	9.647E+09	0.50%
500	1.960E+10	1.964E+10	0.46%
550	3.338E+10	3.346E+10	0.43%
600	4.988E+10	4.995E+10	0.39%
656.3	6.988E+10	7.003E+10	0.37%
700	8.507E+10	8.528E+10	0.35%
800	1.144E+11	1.147E+11	0.32%
900	1.326E+11	1.331E+11	0.30%
1000	1.396E+11	1.401E+11	0.29%
1050	1.396E+11	1.400E+11	0.31%
1200	1.302E+11	1.307E+11	0.40%
1550	9.027E+10	9.059E+10	0.41%
1700	7.424E+10	7.454E+10	0.41%
2100	4.305E+10	4.322E+10	0.41%
2300	3.284E+10	3.296E+10	0.44%
2400	2.887E+10	2.897E+10	0.44%
2500	2.524E+10	2.533E+10	0.46%

6.11. PTB TO VNIIOFI DIFFERENCE.

The percentage differences between PTB measurements, reported for individual rounds, and VNIIOFI measurements are calculated as

$$\Delta_{PTB,j,r} = \left(\frac{L_{PTB,j,r}}{L^{P}_{PTB,j}} - 1 \right) \cdot 100\%, \qquad (6.16)$$

and their uncertainties are calculated as

$$u_{rel}\left(\Delta_{PTB,j,r}\right) = \sqrt{u^2_{rel,PTB} + u^2_{rel,VNIIOFI}}, \qquad (6.17)$$

where

$L_{PTB,j,r}$	Spectral Radiance of lamp *j* of PTB, measured by the PTB in round *r* (=1 to 2);
$L^{P}_{PTB,j}$	Spectral Radiance of lamp *j* of PTB, measured by the pilot (VNIIOFI);
$u_{rel,PTB}$	Total relative uncertainty reported by PTB;
$u_{rel,VNIIOFI}$	Total relative uncertainty reported by VNIIOFI.

Fig. 6.2 and Fig. 6.3 show differences $\Delta_{PTB,j,1}$ and $\Delta_{PTB,j,2}$ respectively and their uncertainties.

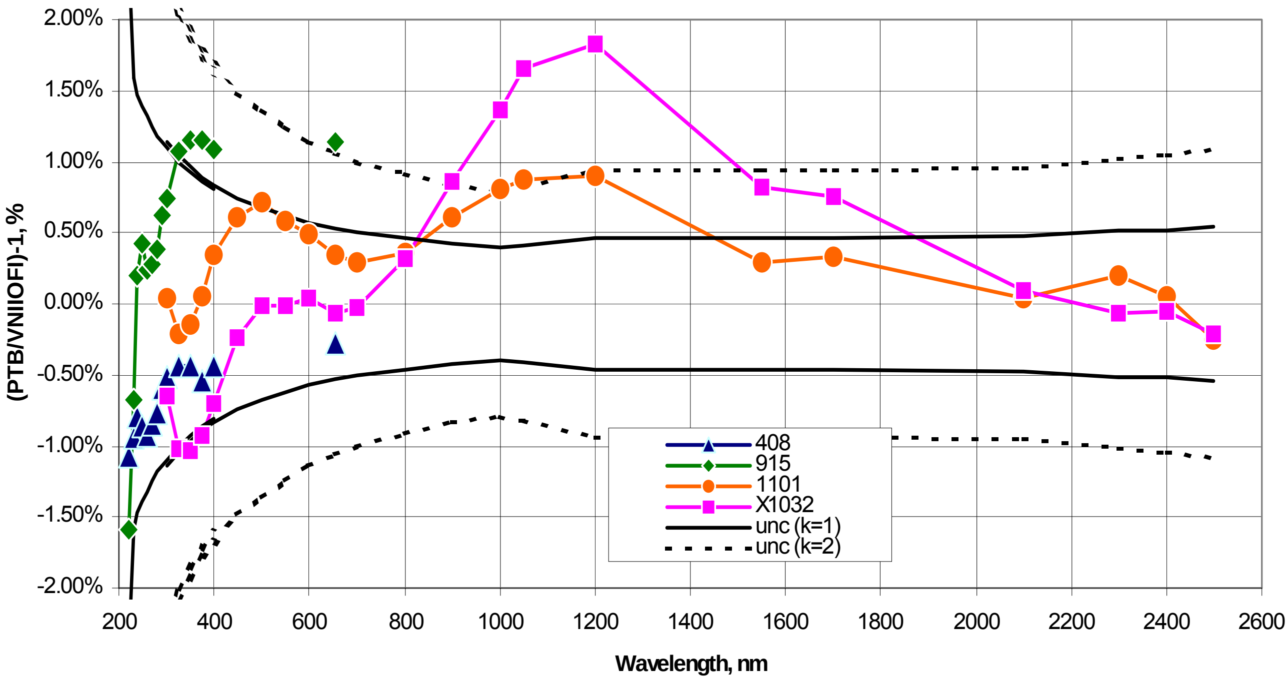

Figure 6.2. Difference $\Delta_{PTB,j,1}$ between 1st round of PTB and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (6.17) and unc(k=2) = unc(k=1)*2.

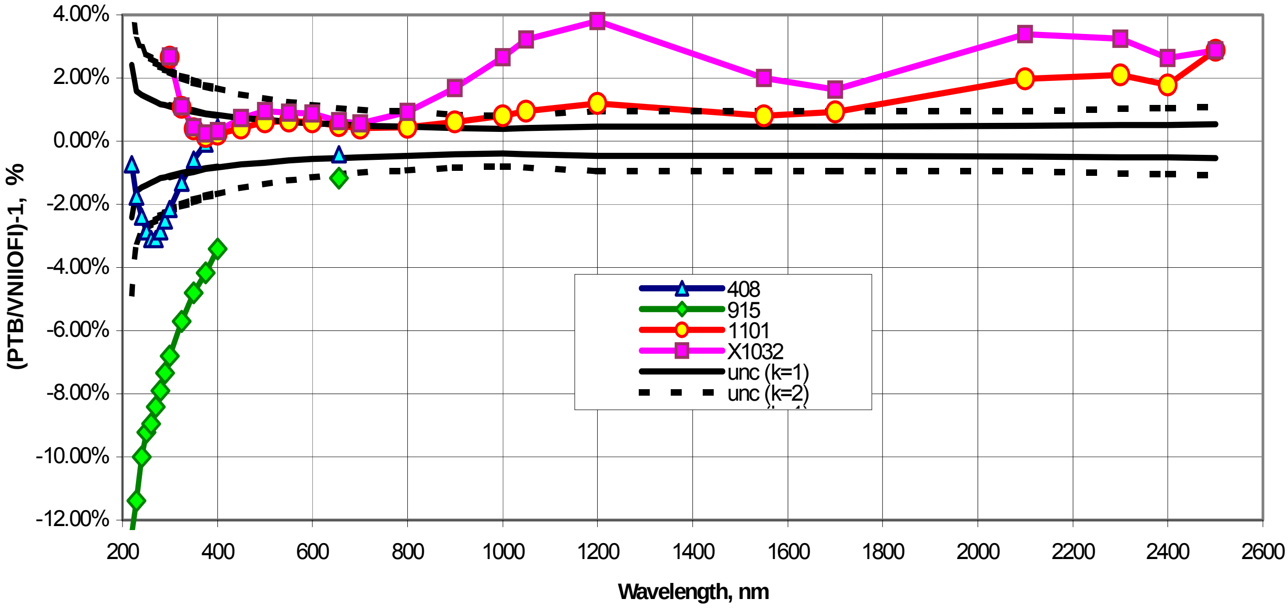

Figure 6.3. Difference $\Delta_{PTB,j,2}$ between 2nd round of PTB and VNIIOFI measurements. Uncertainties unc(k=1) calculated by (6.17) and unc(k=2) = unc(k=1)*2.

Comparing Figure 6.2 and Figure 6.3 one can see that the result of the lamp 915 measurement during the 2nd round demonstrates significant difference from other results. This difference was obviously seen from Relative Data sent by the pilot to the participant during the PreDraft A procedure. Probably, the lamp changed its parameters between the measurements at VNIIOFI and the second round measurements at PTB. The participant has decided to eliminate the data for lamp 915 for round 2 from all further calculations.

Fig. 6.4 shows the PTB to VNIIOFI differences averaged by two rounds calculated as

$$\Delta_{PTB,j} = \left(\frac{\bar{L}_{PTB,j}}{L^P_{PTB,j}} - 1 \right) \cdot 100\% , \qquad (6.18)$$

where $\bar{L}_{PTB,j} = \frac{1}{2} \sum_{r=1}^{2} L_{PTB,j,r}$

Note: $\Delta_{PTB,915} = \Delta_{PTB,915,1}$

One can see the lamp X1032 shows an unexpected large difference in the IR region. Moreover, this difference significantly increases between the first and second rounds (compare the Fig.6.2 and Fig. 6.3) that could be a sign of probable instability of X1032. Investigating such behaviour of the lamp, PTB specialists realised that X1032 demonstrated some instability already at the stage of preparation lamps to the comparison. Fig. 6.5 illustrates the difference between two measurements of three lamps made at PTB in October 1998 and February 1999 respectively. We can see that spectral radiance of X1032 had increased by about three percent while other two lamps showed nearly no change. An original protocol of those measurements is presented in Appendix B. On the base of this fact PTB suggested the second round data of X1032 to be excluded from further analysis. But this was not supported by other participants and the WG-KC because it was made after Draft A report. Therefore, the official comparison results are based on the data that include both rounds of PTB lamp X1032. But in Appendix A an alternative way of analysis is presented on the base of excluding the secont round of X1032 as well as the NIST lamp Q130.

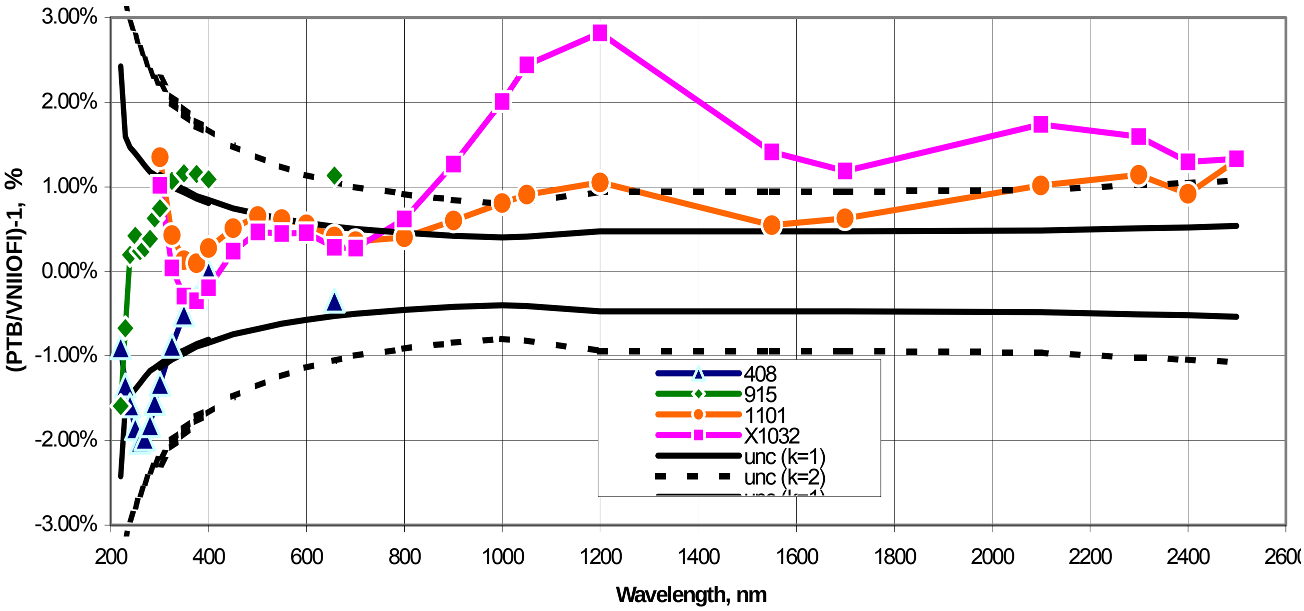

Figure 6.4. Difference $\Delta_{PTB,j}$ between PTB and VNIIOFI measurements, averaged over two rounds. Uncertainties unc(k=1) calculated by (6.17) and unc(k=2) = unc(k=1)*2.

