APMP.PR.K1.a.1-2008

Bilateral Comparison between KRISS (Korea) and VNIIOFI (Russia)

Spectral Irradiance from 250 nm to 2500 nm

Final Report

10 August 2010

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Abstract

Korea Research Institute of Standards and Science (KRISS) and All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) conducted a bilateral comparison on the spectral irradiance over the spectral region from 250 nm to 2500 nm in 2008. The aim of this comparison was to assess the equivalence of the spectral irradiance scales between the two laboratories and to link KRISS spectral irradiance scale to the key comparison CCPR K1.a carried out in the years 2000-2003. The technical protocol was approved by CCPR WG-KC in April 2008. KRISS acted as the pilot to reduce the workload of VNIIOFI as the link laboratory. PTB acted as the neutral partner to ensure blindness of the comparison results. PTB collected the measurement results from and sent them back to both participants. KRISS prepared this report based on the measurement results distributed by PTB. The spectral irradiances measured by KRISS and VNIIOFI agreed within the standard uncertainties (k = 1) from 250 nm to 2500 nm. The unilateral DoE of KRISS was calculated using the unilateral DoE of VNIIOFI to link KRISS spectral irradiance scale to the key comparison CCPR K1.a. The uncertainties of the unilateral DoE of KRISS were determined using the uncertainties of KRISS and VNIIOFI measurements and the uncertainties of the unilateral DoE of VNIIOFI, and taking into account the correlation of VNIIOFI measurements between the CCPR key and this bilateral comparison.

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Contents

1. Introduction

The Korea Research Institute of Standards and Science (KRISS) and All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI) agreed in April 2007 to conduct a bilateral comparison on the spectral irradiance of tungsten halogen lamps over the spectral region from 250 nm to 2500 nm. The aim of this comparison is to assess the equivalence of the spectral irradiance scales between the two laboratories and to link KRISS spectral irradiance scale to the key comparison CCPR K1.a [1], carried out in the years 2000-2003. The bilateral comparison was carried out according to the technical protocol approved by CCPR WG-KC in April 2008.

2. Organization of the bilateral comparison

2.1. Participants

KRISS is the pilot and linked NMI, and VNIIOFI which participated in the key comparison CCPR K1.a is the linking NMI. PTB is the neutral partner to ensure the blindness of results.

2.2. Participants' details

Laboratory	Function	Person in Charge	Contact
Korea Research Institute of Standards and Science(KRISS), P.O. Box 102, 209 Gajeong-Ro, Yuseong-Gu, Daejeon, Korea	Pilot lab (Linked lab)	Dong-Joo Shin	Tel: +82-42-860-5209 Fax: +82-42-868-5022 Email: djshin@kriss.re.kr
All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI), Ozernaya 46, 119361 Moscow, Russia	Link lab	Boris B. Khlevnoy	Tel: +7 (495) 437-29-88 Fax: +7 (495) 437-29-92 Email: khlevnoy-m4@vniiofi.ru
Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany	Neutral partner	Peter Sperfeld	Tel.: (+49) 531 592-4144 Fax: (+49) 531 592-69 4144 Email: Peter.Sperfeld@ptb.de

2.3. Form of the comparison

The comparison was carried out through the calibration of three transfer standard lamps prepared by KRISS which are referred as artifacts in the following sections. These artifacts were 1000 W tungsten halogen lamps of FEL type labeled as BN-9101-440, BN-9101-441, BN-9101-442. The artifacts were initially calibrated by KRISS in May 2008 and then hand-carried to VNIIOFI in June 2008 for calibration. The artifacts calibrated at VNIIOFI, where they were measured in June 2008. The artifacts were hand-carried back to KRISS in June and calibrated again at KRISS in December 2008. KRISS and VNIIOFI sent their measurement results to PTB in February 2009. PTB collected both measurement results and sent them to both participants. KRISS, as the pilot laboratory, made Draft A in May 2009, based on the measurement results distributed by PTB.

3. Description of the artifacts

The artifacts were three 1000 W tungsten halogen lamps of FEL type. The lamps were exactly the same type, made by the same manufacturer, and prepared as the lamps used for the CCPR K1.a comparison. Each lamp was operated at the same DC current, 8.100 A. Each lamp was firmly mounted on a holder supported by a post on a kinematical base. The lamp and its alignment jig are shown in Figure 3-1.

Figure 3-1. Transfer standard lamp and alignment jig.

The alignment jig was positioned in front of each lamp and then whole unit (the mount with the lamp and jig) was aligned in such a way that the center of the jig target was at the optical axis, which went through the center of the entrance aperture of an integrating sphere of a spectroradiometer, and at the same time the jig and aperture planes were perpendicular to the axis. The distance from the surface of the alignment jig to the reference plane of the entrance aperture of the integrating sphere was 50.0 cm as shown in Figure 3-2.

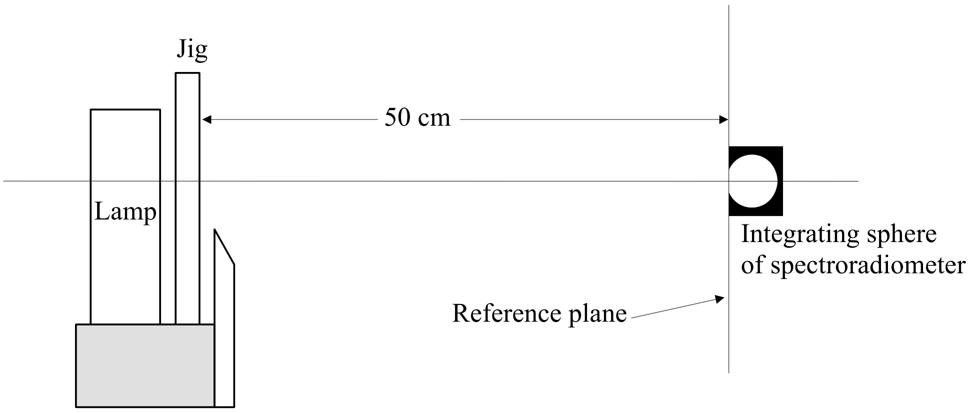


Figure 3-2. Alignment of the lamp and integrating sphere aperture.

4. Measurements at KRISS

4.1. Spectral irradiance scale realization

The spectral irradiance scale of KRISS was realized using a high-temperature blackbody (BB3500MP) made by VNIIOFI. The blackbody has a pyrolytic graphite radiator with a depth of 250 mm and a diameter of 57 mm, and has an opening diameter of 40 mm. The effective blackbody emissivity estimated by VNIIOFI was approximately 0.999. The blackbody was operated at temperatures between 2980 K and 3010 K for this bilateral comparison. The temperature of the blackbody was measured using a radiation thermometer (LP3) calibrated by comparing the KRISS radiance temperature scale [2] based on ITS-90 [3]. The radiance temperature scale realized by the same technique as used in CCT-K5. The blackbody temperature measurement uncertainty in this comparison was estimated as 0.7 K (k = 1) including the KRISS radiance temperature scale uncertainty of 0.51 K. A water-cooled precision aperture with a diameter of (7.9802 ± 0.0036) mm was placed in front of the blackbody and defined the source area of the blackbody. The diameter of the precision aperture was measured using the calibrated vision system at the length standard laboratory of KRSS. The distance from this aperture to the entrance aperture of the integrating sphere was about 427 mm and measured precisely with a micrometer. The spectral irradiance at the entrance aperture of the integrating sphere was calculated using the Planck's radiation law with the measured blackbody temperature and taking into account the geometric parameters of the apertures and distance.

4.2. Description of measurement facility

The KRISS spectral irradiance measurement facility is shown in Figure 4-1. The spectroradiometer consists of an integrating sphere, a mirror as the entrance optics, a monochromator(Mcpherson Model 2061) with a prism predisperser, and detectors to cover the spectral range from 250 nm to 2500 nm. The focal length of the monochromator is 1 m and its numerical aperture is f/8.6. The inside diameter of the integrating sphere coated with PTFE was 26 mm and its entrance and exit aperture diameters were 11 mm with an area of approximately 1 cm^2. Three gratings with 600 grooves/mm blazed at 300 nm, 1000 nm, and 1800 nm were used for the wavelength range from 250 nm to 800 nm, from 800 nm to 1700 nm, and from 1700 nm to 2500 nm, respectively. The bandwidth of the spectroradiometer was set as 4.8 nm over the whole wavelength range from 250 nm to 2500 nm.