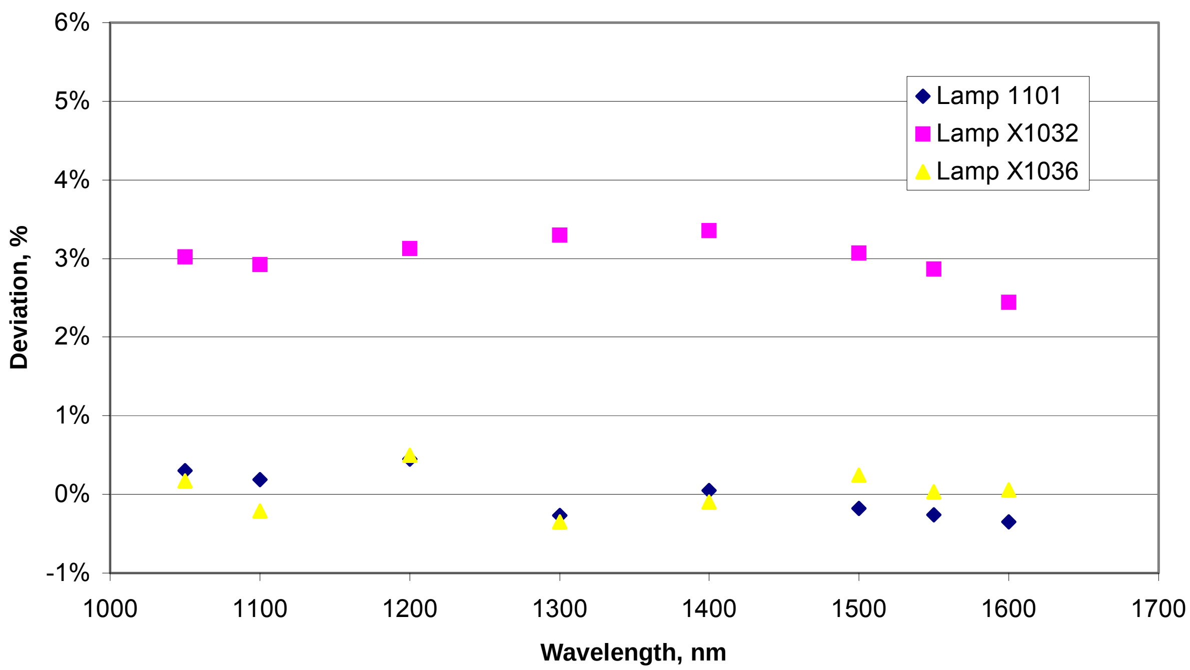

Figure 6.5. Change in spectral radiance of lamps 1101, X1032 and X1036observed at PTB between October 1998 and February 1999.

The total average difference between PTB and VNIIOFI measurements calculated as

$$\Delta_{PTB} = \frac{1}{2}\sum_{j=1}^{2}\Delta_{PTB,j} \qquad (6.19)$$

The values Δ_{PTB} are calculated independently for two groups of lamps: lamps 408 and 915, measured in UV range, form one group; lamps 1101 and x1032, measured in the range 300 to 2500nm, form another group. The differences are shown on Fig. 6.6. The red curve presents the values that based on both rounds of both lamps 1101 and X1032 and will be used for further analysis of the comparison results. Another curve shows the possible view of Δ_{PTB} differences in the case of withdrawing the second round of X1032.

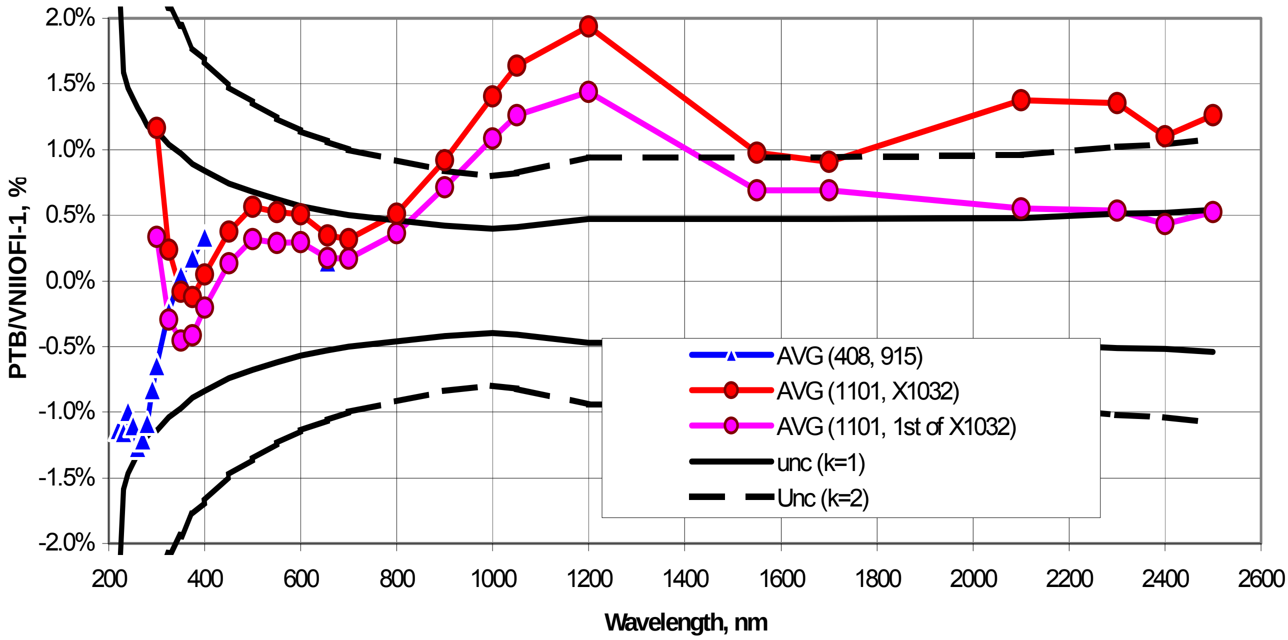

Figure 6.6. Difference Δ_{PTB} between PTB and VNIIOFI measurements, averaged over rounds and lamps. Uncertainties unc(k=1) calculated by (6.17) and unc(k=2) = unc(k=1)*2.

7. COMPARISON REFERENCE VALUE

Comparison Reference Value (CRV) are calculated totally in according to the Guidelines for CCPR Comparison Repost Preparation (CCPR Key Comparison Working Group; Rev.1, March 2006).

The method for calculating CRV is the weighted mean with cut-off.

Note 7.1: CRV and all other calculations will be done independently for two groups of lamps: the first group is formed by the lamps, measured in the spectral range 220 to 400 nm, i.e. the lamps Q122, Q124, Q125 from NIST and 408 and 915 from PTB; all other lamps form the second group. Therefore, only three laboratories (NIST, PTB and VNIIOFI) take part in the first-group comparison, while all five (BNM-INM, NIST, NRC, PTB and VNIIOFI) participate in the second group.

1. Difference between measurements of NMI *i* and the pilot measurements is determined by

$$\Delta_i = \frac{1}{N}\sum_j \left(\left(\frac{1}{2}\sum_{r=1}^{2} L_{i,j,r} \right) \Big/ L_{i,j}^{P} - 1 \right) \cdot 100\% , \qquad (7.1)$$

where

$L_{i,j,r}$ Spectral Radiance of lamp *j* of NMI *i*, measured by the NMI *i* in round *r* (=1 to 2);

$L_{i,j}^{P}$ Spectral Radiance of lamp *j* of NMI *i*, measured by the pilot (VNIIOFI);

N Number of the lamps used by NMI *i*.

Differences Δ_i were calculated and presented in graph form earlier in this report (see Figures 3.8.4, 4.8.4, 5.2 and 6.5). Values of the Δ_i are also presented in Tables 7.3 and 7.4.

Note 7.2: The values Δ_{NIST} of NIST include the lamp Q130, as well as the values Δ_{PTB} of PTB include both rounds of the lamp X1032 and the fist round only of the lamp 915.

2. The relative uncertainty of measurements of NMI *i*, averaged for all lamps and rounds, is determined by

$$u_{rel,i} = \frac{1}{N}\sum_j \frac{1}{2}\sum_{r=1}^{2} u_{rel}\left(L_{i,j,r}\right) \qquad (7.2)$$

Note 7.3: NIST, PTB and VNIIOFI reported the same uncertainties for all lamps and rounds. Therefore for these participants $u_{rel,i}$ simply equals to their reported uncertainties. BNM-INM uncertainties are averaged for two rounds. NRC uncertainties are averaged for three lamps.

3. The uncertainty of Δ_i is determined by

$$u\left(\Delta_i\right) = \sqrt{u_{rel,i}^2 + u_{rel,PR}^2} , \qquad (7.3)$$

where

$u_{rel,PR}$ Reproducibility of Pilot (VNIIOFI) measurements of lamp, including the stability of the comparison scale during the period of comparison and repeatability of the transfer lamp (see Table 2.4)

4. The ***cut-off value*** $u_{cut-off}$ is calculated by

$$u_{cut-off} = \text{average}\{u_{rel,i}\} \text{ for } u_{rel,i} \leq \text{median}\{u_{rel,i}\};\ i = 0 \text{ to } 4 \qquad (7.4)$$

Tables 7.1 and 7.2 present the average uncertainties $u_{rel,i}$ for all participants and the calculated cut-off values.

Table. 7.1. Participant's average uncertainties and the cut-off. Spectral range 220 – 400 nm. Values used for calculating cut-off are marked as bold.

Wavelength, nm	Average uncertainties $u_{rel,i}$			Cut-off
	NIST	PTB	VNIIOFI	
220	**0.89%**	2.14%	**1.13%**	1.01%
230	**0.76%**	1.23%	**1.00%**	0.88%
240	**0.67%**	1.15%	**0.92%**	0.80%
250	**0.61%**	1.08%	**0.87%**	0.74%
260	**0.58%**	1.02%	**0.84%**	0.71%
270	**0.56%**	0.96%	**0.80%**	0.68%
280	**0.54%**	0.90%	**0.77%**	0.66%
290	**0.52%**	0.86%	**0.75%**	0.63%
300	**0.51%**	0.82%	**0.73%**	0.62%
325	**0.48%**	0.74%	**0.67%**	0.58%
350	**0.46%**	0.68%	**0.64%**	0.55%
375	**0.45%**	0.62%	**0.59%**	0.52%
400	**0.44%**	0.58%	**0.56%**	0.50%

Table. 7.2. Participant's average uncertainties and the cut-off. Spectral range 300 – 2500 nm. Values used for calculating cut-off are marked as bold.