Four detectors were used: a photomultiplier tube for the spectral range from 250 nm to 800 nm, Si-photodiode from 800 nm to 1100 nm, InGaAs detector from 1100 nm to 1700 nm, and extended InGaAs detector from 1700 nm to 2500 nm. Gratings and detectors were exchanged manually according to wavelength ranges.

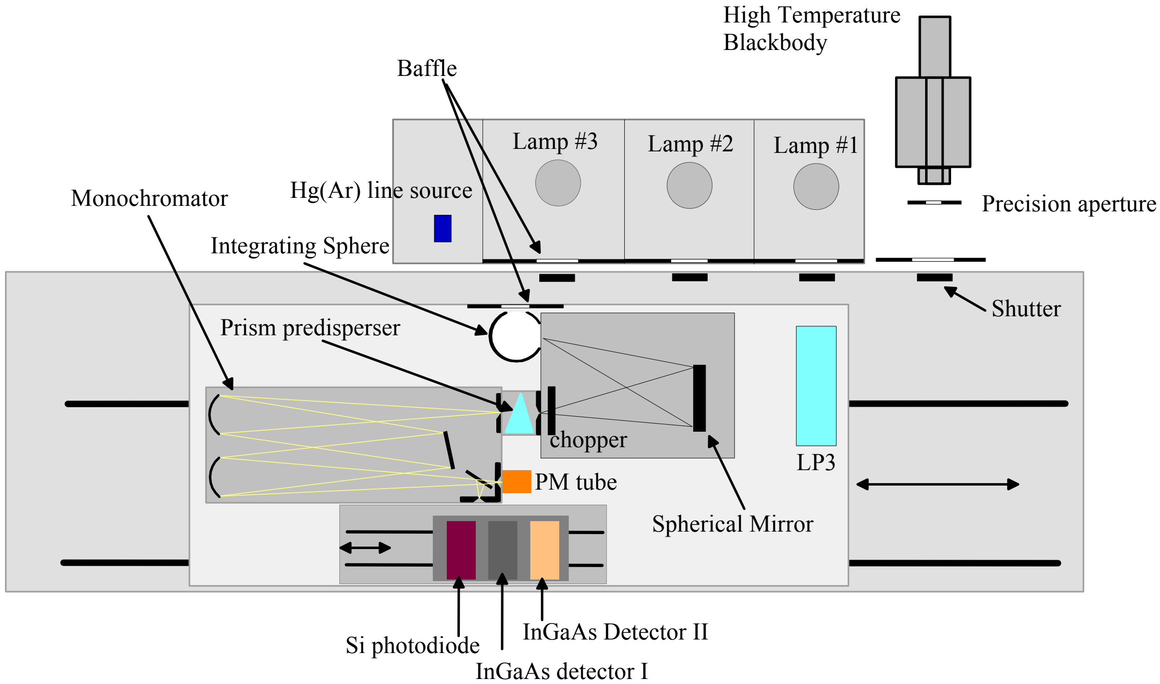


Figure 4-1. Schematic diagram of the KRISS spectral irradiance measurement facility.

4.3. Laboratory conditions

Throughout the calibration the laboratory temperature was controlled to be 23±1 °C.

4.4. Laboratory standards

The artifacts were measured by direct comparison with the blackbody, the temperature of which was determined using LP3 radiation thermometer calibrated with the KRISS temperature scale based on the ITS- 90.

4.5. Measurement procedure

The distance from the water cooled precision aperture placed in front of the blackbody to the entrance aperture of the integrating sphere was measured before the measurement of artifacts. One lamp at a time was aligned as shown in Figure 3-2. The alignment of a lamp was accomplished for the cross hair on the alignment jig to be centered vertically and horizontally onto the optical axis through the center of the entrance aperture of the integrating sphere at a distance of 50.0 cm.

Each lamp was turned on about 30 minutes before the beginning of measurement. The electric current of each lamp was set to be 8.100 A. The wavelength of the spectroradiometer was checked using a low pressure Hg line source every time when the spectroradiometer was turned on. The blackbody temperatures were measured periodically with an interval of about 30 minutes to 1 hour.

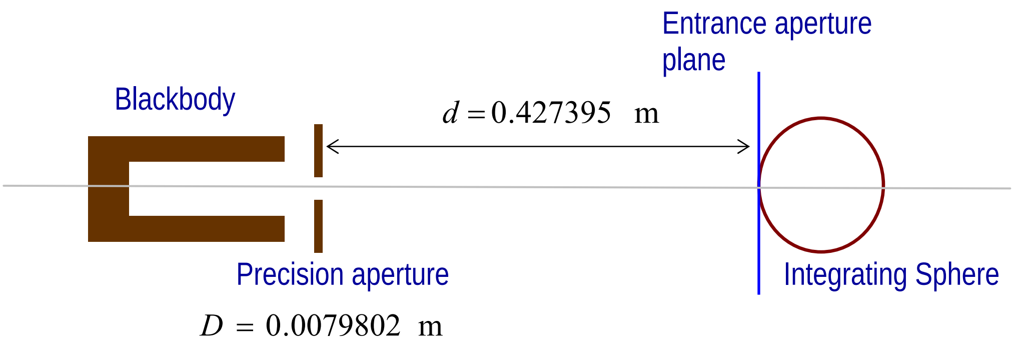
The measurement procedure in each cycle was as follows:

1) wavelength set
2) stage moved to the blackbody position
3) shutter open → blackbody signal read → shutter closed → dark signal read
4) stage moved to the lamp position
5) shutter open → lamp signal read → shutter closed → dark signal read
6) repeat once more from 5) to 2) in the reverse order for the wavelength set
7) all data saved

The spectral irradiance of the lamp at a given wavelength was calculated using the mean ratio of the lamp to the blackbody signal and the spectral irradiance of the blackbody at the entrance aperture of the integrating sphere.

4.6. Analysis of measurement results

The geometry of the blackbody measurement in this comparison is shown in Figure 4-2.



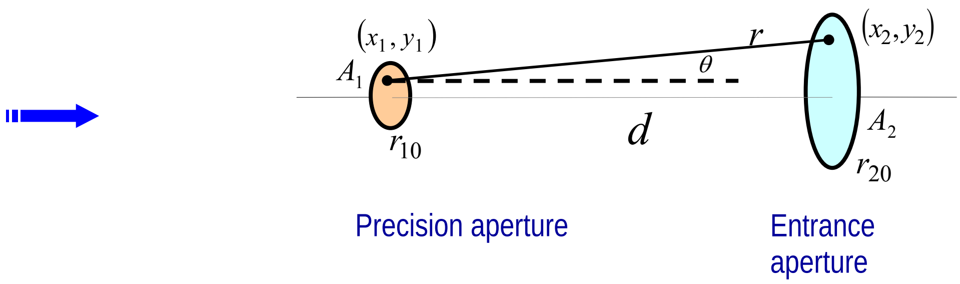


Figure 4-2. Geometry of spectral irradiance measurement of the blackbody.

The spectral irradiance of the blackbody at the entrance aperture of the integrating sphere can be written as Eq (4-1) for coaxial symmetrical circular apertures.

$$E_{BB}(\lambda,T)=\frac{\int_{A_1}\int_{\Omega}L(\lambda,T,\Omega,A_1)\cdot d\Omega\cdot(\cos\theta\cdot dA_1)}{A_2} \qquad (4\text{-}1)$$

$$\cong\overline{L}(\lambda,T)\cdot\frac{\pi\cdot r_{10}^2}{d^2}$$

where $\overline{L}(\lambda,T)$ is the spectral radiance of the blackbody given by the Planck's law as Eq (4-2).

$$\overline{L}(\lambda,T)=\frac{c_1}{\pi\cdot n^2\cdot\lambda^5}\cdot\frac{1}{\left(\exp\left(\frac{c_2}{n\cdot\lambda\cdot T}\right)-1\right)}\qquad (\mathrm{W/(m^3\cdot sr)})\tag{4-2}$$

where
c_1 = 3.741 771 18(19) x 10^{-16} (W·m^2)
c_2 = 1.438 7752 (25) x 10^{-2} (m·K)
n = 1.000285 (air refractive index).