Wavelength, nm	Average uncertainties $u_{rel,i}$					Cut-off
	BNM-INM	NIST	NRC	PTB	VNIIOFI	
300	1.94%	**0.51%**	3.70%	**0.88%**	**0.73%**	0.71%
325	1.24%	**0.48%**	2.53%	**0.80%**	**0.67%**	0.65%
350	1.07%	**0.46%**	2.33%	**0.73%**	**0.64%**	0.61%
375	1.07%	**0.45%**	2.61%	**0.67%**	**0.59%**	0.57%
400	0.88%	**0.44%**	2.17%	**0.63%**	**0.56%**	0.54%
450	0.88%	**0.43%**	2.12%	**0.55%**	**0.50%**	0.49%
500	0.70%	**0.42%**	2.15%	**0.50%**	**0.46%**	0.46%
550	0.70%	**0.41%**	1.77%	**0.45%**	**0.43%**	0.43%
600	0.70%	**0.37%**	1.69%	**0.42%**	**0.39%**	0.39%
656.3	0.44%	**0.31%**	1.52%	**0.38%**	**0.37%**	0.35%
700	0.44%	**0.29%**	1.58%	**0.36%**	**0.35%**	0.33%
800	0.44%	**0.26%**	1.51%	**0.33%**	**0.32%**	0.30%
900	0.40%	**0.24%**		**0.30%**	**0.30%**	0.28%
1000	0.40%	0.61%		**0.27%**	**0.29%**	0.28%
1050	0.53%	0.61%		**0.27%**	**0.31%**	0.29%
1200	0.53%	0.62%		**0.25%**	**0.40%**	0.33%
1550	**0.39**%	0.62%		**0.23%**	0.41%	0.31%
1700	**0.39**%	0.63%		**0.23%**	0.41%	0.31%
2100	**0.39**%	0.65%		**0.24%**	0.41%	0.32%
2300	0.50%	0.66%		**0.26%**	**0.44%**	0.35%
2400	0.50%	0.67%		**0.27%**	**0.44%**	0.36%
2500	0.50%	0.69%		**0.29%**	**0.46%**	0.38%

5. The reported uncertainty $u_{rel,i}$ of each NMI *i* is adjusted by the cut-off:

$$u_{rel,adj,i} = u_{rel,i} \quad \text{for} \quad u_{rel,i} \geq u_{cut-off} \tag{7.5}$$
$$u_{rel,adj,i} = u_{cut-off} \quad \text{for} \quad u_{rel,i} < u_{cut-off}$$

6. The uncertainty of Δ_i after cut-off is given by

$$u_{adj}(\Delta_i) = \sqrt{u^2_{rel,adj,i} + u^2_{rel,PR}} \tag{7.6}$$

7. The ***weights*** w_i for NMI *i* is determined by

$$w_i = u^{-2}_{adj}(\Delta_i) / \sum_{i=0}^{N} u^{-2}_{adj}(\Delta_i) \tag{7.7}$$

8. The ***CRV***, Δ_{CRV}, is determined by

$$\Delta_{CRV} = \sum_{i=0}^{N} w_i \Delta_i \tag{7.8}$$

9. The uncertainty of the CRV (weighted mean with cut-off) is given by

$$u(\Delta_{CRV}) = \sqrt{\sum_{i=0}^{N} \frac{u^2(\Delta_i)}{u^4_{adj}(\Delta_i)}} \bigg/ \sum_{i=0}^{N} u^{-2}_{adj}(\Delta_i) \tag{7.9}$$

The CRV values and their uncertainties calculated in accordance with (7.8) and (7.9) respectively are presented in Tables 7.3 and 7.4 together with the Δ_i differences between each participant and the pilot.

Table 7.3. NMI to Pilot differences Δ_i and CRV values for spectral range 220 – 400 nm. The second round of PTB lamp 915 is not included.

Wavelength, nm	NMI-Pilot differences Δ_i			**CRV**, Δ_{CRV}	$u(\Delta_{CRV})$
	NIST	PTB	VNIIOFI		
220	-2.36%	-1.25%	0.00%	**-1.26%**	0.87
230	-0.86%	-1.01%	0.00%	**-0.61%**	0.70
240	-0.21%	-0.70%	0.00%	**-0.26%**	0.63
250	-0.28%	-0.72%	0.00%	**-0.29%**	0.59
260	0.15%	-0.89%	0.00%	**-0.16%**	0.56
270	0.02%	-0.85%	0.00%	**-0.21%**	0.54
280	0.16%	-0.72%	0.00%	**-0.13%**	0.52
290	0.17%	-0.47%	0.00%	**-0.06%**	0.50
300	0.14%	-0.30%	0.00%	**-0.02%**	0.49
325	0.19%	0.09%	0.00%	**0.10%**	0.45
350	0.35%	0.32%	0.00%	**0.23%**	0.42
375	0.36%	0.42%	0.00%	**0.26%**	0.40
400	0.26%	0.54%	0.00%	**0.26%**	0.38

Table 7.4. NMI to Pilot differences Δ_i and CRV values for spectral range 3000 – 2500 nm. All NIST and PTB lamps and rounds are taken into account (including Q130 and the second round of 915)

Wavelength, nm	NMI-Pilot differences Δ_i					**CRV**, Δ_{CRV}	$u(\Delta_{CRV})$
	BNM-INM	NIST	NRC	PTB	VNIIOFI		
300	-1.83%	1.50%		1.18%	0.00%	0.70%	0.49
325	-2.00%	1.45%		0.24%	0.00%	0.29%	0.44
350	-1.52%	1.47%		-0.08%	0.00%	0.24%	0.40
375	-1.47%	1.18%		-0.12%	0.00%	0.17%	0.38
400	-1.42%	1.20%	0.59%	0.04%	0.00%	0.18%	0.35
450	-1.06%	1.00%	1.02%	0.37%	0.00%	0.29%	0.33
500	-1.17%	0.92%	0.74%	0.56%	0.00%	0.24%	0.30
550	-0.85%	0.98%	0.86%	0.53%	0.00%	0.33%	0.28
600	-0.86%	0.95%	1.18%	0.50%	0.00%	0.34%	0.26
656.3	-1.12%	0.91%	1.01%	0.35%	0.00%	0.13%	0.22
700	-0.90%	0.88%	0.94%	0.31%	0.00%	0.17%	0.21
800	-1.00%	0.46%	1.02%	0.51%	0.00%	0.11%	0.20
900	-0.97%	0.47%		0.94%	0.00%	0.21%	0.19
1000	-0.58%	0.41%		1.41%	0.00%	0.41%	0.21
1050	-0.49%	0.53%		1.67%	0.00%	0.61%	0.23
1200	0.35%	0.68%		1.94%	0.00%	0.90%	0.24
1550	0.08%	1.00%		0.98%	0.00%	0.50%	0.23
1700	0.03%	0.81%		0.91%	0.00%	0.43%	0.24
2100	-0.51%	0.70%		1.38%	0.00%	0.43%	0.24
2300	-1.17%	0.84%		1.37%	0.00%	0.35%	0.26
2400	-1.22%	1.07%		1.10%	0.00%	0.27%	0.27
2500	-1.20%	1.07%		1.32%	0.00%	0.33%	0.28

8. DIFFERENCES FROM CRV

Difference from CRV (DfCRV) is an analogue of the unilateral degree of equivalence (DoE) for KC. The Difference from CRV of NMI *i* and its uncertainty are given by

$$D_i = \Delta_i - \Delta_{CRV} \quad (8.1)$$

$$U_i = k\sqrt{u^2(\Delta_i) + u^2(\Delta_{CRV}) - 2\left(\frac{u^2(\Delta_i)}{u^2_{adj}(\Delta_i)} \Big/ \sum_{i=0}^{N} u^{-2}_{adj}(\Delta_i)\right)}\ ;\ k = 2 \quad (8.2)$$

8.1. Differences from CRV and uncertainties for spectral range 220 – 400 nm.

The Differences from CRV and their uncertainties for the spectral range of 220 – 400 nm are presented in Table 8.1 and shown in graph form on Figures 8.1 – 8.4.

Table 8.1. Differences from CRV and uncertainties (k=2) for spectral range 220 – 400 nm

Wavelength, nm	NIST		PTB		VNIIOFI	
	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%

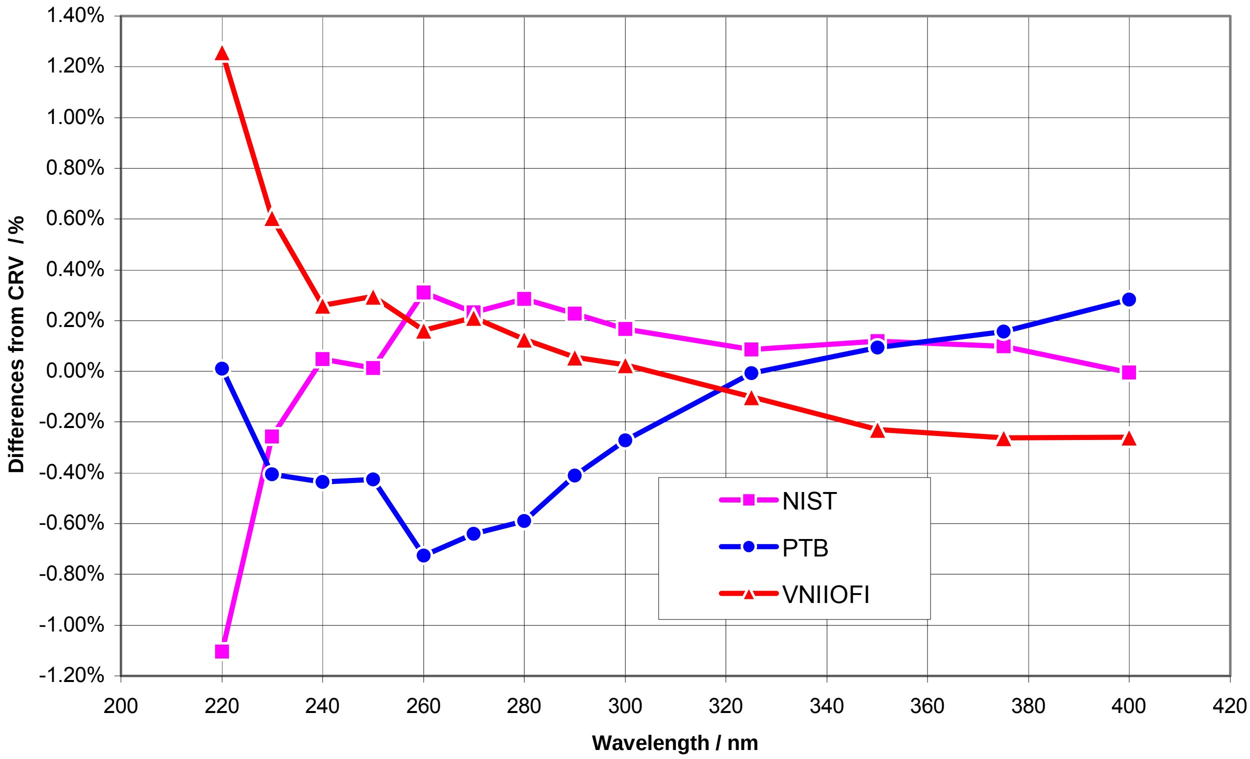

Figure 8.1. Differences from CRV for spectral range 220 – 400 nm.

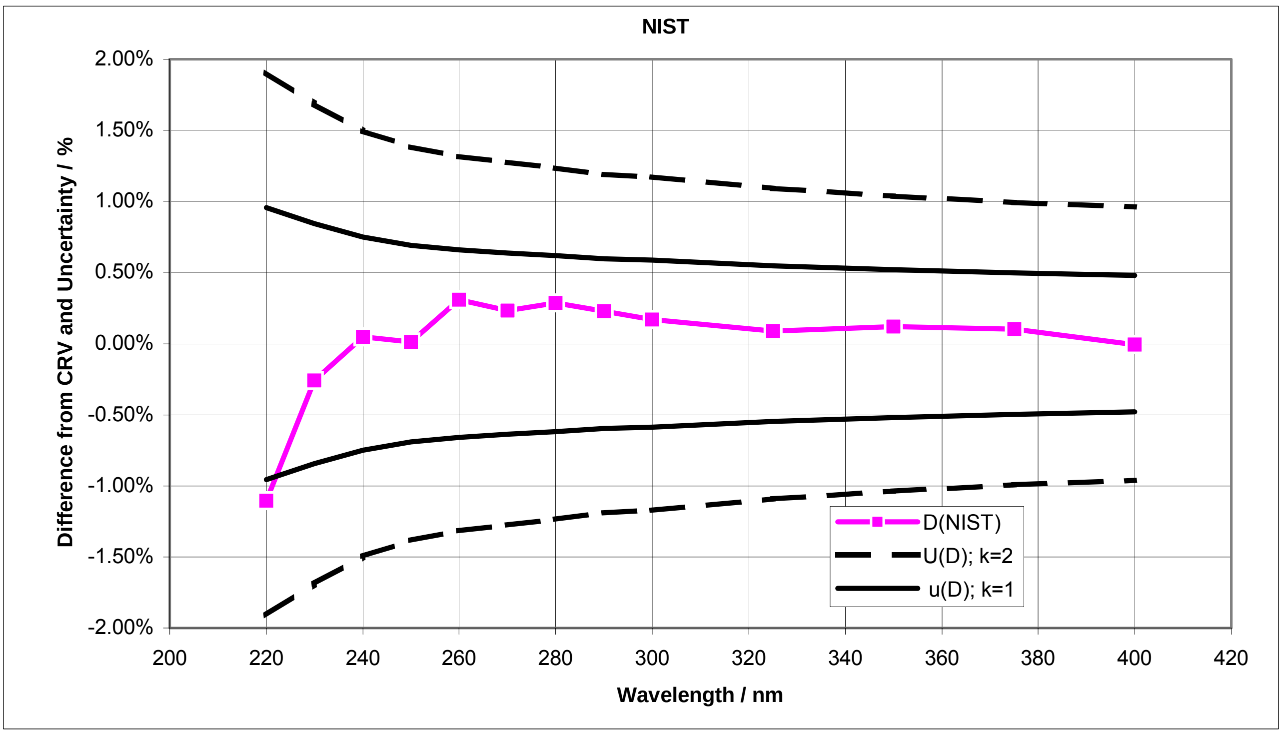

Figure 8.2. NIST Differences from CRV, D(NIST), and their uncertainties for spectral range 220 – 400 nm.

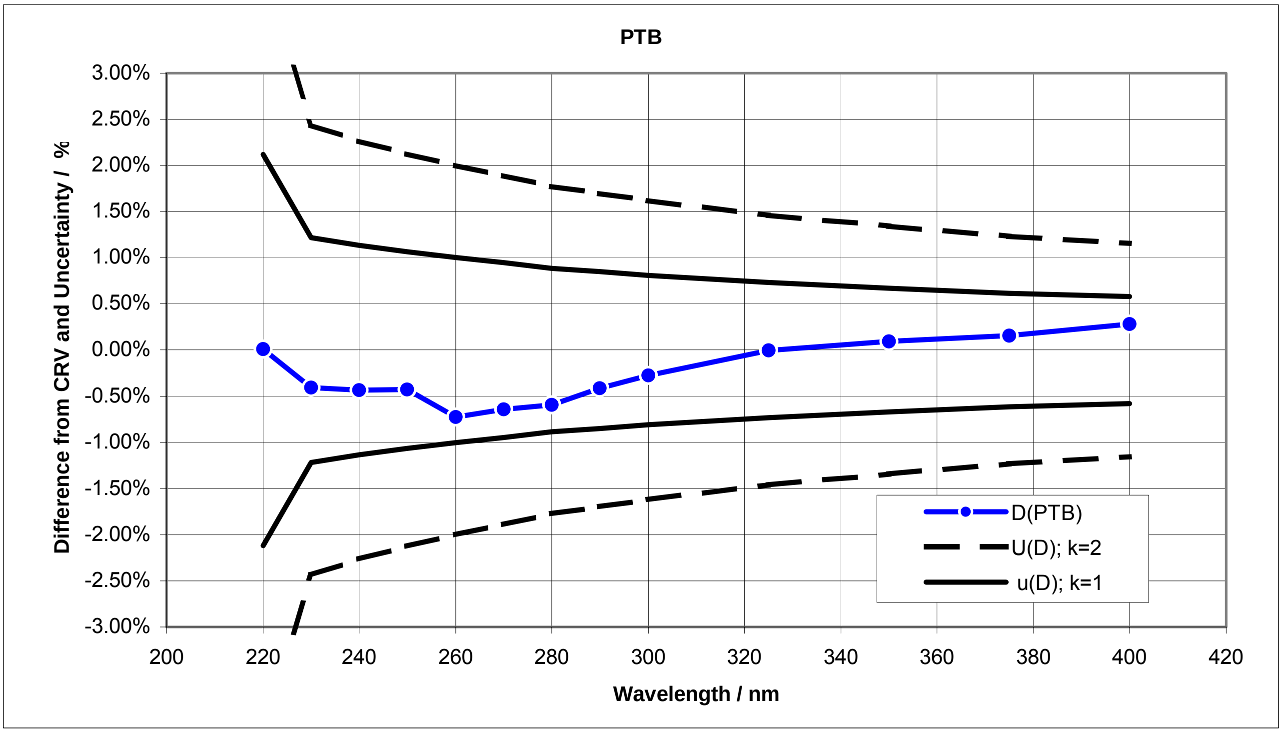

Figure 8.3. PTB Differences from CRV, D(PTB), and their uncertainties for spectral range 220 – 400 nm.

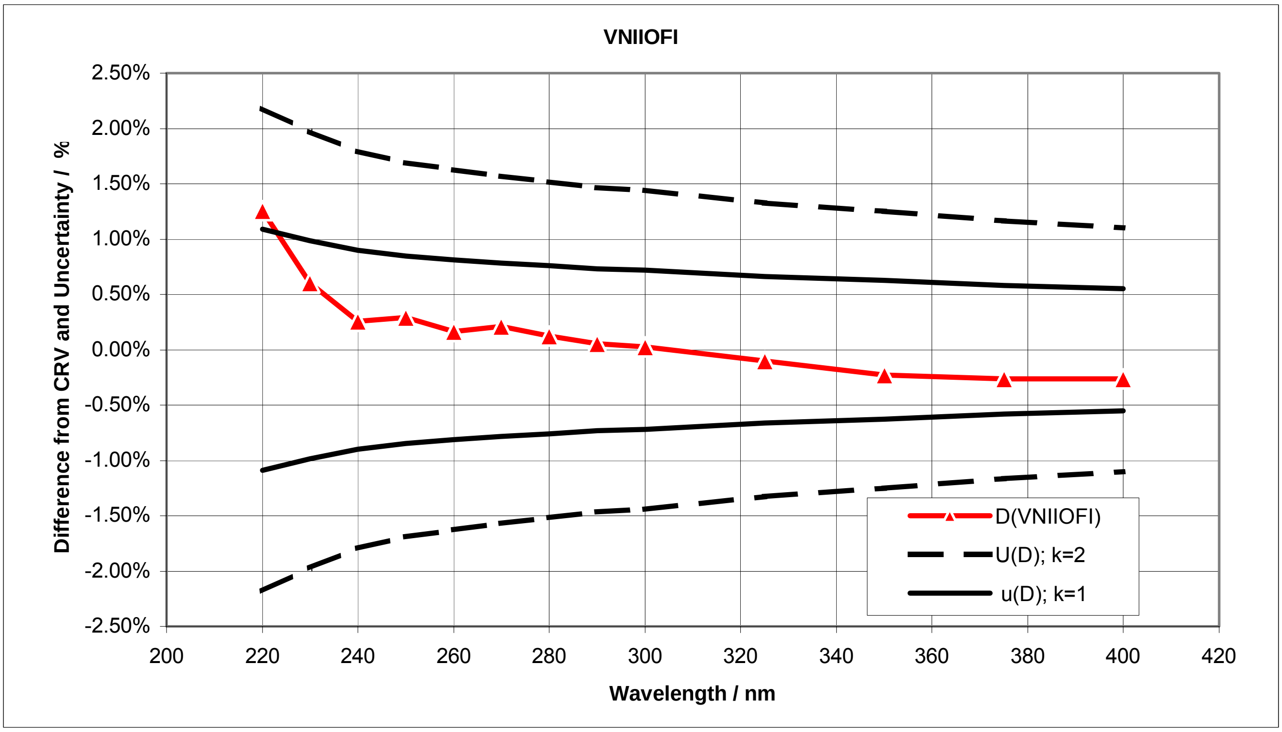

Figure 8.4. VNIIOFI Differences from CRV, D(VNIIOFI), and their uncertainties for spectral range 220 – 400 nm.

8.2. Differences from CRV and uncertainties for spectral range 300 – 2500 nm.

The Differences from CRV and their uncertainties for the spectral range of 300 – 2500 nm are presented in Table 8.2 and shown in graph form on Figures 8.5 – 8.10.

Table 8.2. Differences from CRV and uncertainties (k=2) for spectral range 300 – 2500 nm.

Wavelength, nm	**BNM-INM**		**NIST**		**NRC**		**PTB**		**VNIIOFI**	
	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%

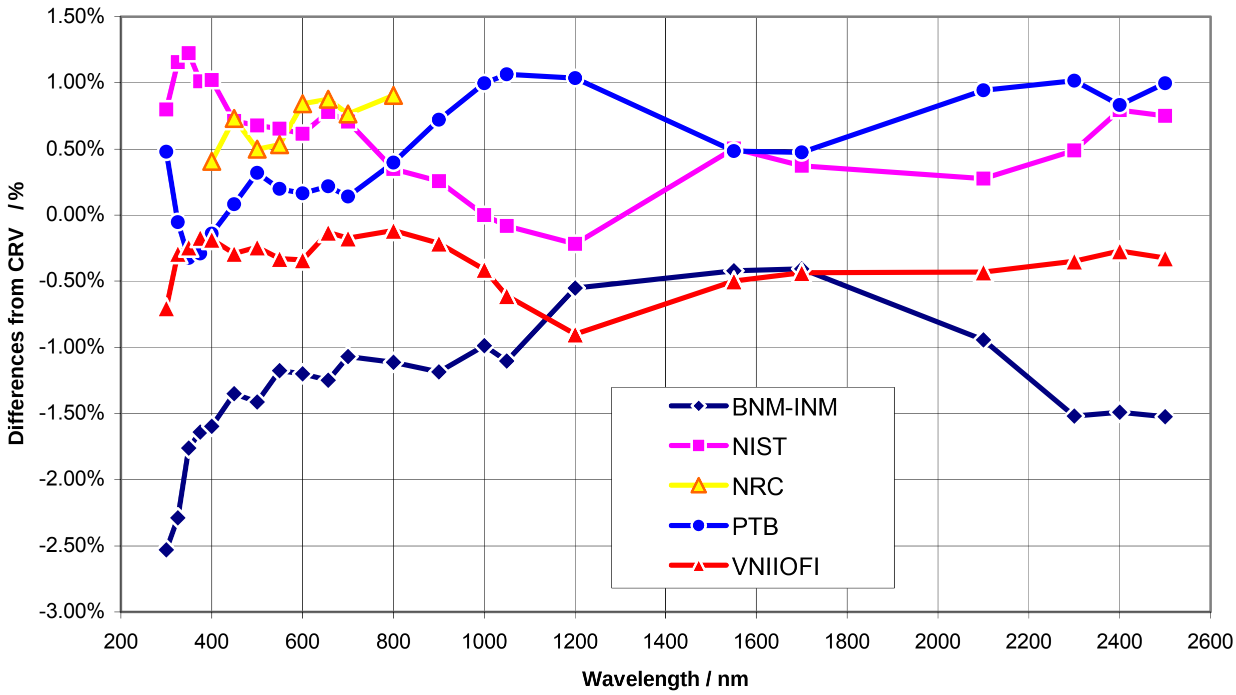

Figure 8.5. Differences from CRV for spectral range 300 – 2500 nm.