The spectral irradiance of the lamp, E_L was given as Eq (4-3).

$$E_{\mathrm{L}}(\lambda)=\frac{S_{\mathrm{L}}(\lambda)}{S_{\mathrm{BB}}(\lambda)}\cdot E_{\mathrm{BB}}(\lambda,T)\tag{4-3}$$

where $S_L(\lambda)$ and $S_{BB}(\lambda)$ are the spectroradiometer output signals subtracted dark readings for the lamp and blackbody, respectively.

4.7. Uncertainty determination

4.7.1. Primary scale uncertainties

The uncertainty budget of KRISS spectral irradiance scale realization is given in Table 4-1.

4.7.2. Calibration uncertainties

Uncertainties associated with the spectral irradiance of a transfer lamp due to parameters such as the electric current of the lamp and alignment parameters were determined experimentally using Eq (4-4). [4]

$$\left.u\left(f\left(x_1,x_2,\cdots,x_j,\cdots\right)\right)\right|_{x_i=x_0}=\left.\frac{\partial f\left(x_1,x_2,\cdots,x_j,\cdots\right)}{\partial x_j}\cdot u\left(x_j\right)\right|_{x_j=x_0}$$
$$=\frac{1}{2}\left|\left[f\left(x_1,x_2,\cdots,x_j+u\left(x_j\right),\cdots\right)-f\left(x_1,x_2,\cdots,x_j-u\left(x_j\right),\cdots\right)\right]\right| \tag{4-4}$$

Table 4-2 shows the KRISS uncertainty budget for spectral irradiance of the lamps used in this comparison. Repeatability was calculated from the standard deviation of measurements in one cycle. The arithmetic mean value of repeatabilities of three transfer lamps is shown in the table.

Table 4-1. Uncertainty budget of KRISS spectral irradiance scale realization

Wavelength (nm)	BB temperature uncertainty (0.71 K)	BB spectral emissivity (0.0006)	BB spatial uniformity (0.3 K)	BB temperature stability (0.4 K)	Precision aperture diameter (0.0000036 m)	Distance (0.0001 m)	Combined standard uncertainty (k = 1)
250	0.46%	0.06%	0.19%	0.26%	0.09%	0.05%	**0.57%**
260	0.44%	0.06%	0.19%	0.25%	0.09%	0.05%	**0.55%**
270	0.42%	0.06%	0.18%	0.24%	0.09%	0.05%	**0.53%**
280	0.41%	0.06%	0.17%	0.23%	0.09%	0.05%	**0.51%**
290	0.40%	0.06%	0.17%	0.22%	0.09%	0.05%	**0.49%**
300	0.38%	0.06%	0.16%	0.22%	0.09%	0.05%	**0.48%**
310	0.37%	0.06%	0.16%	0.21%	0.09%	0.05%	**0.46%**
320	0.36%	0.06%	0.15%	0.20%	0.09%	0.05%	**0.45%**
330	0.35%	0.06%	0.15%	0.20%	0.09%	0.05%	**0.44%**
340	0.34%	0.06%	0.14%	0.19%	0.09%	0.05%	**0.43%**
350	0.33%	0.06%	0.14%	0.18%	0.09%	0.05%	**0.41%**
360	0.32%	0.06%	0.13%	0.18%	0.09%	0.05%	**0.40%**
380	0.30%	0.06%	0.13%	0.17%	0.09%	0.05%	**0.38%**
400	0.29%	0.06%	0.12%	0.16%	0.09%	0.05%	**0.37%**
450	0.25%	0.06%	0.11%	0.14%	0.09%	0.05%	**0.33%**
500	0.23%	0.06%	0.10%	0.13%	0.09%	0.05%	**0.30%**
550	0.21%	0.06%	0.09%	0.12%	0.09%	0.05%	**0.28%**
600	0.19%	0.06%	0.08%	0.11%	0.09%	0.05%	**0.26%**
650	0.18%	0.06%	0.07%	0.10%	0.09%	0.05%	**0.24%**
700	0.16%	0.06%	0.07%	0.09%	0.09%	0.05%	**0.23%**
800	0.14%	0.06%	0.06%	0.08%	0.09%	0.05%	**0.21%**
900	0.13%	0.06%	0.05%	0.07%	0.09%	0.05%	**0.19%**
950	0.12%	0.06%	0.05%	0.07%	0.09%	0.05%	**0.18%**
1000	0.12%	0.06%	0.05%	0.07%	0.09%	0.05%	**0.18%**
1100	0.11%	0.06%	0.04%	0.06%	0.09%	0.05%	**0.17%**
1200	0.10%	0.06%	0.04%	0.05%	0.09%	0.05%	**0.16%**
1300	0.09%	0.06%	0.04%	0.05%	0.09%	0.05%	**0.15%**
1500	0.08%	0.06%	0.03%	0.04%	0.09%	0.05%	**0.14%**
1600	0.08%	0.06%	0.03%	0.04%	0.09%	0.05%	**0.14%**
1700	0.07%	0.06%	0.03%	0.04%	0.09%	0.05%	**0.14%**
2000	0.06%	0.06%	0.03%	0.04%	0.09%	0.05%	**0.13%**
2100	0.06%	0.06%	0.03%	0.03%	0.09%	0.05%	**0.13%**
2300	0.06%	0.06%	0.02%	0.03%	0.09%	0.05%	**0.13%**
2400	0.06%	0.06%	0.02%	0.03%	0.09%	0.05%	**0.13%**
2500	0.05%	0.06%	0.02%	0.03%	0.09%	0.05%	**0.13%**

Table 4-2. KRISS uncertainty budget for spectral irradiance of the lamps

Wavelength (nm)	Scale	Wavelength (0.03 nm)	Lamp Current (0.0014 A)	Alignment	Spectroradiometer stability	Repeatability (Mean value) (Type A)	Combined standard uncertainty (k = 1)
250	0.57%	0.17%	0.22%	0.09%	0.52%	0.07%	**0.83%**
260	0.54%	0.15%	0.18%	0.09%	0.52%	0.04%	**0.80%**
270	0.53%	0.14%	0.18%	0.09%	0.42%	0.06%	**0.72%**
280	0.51%	0.13%	0.18%	0.09%	0.41%	0.12%	**0.70%**
290	0.49%	0.12%	0.19%	0.09%	0.37%	0.07%	**0.66%**
300	0.47%	0.11%	0.17%	0.09%	0.36%	0.05%	**0.64%**
310	0.46%	0.10%	0.17%	0.09%	0.40%	0.05%	**0.65%**
320	0.45%	0.09%	0.16%	0.09%	0.37%	0.05%	**0.62%**
330	0.43%	0.09%	0.14%	0.09%	0.31%	0.04%	**0.57%**
340	0.42%	0.08%	0.14%	0.09%	0.30%	0.04%	**0.55%**
350	0.41%	0.07%	0.13%	0.09%	0.21%	0.03%	**0.49%**
360	0.40%	0.07%	0.13%	0.09%	0.25%	0.02%	**0.51%**
380	0.38%	0.06%	0.12%	0.09%	0.21%	0.02%	**0.46%**
400	0.36%	0.05%	0.11%	0.09%	0.20%	0.02%	**0.44%**
450	0.33%	0.04%	0.10%	0.09%	0.22%	0.01%	**0.42%**
500	0.30%	0.03%	0.09%	0.09%	0.17%	0.01%	**0.36%**
550	0.27%	0.02%	0.07%	0.09%	0.15%	0.01%	**0.34%**
600	0.26%	0.01%	0.07%	0.09%	0.15%	0.01%	**0.32%**
650	0.24%	0.01%	0.07%	0.09%	0.18%	0.01%	**0.32%**
700	0.23%	0.01%	0.07%	0.09%	0.15%	0.02%	**0.29%**
800	0.20%	0.01%	0.06%	0.09%	0.26%	0.02%	**0.35%**
900	0.19%	0.01%	0.06%	0.09%	0.29%	0.01%	**0.36%**
950	0.18%	0.01%	0.06%	0.09%	0.30%	0.01%	**0.37%**
1000	0.18%	0.01%	0.05%	0.09%	0.29%	0.01%	**0.36%**
1100	0.17%	0.01%	0.05%	0.09%	0.40%	0.02%	**0.45%**
1200	0.16%	0.01%	0.05%	0.09%	0.39%	0.01%	**0.43%**
1300	0.15%	0.01%	0.03%	0.09%	0.38%	0.01%	**0.42%**
1500	0.14%	0.01%	0.03%	0.09%	0.38%	0.01%	**0.42%**
1600	0.14%	0.01%	0.03%	0.09%	0.32%	0.01%	**0.36%**
1700	0.14%	0.01%	0.03%	0.09%	0.36%	0.05%	**0.40%**
2000	0.13%	0.01%	0.03%	0.09%	0.30%	0.07%	**0.35%**
2100	0.13%	0.01%	0.03%	0.09%	0.59%	0.09%	**0.62%**
2300	0.13%	0.01%	0.03%	0.09%	0.66%	0.14%	**0.69%**
2400	0.13%	0.01%	0.03%	0.09%	0.70%	0.24%	**0.76%**
2500	0.13%	0.01%	0.03%	0.09%	0.63%	0.48%	**0.80%**