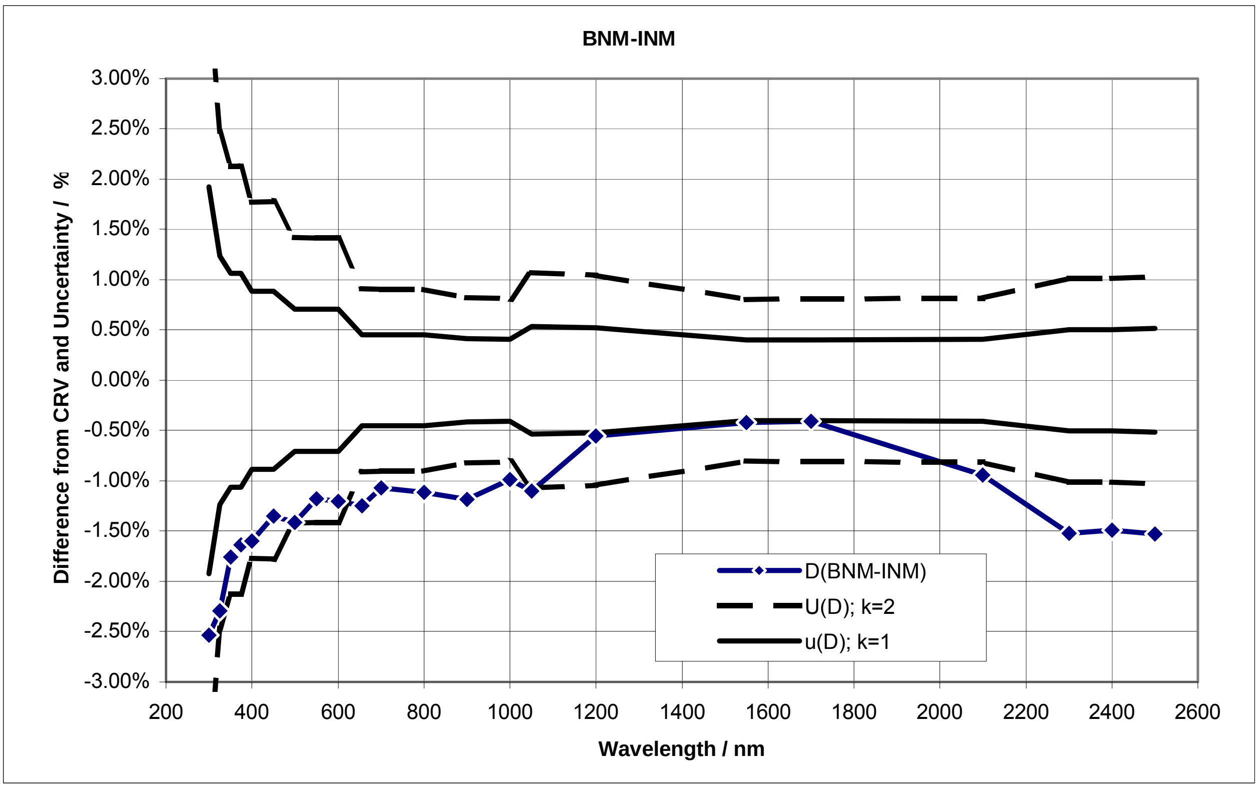

Figure 8.6. BNM-INM Differences from CRV, D(BNM-INM), and their uncertainties for spectral range 300 – 2500 nm.

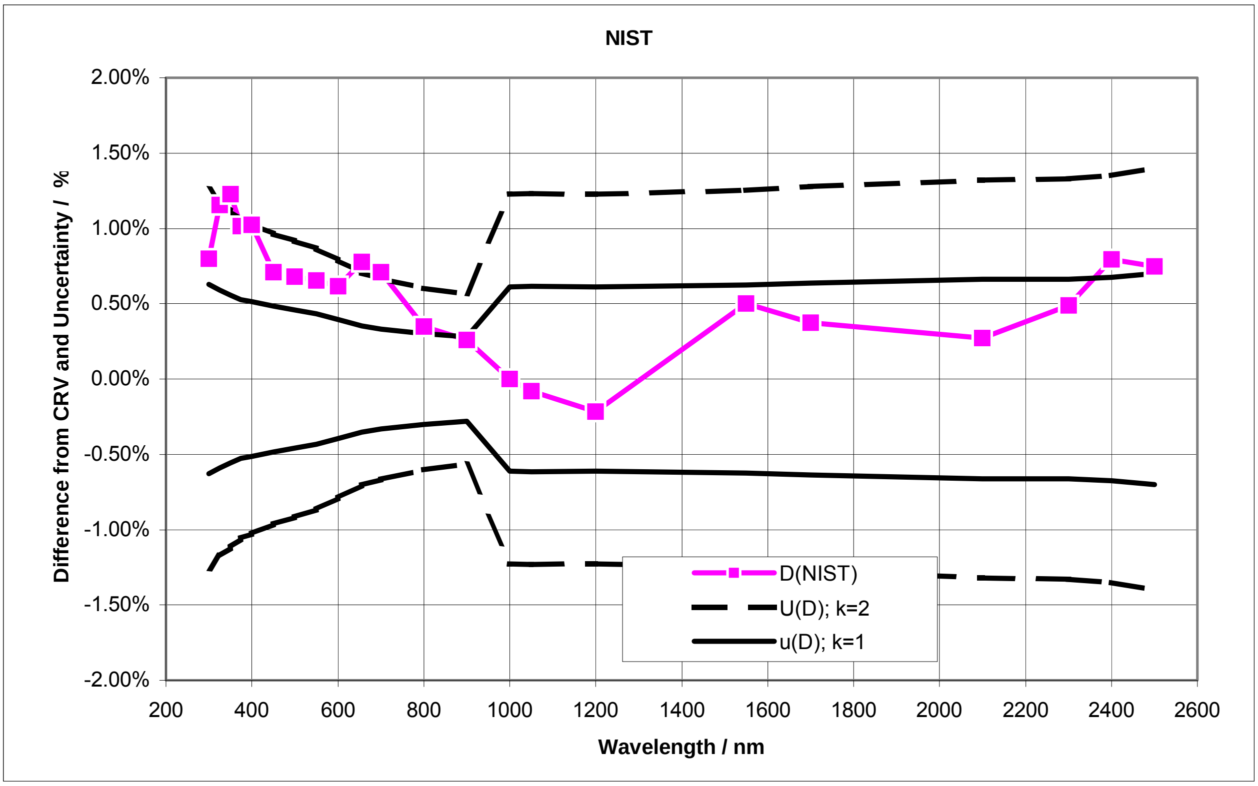

Figure 8.7. NIST Differences from CRV, D(NIST), and their uncertainties for spectral range 300 – 2500 nm.

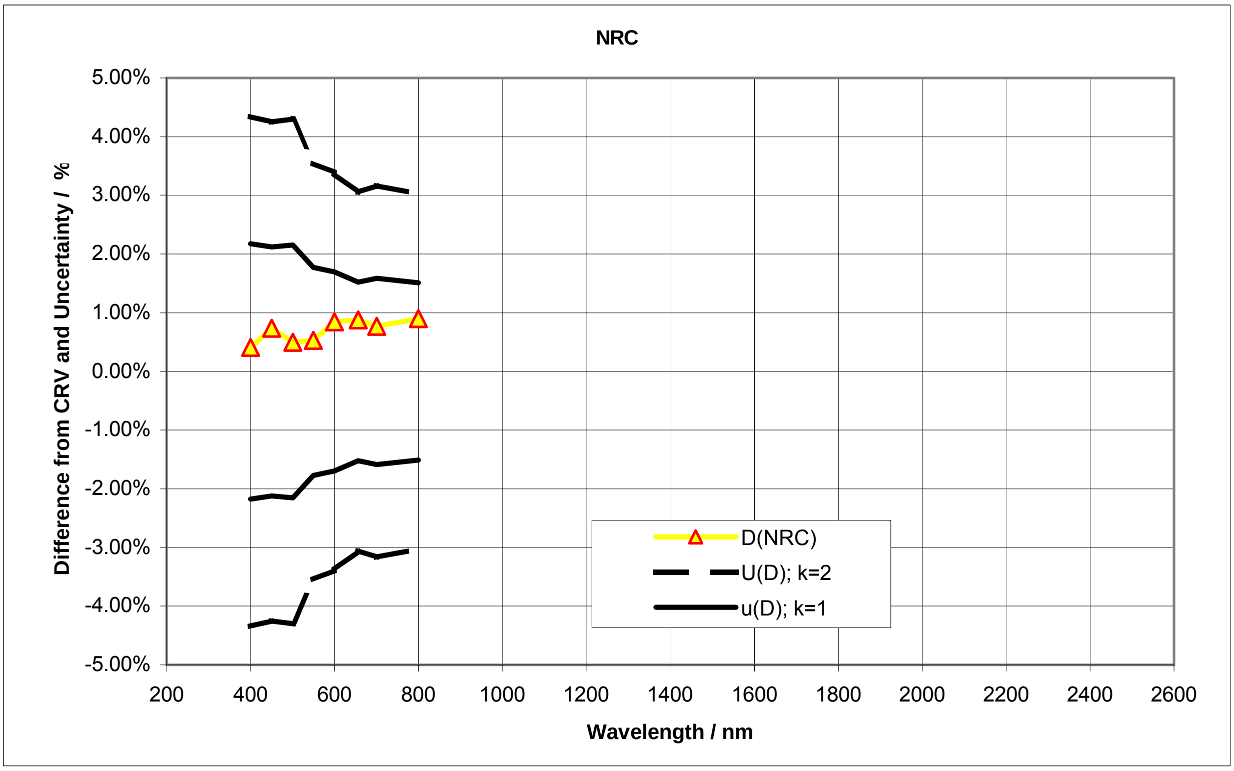

Figure 8.8. NRC Differences from CRV, D(NRC), and their uncertainties for spectral range 300 – 2500 nm.

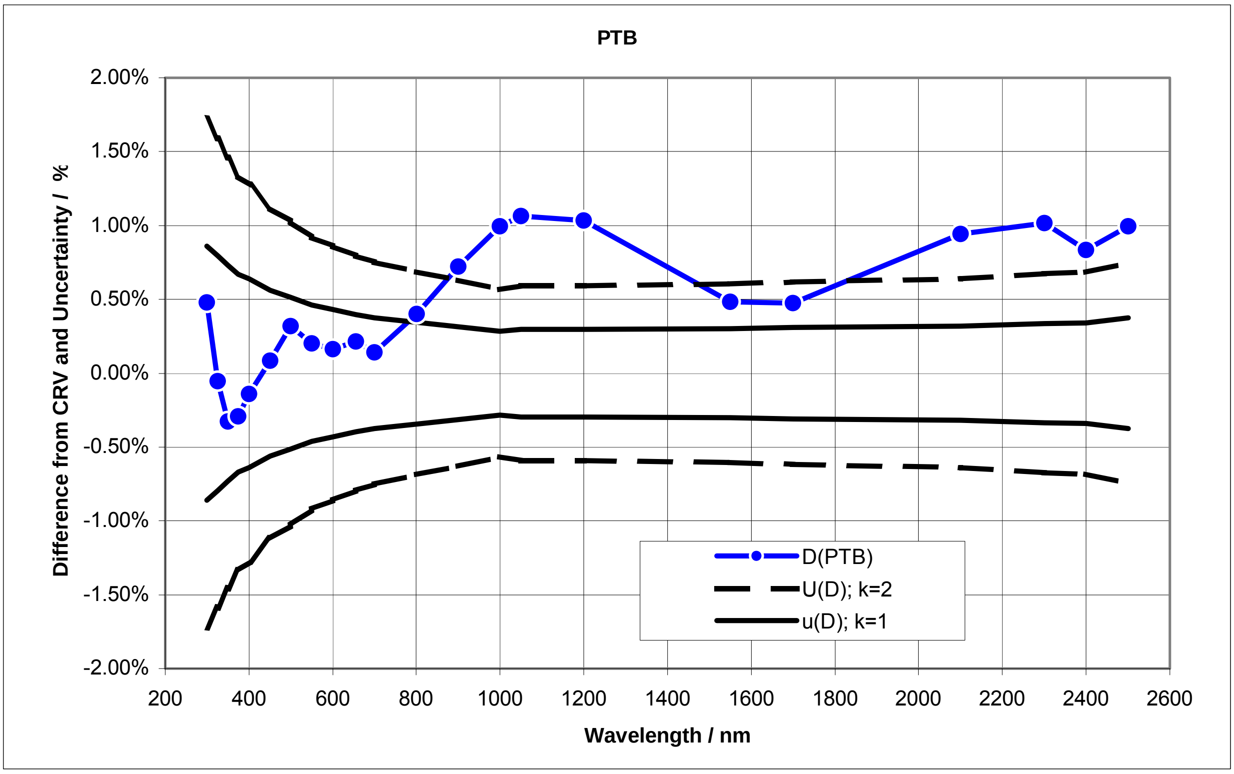

Figure 8.9. PTB Differences from CRV, D(PTB), and their uncertainties for spectral range 300 – 2500 nm.