5. Measurements at VNIIOFI

5.1. Spectral irradiance scale of VNIIOFI

VNIIOFI participated in the CCPR K1.a key comparison and its DoEs over the wavelength range from 250 nm to 2500 nm were listed in the CCPR K1.a final report. The VNIIOFI measurements for the present bilateral comparison were made on the same facility and in exactly the same way as those made during the CCPR K1.a. Only minor changes in the facility were made, such as using an additional detector (InGaAs) for the spectral comparator. Therefore, any drift in the primary spectral irradiance scale of VNIIOFI is considered insignificant compare with the random uncertainty associated with the measurement results.

5.2. Scale realization

The Spectral Irradiance Scale was realized using a high-temperature blackbody (1 in Figure 5-1). The blackbody was a BB3200pg [5] type with a pyrolytic graphite radiator. The cylindrical cavity of the BB3200pg had a depth of 200 mm, a diameter of 38 mm and an opening diameter of 25 mm. The bottom of the cavity was a graphite v-grooved disc. The BB3200pg was a windowless blackbody: no glass plate covered the radiation output opening. The BB3200pg was continuously blown through with argon, which went out through the output opening. The effective emissivity was estimated to be approximately 0.999.

A feedback system was used to stabilise the blackbody temperature. The feedback optics (2 in the diagram) were placed in the rear part of the blackbody. They consisted of a 5 mm aperture, focusing lens and an optical fibre. The radiation of the rear side of the blackbody bottom was collected by the lens and transfer by the fibre to the silicon photodiode S1337 combined with a glass filter with central wavelength of about 510 nm. The photodiode and a DC amplifier were assembled in the temperature stabilized case.

In front of the blackbody opening there was a precision aperture with diameter of approximately 8 mm. The temperature of the aperture holder was controlled by a water thermostat.

The Spectral Irradiance realized by the blackbody was calculated as:

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

where

c_1 = 3.74177 x 10^{-16} W m^2

c_2 = 1.4388 x 10^{-2} K m

λ - wavelength in vacuum

T – temperature of the blackbody

n = 1.000285 – air refractive index

$\varepsilon_{\mathrm{eff}}$ – effective emissivity of the blackbody

A – Area of the precision blackbody aperture

d – distance from the blackbody aperture to the sphere entrance aperture. The distance was set up equal to 455 mm using a micrometer.

The temperature of the B3200pg was 2800 to 3020 K. The TSP-2 [6] pyrometer was used to accurately measure the BB3200pg temperature. The TSP-2 was based on a temperature-stabilized detector, which was a combination of a Si photodiode and an interference filter with a central wavelength of 650 nm and a bandpass of 20 nm. The relative responsivity of the TSP-2 was accurately measured. The TSP-2 was calibrated against a copper fixed-point blackbody and a set of temperature standard lamps. Just before the spectral irradiance comparison, the calibration of the TSP-2 was checked against a Re-C fixed-point blackbody.

5.3. Laboratory standards

The lamps that took part in the comparison were measured by direct comparison with the BB3200pg. Therefore there were no transfer standards for the comparison lamp measurements.

5.4. Description of the measurement facility and measurement procedure

The spectral irradiance measurement facility used for this comparison is shown schematically in Figure 5-1.

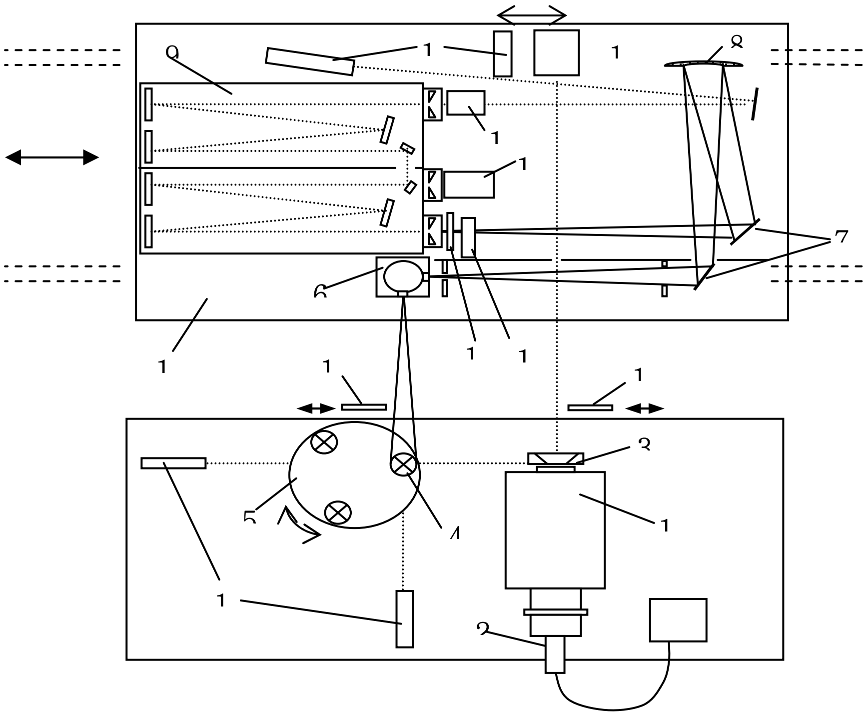


Figure 5-1. Spectral Irradiance Facility (Number labels on diagram correspond to numbers in the text)

The facility consists of the following elements:

1) High-temperature blackbody of type BB3200pg
2) Feedback optics for blackbody temperature stabilisation system
3) Precision aperture
4) Lamp being measured
5) Rotating table for the lamps
6) Integrating sphere
7) System of flat mirrors
8) Focusing mirror
9) Double grating monochromator
10) Set of order-sorting filters for the monochromator
11) Chopper for the monochromator
12) Set of replaceable detectors (photomultiplier, Si or InGaAs)
13) PbS photoresistor

The measurement lamp position was next to the blackbody, about 300 mm from it. Lamps were set up on the rotating Table 5-1 (Figure 5-1). This allowed three lamps to be aligned in advance, but only one lamp was turned on and measured at any time.

All elements of the spectral comparator were set up on the translation stage opposite the source table with the blackbody and lamps. Therefore, the comparator could be moved along the source table as a whole. The translation of the stage was 500 mm, thus only two sources could be measured (one lamp and the blackbody). There were three working positions of the stage: the first where the integrating sphere was opposite the BB3200pg, the second where it was opposite the lamp and the third where the TSP-2 was opposite the BB3200pg for temperature measurement.

The integrating sphere had an internal diameter of 40 mm, a circular entrance hole of 10 mm diameter and an exit slit with the dimensions 4x15 mm. The exit slit of the sphere was refocused onto the entrance slit of the monochromator by the mirror pair (7 and 8 in Figure 5-1).

The monochromator was a JOBIN YVON HRD1 double grating type. Three pairs of gratings (1200, 600 and 300 grooves/mm) were used to cover the entire spectral range from 250 to 2500 nm. The gratings were changed manually. Bandwidth of the monochromator was 1.8 nm in the range 250 nm to 650 nm, 3.6 nm in the range 700 nm to 1500 nm, 7.2 nm in the range 1600 nm to 2000 nm and 14.4 nm in the range 2000 nm to 2500 nm.

Five detectors were used: a multialkali PMT, a Si photodiode, an InGaAs photodiode, an extended InGaAs photodiode and a PbS photoresistor. The PMT, Si and InGaAs detectors were alternatively mounted in front of the main exit slit of the double monochromator (position 12 in the diagram), and were changed manually. The PbS, which was used for the range from 2000 to 2500 nm, was mounted on the additional exit slit. For this detector, the monochromator was operated as a single monochromator.

The wavelength setting, stage positioning and detector signal readings were made automatically within several spectral ranges.

The measurement procedure was as follows:

- wavelength set
- stage moved to the lamp position
- detector signal read
- shutter closed, dark signal read
- stage moved to the position of BB temperature measurement and TSP-2 signal read
- stage moved to the BB, shutter opened, BB signal read
- shutter closed, dark signal read
- ratio LAMP/BB calculated
- signals and ratio saved to the file

After this, the measurements were repeated so that two to four ratios were measured for each wavelength with necessary stage movements. Following that, the new wavelength was set and the measurement cycle repeated.

The spectral irradiance of the lamp was then calculated as follows:

$$E_{\text{lamp}}(\lambda) = R(\lambda) \cdot E_{\text{BB}}(\lambda, T) \quad (5\text{-}2)$$

where $R(\lambda)$ is the LAMP/BB signal ratio taking account of the dark readings.

5.5. Laboratory conditions

Throughout the calibration of the comparison lamps the laboratory temperature was controlled and at 22 ± 1 °C. The humidity was not controlled.

5.6. Uncertainty determination

5.6.1. Primary scale uncertainties

The uncertainty of the TSP-2 during the spectral irradiance comparison was estimated to be 0.8 K (see Table 5-1). The uncertainty of the spectral irradiance realization is shown in Table 5-2.

Table 5-1. Uncertainty budget of the temperature measurement

Uncertainty Sources for the temperature level of 3050 K (k = 1), K	
Cu blackbody realization	0.2
Relative Spectral responsivity	0.55
Size-of-source effect	0.3
Non-linearity and gain ratio	0.1
Stability	0.4
Alignment and focusing repeatability	0.15
Ambient temperature	0.1

5.6.2. Calibration uncertainties

The typical uncertainties associated with the lamp measurements are shown in Table 5-3. This combines the uncertainty of the primary scale as realized on the blackbody (Table 5-2) and the uncertainty due to the transfer to lamps. Table 5-3 lists the spectral points that were directly measured.

The Type A uncertainty combines both the standard deviation of the measurements during one calibration cycle (without turning the lamp off – system repeatability) and a larger component due to the standard deviation of multiple measurements of the lamp (lamp repeatability).

Table 5-2. Uncertainty budget of the primary scale spectral irradiance realization

Wavelength nm	Uncertainty (k = 1), %									
	n	c_1	c_2	ε_{eff}	T (0.8 K)	Blackbody Uniformity (0. 3 K)	Blackbody Stability (0.25 K)	Aperture Area	Distance	Combined standard uncertainty (k = 1)
250	0.05	0.01	0.1	0.1	0.51	0.19	0.16	0.02	0.06	**0.59**
260	0.05	0.01	0.09	0.1	0.49	0.18	0.15	0.02	0.06	**0.57**
270	0.05	0.01	0.09	0.1	0.47	0.18	0.15	0.02	0.06	**0.55**
280	0.05	0.01	0.09	0.1	0.46	0.17	0.14	0.02	0.06	**0.53**
290	0.04	0.01	0.08	0.1	0.44	0.17	0.14	0.02	0.06	**0.51**
300	0.04	0.01	0.08	0.1	0.43	0.16	0.13	0.02	0.06	**0.50**
310	0.04	0.01	0.08	0.1	0.41	0.15	0.13	0.02	0.06	**0.48**
320	0.04	0.01	0.08	0.1	0.40	0.15	0.12	0.02	0.06	**0.47**
330	0.04	0.01	0.07	0.1	0.39	0.15	0.12	0.02	0.06	**0.46**
340	0.04	0.01	0.07	0.1	0.38	0.14	0.12	0.02	0.06	**0.44**
350	0.04	0.01	0.07	0.1	0.37	0.14	0.11	0.02	0.06	**0.43**
360	0.03	0.01	0.07	0.05	0.36	0.13	0.11	0.02	0.06	**0.41**
380	0.03	0.01	0.06	0.05	0.34	0.13	0.11	0.02	0.06	**0.39**
400	0.03	0.01	0.06	0.05	0.32	0.12	0.10	0.02	0.06	**0.37**
450	0.03	0.01	0.05	0.05	0.28	0.11	0.09	0.02	0.06	**0.33**
500	0.02	0.01	0.05	0.05	0.26	0.10	0.08	0.02	0.06	**0.30**
550	0.02	0.01	0.04	0.05	0.23	0.09	0.07	0.02	0.06	**0.28**
600	0.02	0.01	0.04	0.05	0.21	0.08	0.07	0.02	0.06	**0.25**
650	0.02	0.01	0.04	0.05	0.20	0.07	0.06	0.02	0.06	**0.24**
700	0.02	0.01	0.03	0.05	0.18	0.07	0.06	0.02	0.06	**0.22**
800	0.01	0.01	0.03	0.05	0.16	0.06	0.05	0.02	0.06	**0.20**
900	0.01	0.01	0.03	0.05	0.14	0.05	0.04	0.02	0.06	**0.18**
950	0.01	0.01	0.03	0.05	0.14	0.05	0.04	0.02	0.06	**0.17**
1000	0.01	0.01	0.02	0.05	0.13	0.05	0.04	0.02	0.06	**0.17**
1100	0.01	0.01	0.02	0.05	0.12	0.04	0.04	0.02	0.06	**0.16**
1200	0.01	0.01	0.02	0.05	0.11	0.04	0.03	0.02	0.06	**0.15**
1300	0.01	0.01	0.02	0.05	0.10	0.04	0.03	0.02	0.06	**0.14**
1500	0	0.01	0.02	0.05	0.09	0.03	0.03	0.02	0.06	**0.13**
1600	0	0.01	0.02	0.05	0.08	0.03	0.03	0.02	0.06	**0.13**
1700	0	0.01	0.02	0.05	0.08	0.03	0.02	0.02	0.06	**0.12**
2000	0	0.01	0.01	0.05	0.07	0.03	0.02	0.02	0.06	**0.11**
2100	0	0.01	0.01	0.05	0.07	0.03	0.02	0.02	0.06	**0.11**
2300	0	0.01	0.01	0.05	0.06	0.02	0.02	0.02	0.06	**0.11**
2400	0	0.01	0.01	0.05	0.06	0.02	0.02	0.02	0.06	**0.11**
2500	0	0.01	0.01	0.05	0.06	0.02	0.02	0.02	0.06	**0.11**

Table 5-3. Uncertainty budget for spectral irradiance lamp measurement. “Scale” corresponds to the information in Table 5-2

Wavelength, nm	Uncertainty in Spectral Irradiance (k = 1), %							
	Type A	Type B						**Overall**
		Scale	Distance	Lamp current	Wavelength	Alignment	Cut off filters	
250	1.37	0.59	0.06	0.12	0.03	0.10		**1.50**
260	0.90	0.57	0.06	0.11	0.03	0.10		**1.08**
270	0.70	0.55	0.06	0.11	0.03	0.10		**0.90**
280	0.57	0.53	0.06	0.10	0.03	0.10		**0.79**
290	0.50	0.51	0.06	0.10	0.02	0.10		**0.73**
300	0.44	0.5	0.06	0.10	0.02	0.10		**0.68**
310	0.39	0.48	0.06	0.09	0.02	0.10		**0.64**
320	0.36	0.47	0.06	0.09	0.02	0.10		**0.61**
330	0.32	0.46	0.06	0.09	0.02	0.10		**0.58**
340	0.30	0.44	0.06	0.08	0.02	0.10		**0.55**
350	0.28	0.43	0.06	0.08	0.02	0.10		**0.53**
360	0.26	0.41	0.06	0.08	0.02	0.10		**0.51**
380	0.23	0.39	0.06	0.08	0.02	0.10		**0.47**
400	0.21	0.37	0.06	0.07	0.02	0.10		**0.45**
450	0.18	0.33	0.06	0.06	0.02	0.10		**0.40**
500	0.15	0.3	0.06	0.06	0.01	0.10		**0.36**
550	0.14	0.28	0.06	0.05	0.01	0.10		**0.34**
600	0.13	0.25	0.06	0.05	0.01	0.10		**0.31**
650	0.11	0.24	0.06	0.04	0.01	0.10		**0.29**
700	0.10	0.22	0.06	0.04	0.02	0.10		**0.27**
800	0.09	0.2	0.06	0.04	0.02	0.10		**0.25**
900	0.08	0.18	0.06	0.03	0.01	0.10		**0.23**
950	0.08	0.17	0.06	0.03	0.01	0.10		**0.22**
1000	0.08	0.17	0.06	0.03	0.01	0.10		**0.22**
1100	0.09	0.16	0.06	0.03	0.01	0.10	0.10	**0.24**
1200	0.10	0.15	0.06	0.02	0.01	0.10	0.15	**0.26**
1300	0.11	0.14	0.06	0.02	0.01	0.10	0.15	**0.26**
1500	0.15	0.13	0.06	0.02	0.01	0.10	0.15	**0.28**
1600	0.17	0.13	0.06	0.02	0.01	0.10	0.15	**0.29**
1700	0.20	0.12	0.06	0.02	0.01	0.10	0.15	**0.30**
2000	0.33	0.11	0.06	0.01	0.01	0.10	0.15	**0.40**
2100	0.40	0.11	0.06	0.01	0.01	0.10	0.15	**0.46**
2300	0.57	0.11	0.06	0.01	0.01	0.10	0.20	**0.63**
2400	0.70	0.11	0.06	0.01	0.01	0.10	0.20	**0.75**
2500	0.85	0.11	0.06	0.01	0.01	0.10	0.20	**0.89**