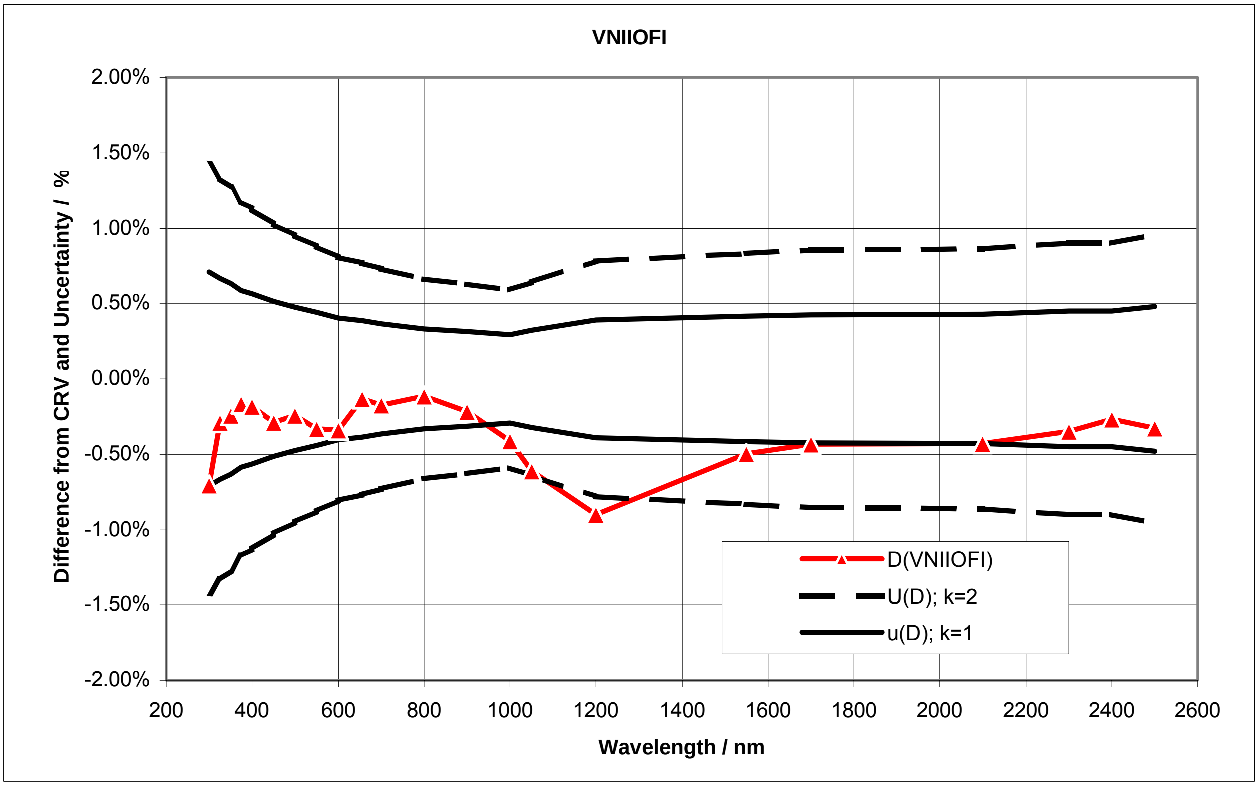

Figure 8.10. VNIIOFI Differences from CRV, D(VNIIOFI), and their uncertainties for spectral range 300 – 2500 nm.

Appendix A: Alternative evaluation of CRV and Differences from CRV

Here are presented alternative values of CRV and differences from CRV for the spectral range 300 to 2500 nm based strongly on the same methods as described in Parts 7 and 8, but on the alternative values of NIST-VNIIOFI and PTB-VNIIOFI differences, namely:

NIST-VNIIOFI difference is based on two lams (Q129 and Q133) only, i.e. the lamp Q130 is excluded from the analysis;

PTB-VNIIOFI difference the lamp 1101 (both rounds) and first round of lamp X1032 only, i.e. the second round of X1032 is eliminated from the analysis.

BNM/INM-VNIIOFI and NRC-VNIIOFI differences are not changed in compare with the main part of the report.

Values of the NMIs to pilot (VNIIOFI) differences Δ_i and CRV are presented in Table A.7.4.

The Differences from CRV and their uncertainties for the spectral range of 300 – 2500 nm are presented in Table A.8.2 and shown in graph form on Figures A.8.5 – A.8.10.

Table A. 7.4. NMI to Pilot differences Δ_i and CRV values for spectral range 3000 – 2500 nm. Lamp Q130 of NIST and the second round of lamp X1032 of PTB are not taken into account.

Wavelength, nm	NMI-Pilot differences Δ_i					**CRV**, Δ_{CRV}	$u(\Delta_{CRV})$
	BNM-INM	NIST	NRC	PTB	VNIIOFI		
300	-1.83%	0.71%		0.33%	0.00%	0.21%	0.49
325	-2.00%	0.63%		-0.29%	0.00%	-0.11%	0.44
350	-1.52%	0.69%		-0.45%	0.00%	-0.10%	0.40
375	-1.47%	0.53%		-0.41%	0.00%	-0.12%	0.38
400	-1.42%	0.50%	0.59%	-0.20%	0.00%	-0.09%	0.35
450	-1.06%	0.30%	1.02%	0.14%	0.00%	0.02%	0.33
500	-1.17%	0.27%	0.74%	0.32%	0.00%	-0.01%	0.30
550	-0.85%	0.37%	0.86%	0.29%	0.00%	0.09%	0.28
600	-0.86%	0.41%	1.18%	0.29%	0.00%	0.12%	0.26
656.3	-1.12%	0.40%	1.01%	0.17%	0.00%	-0.05%	0.22
700	-0.90%	0.45%	0.94%	0.17%	0.00%	0.02%	0.21
800	-1.00%	-0.01%	1.02%	0.36%	0.00%	-0.06%	0.20
900	-0.97%	0.02%		0.71%	0.00%	0.02%	0.19
1000	-0.58%	-0.04%		1.09%	0.00%	0.25%	0.21
1050	-0.49%	0.16%		1.26%	0.00%	0.41%	0.23
1200	0.35%	0.36%		1.44%	0.00%	0.67%	0.24
1550	0.08%	0.76%		0.69%	0.00%	0.36%	0.23
1700	0.03%	0.49%		0.69%	0.00%	0.32%	0.24
2100	-0.51%	0.24%		0.55%	0.00%	0.08%	0.24
2300	-1.17%	0.39%		0.53%	0.00%	-0.02%	0.26
2400	-1.22%	0.64%		0.43%	0.00%	-0.03%	0.27
2500	-1.20%	0.57%		0.52%	0.00%	-0.02%	0.28

Table A.8.2. Differences from CRV and uncertainties (k=2) for spectral range 300 – 2500 nm.

Wavelength,	BNM-INM		NIST		NRC		PTB		VNIIOFI	
nm	D	U(D)	D	U(D)	D	U(D)	D	U(D)	D	U(D)
300	-2.04%	3.85%	0.50%	1.26%			0.12%	1.72%	-0.21%	1.42%
325	-1.89%	2.47%	0.74%	1.18%			-0.19%	1.59%	0.11%	1.33%
350	-1.42%	2.13%	0.79%	1.11%			-0.36%	1.46%	0.10%	1.27%
375	-1.36%	2.13%	0.64%	1.06%			-0.30%	1.34%	0.12%	1.18%
400	-1.33%	1.77%	0.59%	1.03%	0.68%	4.34%	-0.11%	1.28%	0.09%	1.13%
450	-1.08%	1.77%	0.28%	0.96%	1.00%	4.25%	0.12%	1.12%	-0.02%	1.03%
500	-1.17%	1.42%	0.28%	0.92%	0.74%	4.31%	0.33%	1.03%	0.01%	0.95%
550	-0.94%	1.41%	0.28%	0.87%	0.77%	3.55%	0.20%	0.92%	-0.09%	0.88%
600	-0.99%	1.41%	0.29%	0.79%	1.06%	3.38%	0.17%	0.86%	-0.12%	0.81%
656.3	**-1.07%**	**0.91%**	0.45%	0.71%	1.06%	3.05%	0.22%	0.79%	0.05%	0.77%
700	-0.91%	0.91%	0.43%	0.67%	0.92%	3.17%	0.15%	0.75%	-0.02%	0.73%
800	**-0.94%**	**0.90%**	0.05%	0.60%	1.08%	3.03%	0.42%	0.69%	0.06%	0.66%
900	**-0.99%**	**0.82%**	0.00%	0.56%			**0.69%**	**0.63%**	-0.02%	0.63%
1000	**-0.83%**	**0.81%**	-0.29%	1.23%			**0.83%**	**0.57%**	-0.25%	0.59%
1050	-0.90%	1.07%	-0.25%	1.23%			**0.85%**	**0.59%**	-0.41%	0.64%
1200	-0.32%	1.04%	-0.31%	1.23%			**0.77%**	**0.59%**	-0.67%	0.78%
1550	-0.29%	0.80%	0.40%	1.25%			0.32%	0.60%	-0.36%	0.83%
1700	-0.29%	0.81%	0.17%	1.28%			0.38%	0.62%	-0.32%	0.85%
2100	-0.60%	0.82%	0.15%	1.32%			0.47%	0.64%	-0.08%	0.86%
2300	-1.15%	**1.01%**	0.40%	1.33%			0.55%	0.68%	0.02%	0.90%
2400	-1.19%	**1.01%**	0.68%	1.35%			0.46%	0.68%	0.03%	0.90%
2500	-1.18%	**1.03%**	0.60%	1.40%			0.55%	0.75%	0.02%	0.96%

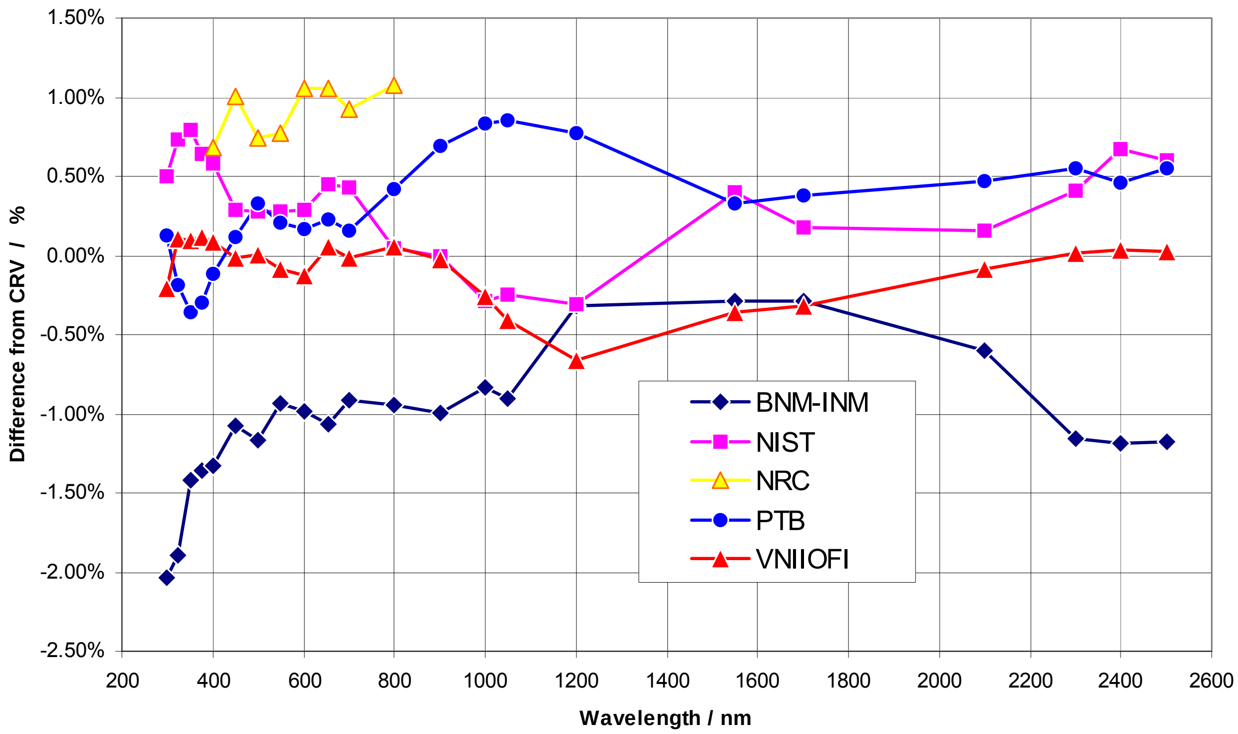

Figure A.8.5. Differences from CRV for spectral range 300 – 2500 nm.