6. Results

6.1. Measurement results

KRISS and VNIIOFI measured three lamps: BN-9101-440, BN-9101-441, and BN-9101-442. All lamps were measured at DC current of 8.100 A and at a distance of 50.0 cm. The lamps were aligned as described in Section 3. In the technical protocol of this comparison, the distance should be measured from the surface of the lamp socket, but it was difficult to measure the distance from that surface with a micrometer because the bottom of the integrating sphere surface was higher than that surface at KRISS. Both participants agreed to change the surface for distance measurement as shown in Figure 3-2.

KRISS measured the three lamps for the first time in May 2008, then VNIIOFI measured them in June 2008, and KRISS measured the lamps again in December 2008. Originally it was planned that each lamp would be measured three times, each time after independent realignment. At KRISS, however, all three lamps were measured twice in the first and second measurement. At VNIIOFI, only BN-9101-441 was measured three times, while other two lamps were measured only twice. The spectral irradiance of each lamp and its uncertainty for KRISS and VNIIOFI measurements, and record of lamp burn hours are given in Appendices. Spectral irradiances of each lamp measured four times by KRISS and measured twice (three times for BN-9101-441) by VNIIOFI were averaged and the averaged values were used in this analysis.

Figure 6-1 shows the relative difference in spectral irradiance of the lamps and uncertainty associated with the difference calculated as Eq (6-1).

$$\Delta_{\alpha i} = \frac{E_\alpha}{E_i} - 1$$
$$u(\Delta_{\alpha i}) = (1+\Delta_{\alpha i})\cdot\left[u_{\mathrm{rel}}^2(E_\alpha)+u_{\mathrm{rel}}^2(E_i)\right]^{1/2} \qquad (6\text{-}1)$$

where E_α and E_i are the measured values for the spectral irradiances by KRISS and VNIIOFI, respectively. $\Delta_{\alpha i}$ is the relative difference between the KRISS and VNIIOFI measured values. $u(\Delta_{\alpha i})$ is the standard uncertainty associated with the relative difference. $u_{\mathrm{rel}}(E_\alpha)$ and $u_{\mathrm{rel}}(E_i)$ are the relative standard uncertainties associated with KRISS and VNIIOFI measurements, respectively.

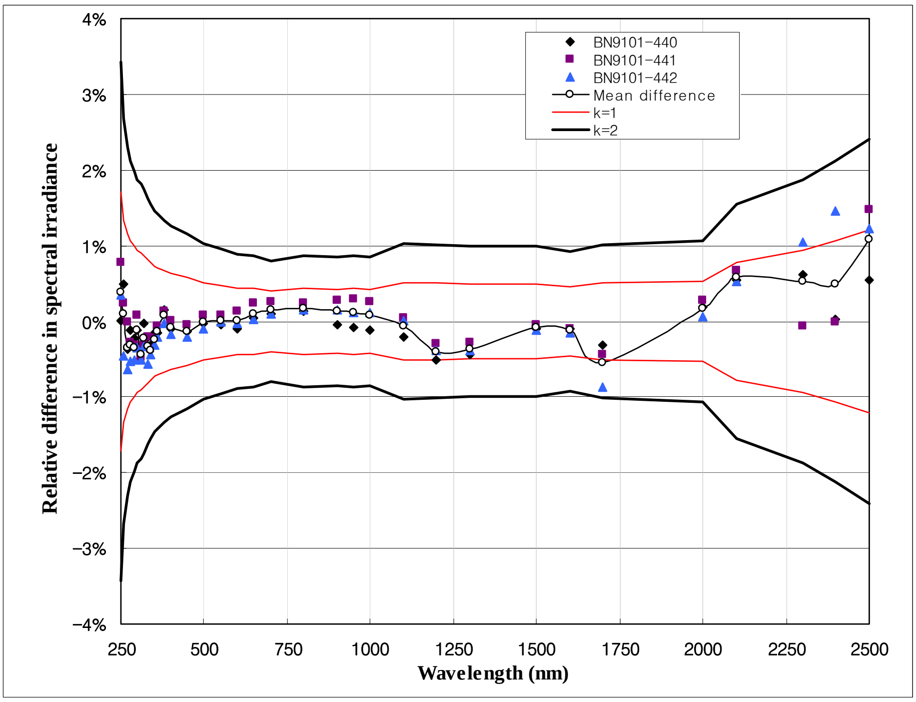


Figure 6-1. Relative differences in spectral irradiances of three lamps measured by KRISS and VNIIOFI.

Table 6-1 shows the relative differences and the mean difference of spectral irradiances between KRISS and VNIIOFI measurements of the lamps, and uncertainty associated with the mean differences.

Table 6-1. Relative differences and mean difference of spectral irradiances between KRISS and VNIIOFI measurements of the lamps, and the uncertainty associated with the mean difference

Wavelength	*E* (KRISS)/*E* (VNIIOFI)-1			Mean difference	Uncertainty associated with the mean difference (k = 1)
	BN-9101-440	BN-9101-441	BN-9101-442		
250	0.01%	0.36%	0.79%	0.38%	1.72%
260	0.49%	-0.45%	0.25%	0.10%	1.34%
270	-0.37%	-0.64%	-0.02%	-0.34%	1.15%
280	-0.11%	-0.52%	-0.28%	-0.30%	1.06%
290	-0.23%	-0.52%	-0.31%	-0.35%	0.98%
300	-0.12%	-0.34%	0.09%	-0.12%	0.94%
310	-0.32%	-0.51%	-0.48%	-0.44%	0.90%
320	-0.03%	-0.34%	-0.30%	-0.22%	0.87%
330	-0.21%	-0.56%	-0.20%	-0.32%	0.81%
340	-0.32%	-0.44%	-0.37%	-0.38%	0.77%
350	-0.15%	-0.32%	-0.23%	-0.23%	0.72%
360	-0.15%	-0.21%	-0.07%	-0.14%	0.71%
380	0.15%	-0.04%	0.14%	0.08%	0.66%
400	-0.10%	-0.17%	0.01%	-0.09%	0.63%
450	-0.14%	-0.20%	-0.05%	-0.13%	0.58%
500	-0.04%	-0.09%	0.08%	-0.02%	0.51%
550	-0.04%	-0.01%	0.07%	0.00%	0.48%
600	-0.09%	-0.04%	0.14%	0.00%	0.44%
650	0.04%	0.03%	0.25%	0.11%	0.43%
700	0.10%	0.10%	0.25%	0.15%	0.40%
800	0.13%	0.15%	0.24%	0.17%	0.43%
900	-0.04%	0.15%	0.29%	0.13%	0.43%
950	-0.08%	0.12%	0.30%	0.11%	0.43%
1000	-0.12%	0.11%	0.27%	0.09%	0.42%
1100	-0.21%	0.00%	0.04%	-0.06%	0.51%
1200	-0.51%	-0.39%	-0.29%	-0.40%	0.50%
1300	-0.43%	-0.39%	-0.27%	-0.36%	0.49%
1500	-0.10%	-0.12%	-0.04%	-0.08%	0.50%
1600	-0.10%	-0.15%	-0.10%	-0.12%	0.46%
1700	-0.32%	-0.86%	-0.44%	-0.54%	0.50%
2000	0.18%	0.06%	0.28%	0.18%	0.53%
2100	0.55%	0.54%	0.68%	0.59%	0.78%
2300	0.62%	1.05%	-0.07%	0.54%	0.94%
2400	0.02%	1.47%	-0.01%	0.49%	1.07%
2500	0.54%	1.23%	1.48%	1.08%	1.21%

6.2. Comparison results

6.2.1. Unilateral degree of equivalence of KRISS

The same definitions of unilateral and bilateral degree of equivalences (DoE) and their uncertainties as defined in the CCPR K1.a final report were used in this report. The symbols and uncertainties described in this report are used according to *Guide to the Expression of Uncertainty in Measurement* (GUM)[4]. There are some reports of bilateral comparisons on spectral irradiance and uncertainty evaluation methods. [7], [8], [9] Some of those reports use approaches that require information that was not directly reported in the CCPR K1.a comparison report but requires further calculation, such as the individual weights of participants, or the uncertainty associated with the KCRV. In this report, we tried to calculate the KRISS DoE and its uncertainty using only the final results available in the CCPR K1.a final report, such as the unilateral DoE and its uncertainty, and spectral irradiance measurement uncertainty of the linking NMI (VNIIOFI), without further calculations that, for the sake of linking comparisons, perhaps should have been presented in the CCPR K1.a report.

The unilateral DoE of KRISS D_α as the linked NMI α was calculated from the unilateral DoE of VNIIOFI D_i as the linking NMI i, as below.

$$\begin{aligned} D_i &= \frac{E_{i,\mathrm{KC}}}{X_{\mathrm{ref,KC}}} - 1 \\ &= \frac{E_{i,\mathrm{BC}}}{X_{\mathrm{ref,BC}}} - 1 \\ D_{\alpha(i)} &= \frac{E_\alpha}{X_{\mathrm{ref,BC}}} - 1 \\ &= \frac{E_\alpha}{E_{i,\mathrm{BC}}} \cdot (D_i + 1) - 1 \\ &= R \cdot (D_i + 1) - 1 \end{aligned} \quad . \qquad (6\text{-}2)$$

Here we consider the irradiance of a single 'virtual' lamp and assume that the KCRV, $X_{\mathrm{ref,KC}}$, is the measured value for that 'virtual' lamp that would be obtained by the world-mean of the CCPR K1.a comparison. This concept allows us to account for the fact that each actual comparison artifact has a different irradiance value.

D_i is the unilateral DoE of VNIIOFI; $D_{\alpha(i)}$ is the unilateral DoE of KRISS obtained through linking NMI i (VNIIOFI);

$E_{i,\mathrm{KC}}$ is the VNIIOFI measured value for the spectral irradiance of a 'virtual' transfer standard lamp for the CCPR K1.a comparison;

$X_{\mathrm{ref,KC}}$ is the CCPR KCRV determined for the lamps used for the CCPR K1.a comparison, it represents the world-mean irradiance of the 'virtual' lamp;

$X_{\mathrm{ref,BC}}$ is equivalent to the CCPR KCRV for the lamps used for this bilateral comparison and it can be deduced from the DoE of VNIIOFI and spectral irradiance measured by VNIIOFI for the lamps as included in the equation. It can be considered as the world-mean value of the irradiance of the 'virtual' lamp used in the bilateral comparison;

$E_{i,\mathrm{BC}}$ is the VNIIOFI measured value of the spectral irradiance of a 'virtual' transfer standard lamp for the bilateral comparison;

E_α is the KRISS measured value of the spectral irradiance of the 'virtual' transfer standard lamp; and

R is the mean ratio of the KRISS measured value to the VNIIOFI measured value of the spectral irradiances of the transfer standard lamps. This is how a value for a virtual lamp can be considered from the actual measured values.

The more detailed derivation of Eq (6-2) is given in Appendix C. The unilateral DoE values of VNIIOFI given in the final report of CCPR K1.a comparison were used to calculate the unilateral DoE of KRISS.

6.2.2. Uncertainty of the unilateral DoE of KRISS

The uncertainty associated with the unilateral DoE of KRISS was calculated from the uncertainty associated with the unilateral DoE of VNIIOFI listed in the final report of CCPR K1.a comparison and uncertainties of spectral irradiance measurements of KRISS and VNIIOFI. The uncertainty of the unilateral DoE of KRISS was calculated as below. A more detailed derivation of the equation is given in Appendix C.

$$U\left(d_{\alpha(i)}\right) = 2 \cdot \left(1 + d_{\alpha(i)}\right) \cdot \sqrt{u_{\mathrm{rel}}^2\left(e_\alpha\right) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}} + \left\{ \left(\frac{U\left(d_i\right)}{2 \cdot \left(1 + d_i\right)} \right)^2 - (1 - 2w_i) \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{correlated}}\right) \right\}} \qquad (6\text{-}3)$$

where $U\left(d_{\alpha(i)}\right)$ is the expanded uncertainty(k = 2) associated with the unilateral DOE of KRISS obtained through linking NMI i (VNIIOFI); $U\left(d_i\right)$ is the expanded uncertainty(k = 2) associated with the unilateral DOE of VNIIOFI, as given in the final report of CCPR K1.a comparison; $u_{\mathrm{rel}}\left(e_\alpha\right)$ is the relative standard uncertainty associated with the spectral irradiance measurement of KRISS; $u_{\mathrm{rel}}\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}}$ is the relative standard uncertainty associated with random effects of the spectral irradiance measurement of VNIIOFI for this bilateral comparison; $u_{\mathrm{rel}}\left(f_{i,\mathrm{correlated}}\right)$ is the relative standard uncertainty associated with effects that are correlated between both spectral irradiance measurements for the CCPR K1.a comparison and for this bilateral comparison; and w_i is the weight of VNIIOFI used to determine the KCRV at the CCPR K1.a comparison. This was not listed in the final report of CCPR K1.a comparison.

The last term of Eq (6-3) takes into account the effect of correlation between the VNIIOFI measurements at the CCPR K1.a and at this bilateral comparison. The scale realization of VNIIOFI was regarded as the correlated effect between the two comparisons and its associated uncertainty is the $u_{\mathrm{rel}}\left(f_{i,\mathrm{correlated}}\right)$ term. The remaining influences on VNIIOFI's measurements for this bilateral comparison were regarded as the uncorrelated components. As the VNIIOFI measurements for this comparison were made on the same facility as those made during CCPR K1.a comparison, any drift in the VNIIOFI primary scale was considered insignificant in comparison to the random uncertainty associated with the measurement results.

It should also be noted that the measurements of KRISS and VNIIOFI were considered entirely independent (no correlation) for this analysis.

In Eq (6-3), the weight of the VNIIOFI measurement in determining the KCRV of the CCPR K1.a comparison, w_i, is used, but this was not listed in the final report of CCPR K1.a comparison. It can be calculated using uncertainties of participants listed in the report. However, its inclusion in the equation changed the results very little (the maximum difference was 0.006 % at 250 nm). Hence, the uncertainty of the KRISS DoE can be calculated using Eq (6-4) rather than Eq (6-3) with no further calculation of the weight of VNIIOFI, nor a considerable differences in the results.

$$U\left(d_{\alpha(i)}\right)=2\cdot\left(1+d_{\alpha(i)}\right)\cdot\sqrt{u_{\mathrm{rel}}^2\left(e_\alpha\right)+u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}}+\left\{\left(\frac{U\left(d_i\right)}{2\cdot\left(1+d_i\right)}\right)^2-u_{\mathrm{rel}}^2\left(f_{i,\mathrm{correlated}}\right)\right\}}. \qquad (6\text{-}4)$$

Figure 6-2 and Table 6-2 show the unilateral DoE values of KRISS and their uncertainties.