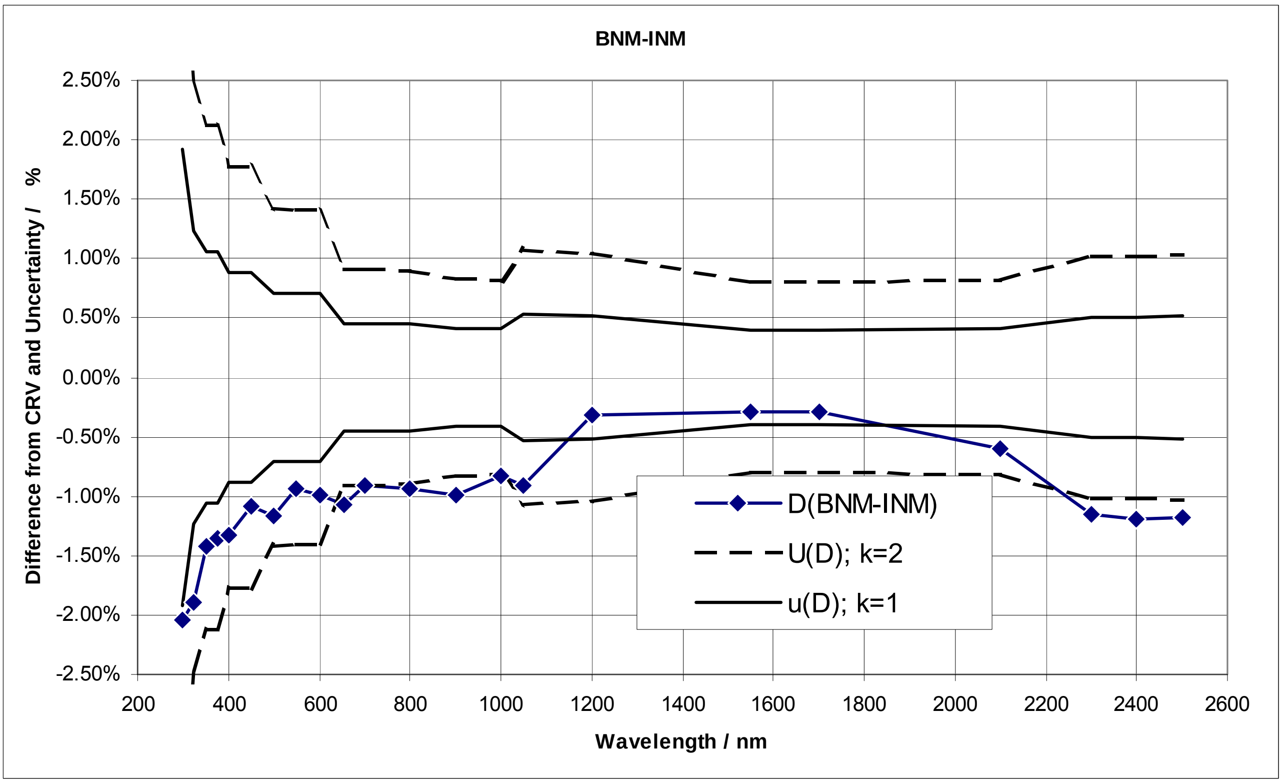

Figure A.8.6. BNM-INM Differences from CRV, D(BNM-INM), and their uncertainties for spectral range 300 – 2500 nm.

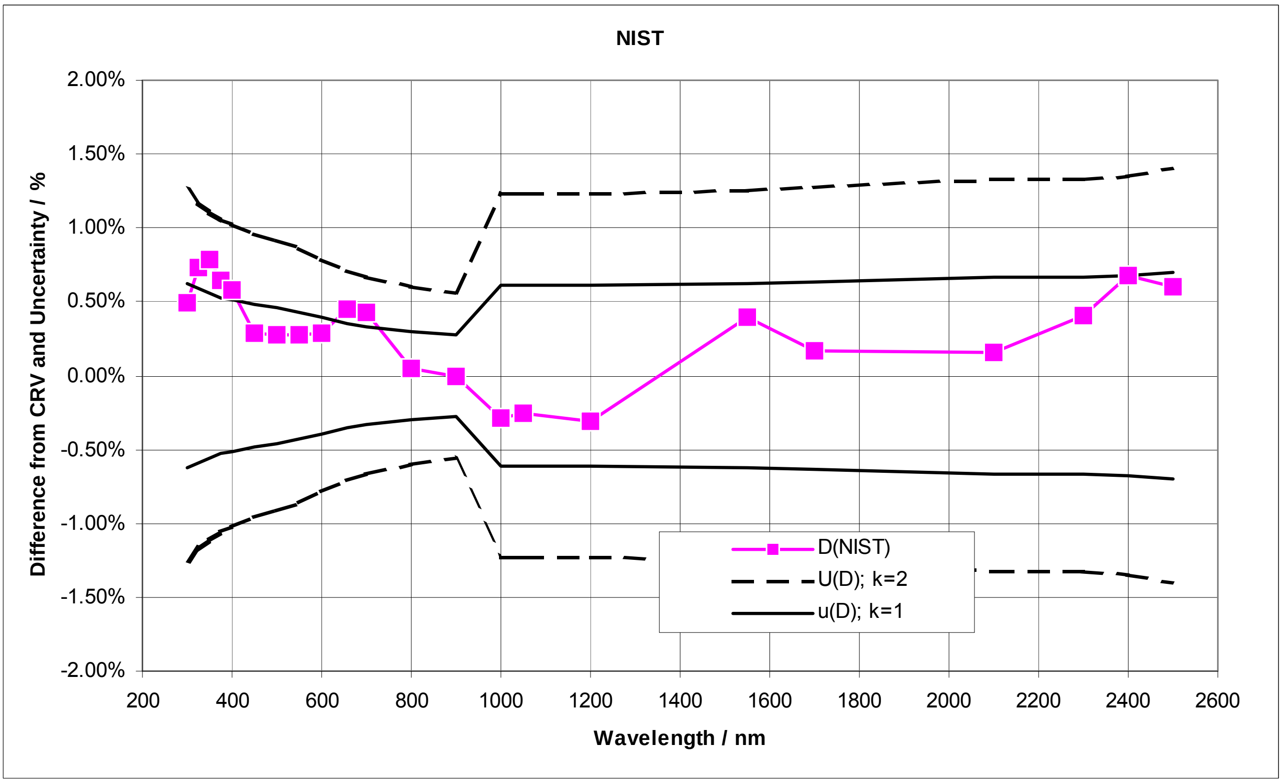

Figure A.8.7. NIST Differences from CRV, D(NIST), and their uncertainties for spectral range 300 – 2500 nm.

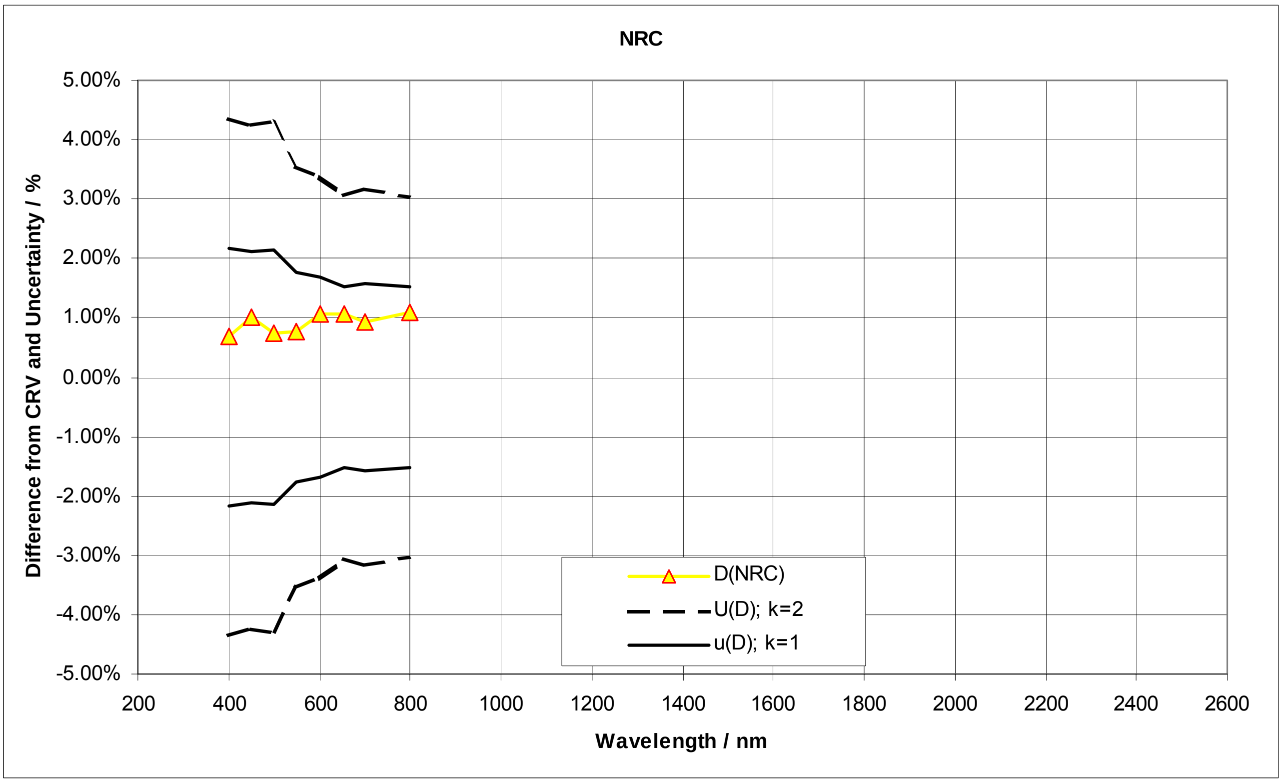

Figure A.8.8. NRC Differences from CRV, D(NRC), and their uncertainties for spectral range 300 – 2500 nm.

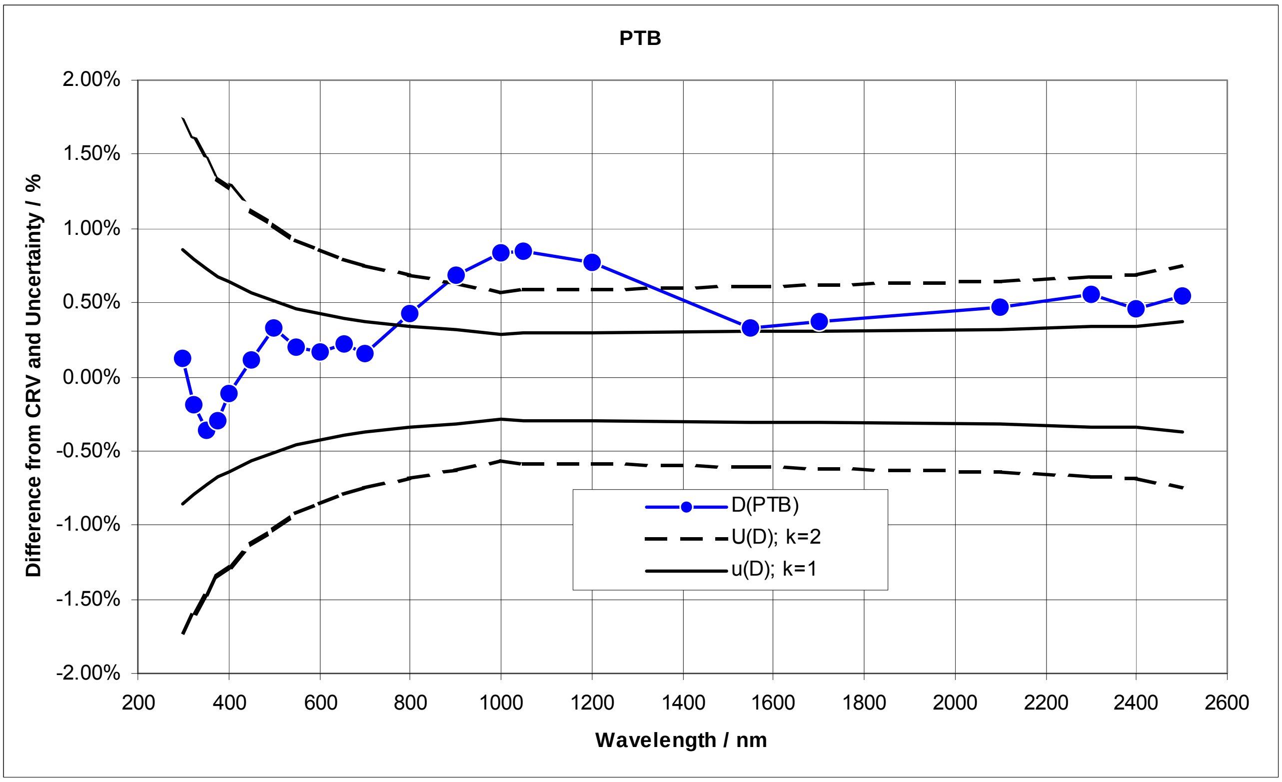

Figure A.8.9. PTB Differences from CRV, D(PTB), and their uncertainties for spectral range 300 – 2500 nm.

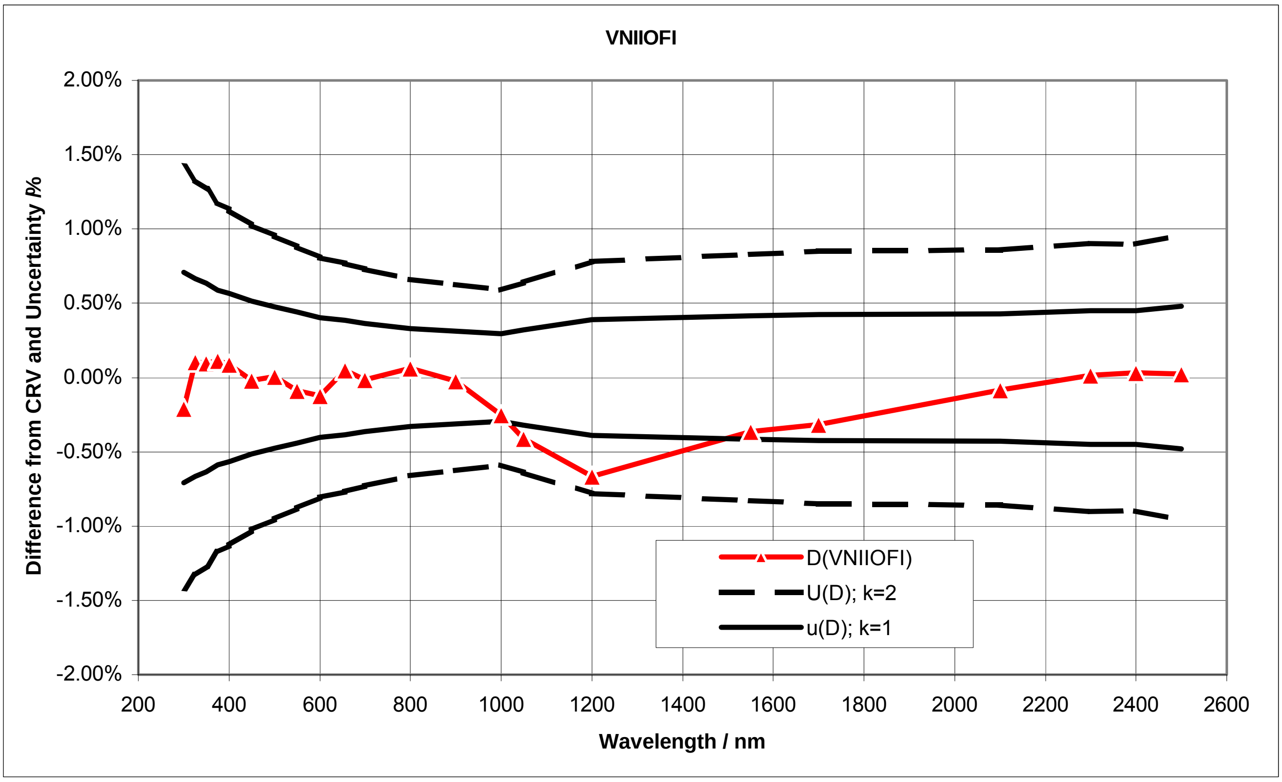

Figure A.8.10. VNIIOFI Differences from CRV, D(VNIIOFI), and their uncertainties for spectral range 300 – 2500 nm.

Appendix B: Original PTB protocol of checking stability of lamps in the period between October 1998 and February 1999.

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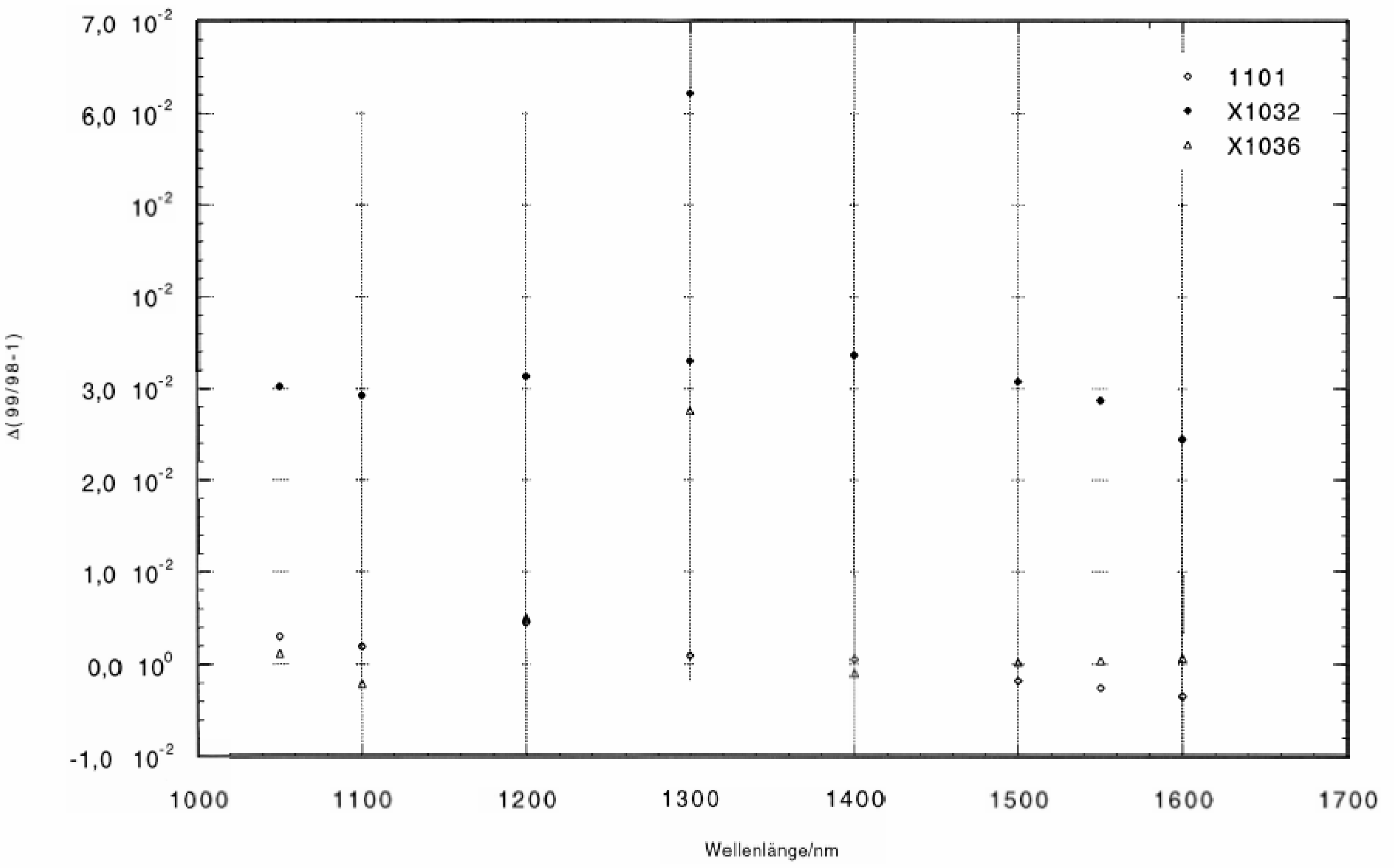
	Wellenl./nm	1101/10.98	1101/2.99	D(99/98-1)	X1032/10.98	X1032/2.99	D(99/98-1)	X1036/10.98	X1036/2.99	D(99/98-1)
0	1050.00	1.41245e+11	1.41666e+11	2.98274e-03	1.41820e+11	1.46103e+11	3.02037e-02	1.37790e+11	1.37952e+11	1.17598e-03
1	1100.00	1.39553e+11	1.39814e+11	1.87717e-03	1.41226e+11	1.45353e+11	2.92295e-02	1.36787e+11	1.36499e+11	-2.10892e-03
2	1200.00	1.32183e+11	1.32781e+11	4.51931e-03	1.35129e+11	1.39358e+11	3.12924e-02	1.29738e+11	1.30379e+11	4.94401e-03
3	1300.00	1.22399e+11	1.22509e+11	9.02066e-04	1.23720e+11	1.31408e+11	6.21436e-02	1.17152e+11	1.20377e+11	2.75328e-02
4	1300.00	1.22399e+11	1.22068e+11	-2.70432e-03	1.23720e+11	1.27803e+11	3.30009e-02	1.17152e+11	1.16744e+11	-3.48353e-03
5	1400.00	1.09765e+11	1.09820e+11	4.99439e-04	1.10985e+11	1.14709e+11	3.35615e-02	1.05533e+11	1.05430e+11	-9.75749e-04
6	1500.00	9.83591e+10	9.81827e+10	-1.79308e-03	9.97436e+10	1.02806e+11	3.07055e-02	9.44816e+10	9.45047e+10	2.44247e-04
7	1550.00	9.25403e+10	9.23039e+10	-2.55479e-03	9.38055e+10	9.64928e+10	2.86475e-02	8.89328e+10	8.89645e+10	3.57128e-04
8	1600.00	8.68577e+10	8.65551e+10	-3.48353e-03	8.81895e+10	9.03427e+10	2.44159e-02	8.34852e+10	8.35368e+10	6.17992e-04

Vergleich Messung 98 zu Messung 99
ohne Polarisationsfilter

9.2.1999

Vergleich der Messungen 10/98 und 2/99



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