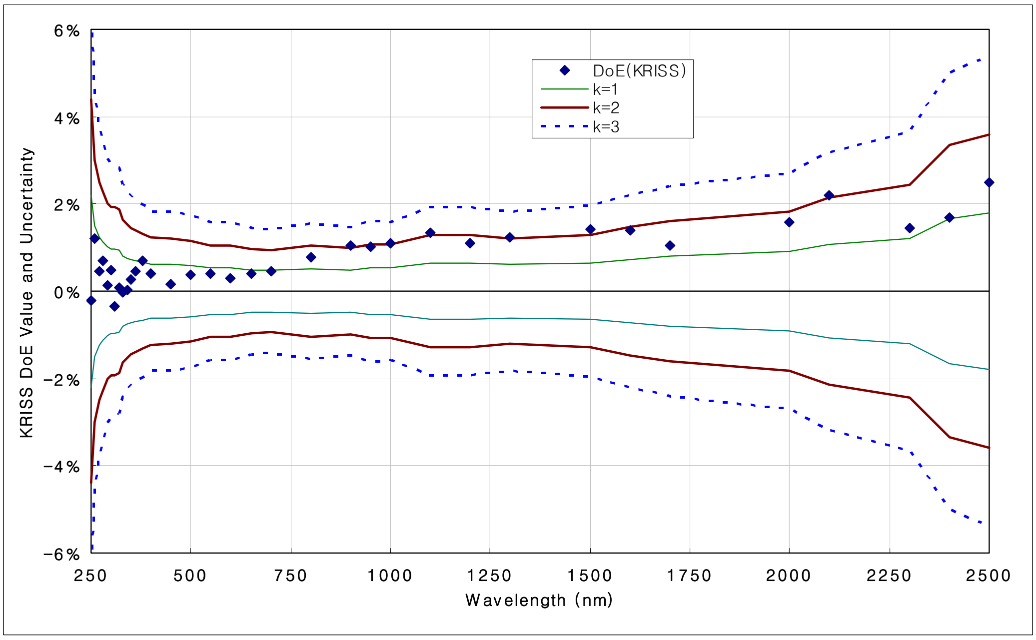


Figure 6-2. Unilateral DoE value of KRISS and their uncertainties.

Table 6-2. Uncertainties of KRISS and VNIIOFI measurements, and the unilateral DoE of KRISS and their uncertainties

	Uncertainty of KRISS measurement	Uncertainty of VNIIOFI measurement			**DoE of KRISS**	
Wavelength	u_{KRISS}	$u_{uc,\text{ VNIIOFI}}$	$u_{c,\text{ VNIIOFI}}$	$U(D_{\text{VNIIOFI}})$	**DoE**	**U(DoE) (k = 2)**
250	0.83%	1.38%	0.59%	3.2%	**-0.2%**	**4.4%**
260	0.80%	0.91%	0.57%	2.1%	**1.2%**	**3.1%**
270	0.72%	0.72%	0.55%	1.8%	**0.5%**	**2.6%**
280	0.70%	0.59%	0.53%	1.7%	**0.7%**	**2.4%**
290	0.66%	0.52%	0.51%	1.5%	**0.1%**	**2.1%**
300	0.64%	0.47%	0.50%	1.5%	**0.5%**	**2.0%**
310	0.65%	0.42%	0.48%	1.5%	**-0.3%**	**2.0%**
320	0.62%	0.39%	0.47%	1.5%	**0.1%**	**1.9%**
330	0.57%	0.35%	0.46%	1.3%	**0.0%**	**1.7%**
340	0.55%	0.33%	0.44%	1.2%	**0.0%**	**1.6%**
350	0.49%	0.31%	0.43%	1.2%	**0.3%**	**1.5%**
360	0.51%	0.30%	0.41%	1.1%	**0.5%**	**1.4%**
380	0.46%	0.27%	0.39%	1.1%	**0.7%**	**1.4%**
400	0.44%	0.25%	0.37%	1.0%	**0.4%**	**1.3%**
450	0.42%	0.22%	0.33%	1.0%	**0.2%**	**1.3%**
500	0.36%	0.20%	0.30%	1.0%	**0.4%**	**1.2%**
550	0.34%	0.19%	0.28%	0.9%	**0.4%**	**1.1%**
600	0.32%	0.18%	0.25%	0.9%	**0.3%**	**1.1%**
650	0.32%	0.17%	0.24%	0.8%	**0.4%**	**1.0%**
700	0.29%	0.16%	0.22%	0.8%	**0.5%**	**1.0%**
800	0.35%	0.15%	0.20%	0.8%	**0.8%**	**1.1%**
900	0.36%	0.14%	0.18%	0.7%	**1.0%**	**1.0%**
950	0.37%	0.14%	0.17%	0.8%	**1.0%**	**1.1%**
1000	0.36%	0.14%	0.17%	0.8%	**1.1%**	**1.1%**
1100	0.45%	0.18%	0.16%	0.9%	**1.3%**	**1.3%**
1200	0.43%	0.22%	0.15%	0.9%	**1.1%**	**1.3%**
1300	0.42%	0.22%	0.14%	0.8%	**1.2%**	**1.2%**
1500	0.42%	0.24%	0.13%	0.9%	**1.4%**	**1.3%**
1600	0.36%	0.26%	0.13%	1.2%	**1.4%**	**1.5%**
1700	0.40%	0.28%	0.12%	1.3%	**1.0%**	**1.6%**
2000	0.35%	0.38%	0.11%	1.5%	**1.6%**	**1.8%**
2100	0.62%	0.44%	0.11%	1.5%	**2.2%**	**2.2%**
2300	0.69%	0.62%	0.11%	1.6%	**1.4%**	**2.5%**
2400	0.76%	0.74%	0.11%	2.6%	**1.7%**	**3.4%**
2500	0.80%	0.88%	0.11%	2.7%	**2.5%**	**3.7%**

6.2.3. Bilateral DoE between KRISS and other NMI and its uncertainty

The bilateral DoE between KRISS and any other NMI j which participated in the CCPR K1.a comparison can be calculated by Eq (6-5) according to its definition defined in the CCPR K1.a final report.

$$D_{\alpha(i)j} = D_{\alpha(i)} - D_j \tag{6-5}$$

where D_j is the DoE of the NMI j listed in the report.

The expanded uncertainty(k = 2) of the bilateral DoE between KRISS and other NMI j is given by Eq(6-6).

$$U\left(d_{\alpha(i)j}\right)=2\cdot\left[\left(\frac{U\left(d_{\alpha(i)}\right)}{2}\right)^2+\left(\frac{U\left(d_j\right)}{2}\right)^2\right.$$
$$-\left(1+d_{\alpha(i)}\right)\cdot\left(1+d_j\right)\cdot\left(\left\{\left(\frac{U\left(d_{\alpha(i)}\right)}{2\cdot\left(1+d_{\alpha(i)}\right)}\right)^2-\left\{u_{\rm rel}^2\left(e_{i,\rm BC,r}\right)+u_{\rm rel}^2\left(e_\alpha\right)+u_{\rm rel}^2\left(e_{i,\rm KC,r}\right)+u_{\rm rel}^2\left(\delta_i\right)\right\}\right\}\right. \quad (6\text{-}6)$$
$$\left.\left.+\left\{\left(\frac{U\left(d_j\right)}{2\cdot\left(1+d_j\right)}\right)^2-\left\{u_{\rm rel}^2\left(e_j\right)+u_{\rm rel}^2\left(\delta_i\right)\right\}\right\}\right)\right]^{\frac{1}{2}}$$

where $U\left(d_j\right)$ is the expanded uncertainty of the DoE of NMI j listed in the CCPR K1.a final report; d_j is the value of the the DoE of NMI j; $u_{\rm rel}\left(e_{i,\rm BC,r}\right)$ is the random component of the relative standard uncertainty of the VNIIOFI at this bilateral comparison; $u_{\rm rel}\left(e_{i,\rm KC,r}\right)$ is the random component of the relative standard uncertainty of the VNIIOFI at the CCPR K1.a comparison; $u_{\rm rel}\left(e_j\right)$ is the relative standard uncertainty of NMI j listed in the CCPR K1.a final report; and $u_{\rm rel}\left(\delta_i\right)$ is the relative standard uncertainty associated with the instability of the transfer standard lamps used in the analysis of CCPR K1.a comparison. A more detailed derivation is given in Appendix C.

7. Conclusions

The spectral irradiances measured by KRISS and VNIIOFI in this comparison agreed within the standard uncertainties (k = 1) from 250 nm to 2500 nm. The unilateral DoE of KRISS was calculated using the unilateral DoE of VNIIOFI to link KRISS spectral irradiance scale to the key comparison CCPR K1.a. The uncertainties associated with the unilateral DoE of KRISS were determined using uncertainties of KRISS and VNIIOFI measurements and uncertainties of the unilateral DoE of VNIIOFI, and taking into account the correlation of VNIIOFI measurements between CCPR key and this bilateral comparison.

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Appendix A. Measurement data

A.1. KRISS measurement data

A.1.1 Reference Number of artifact: BN-9101-440

Current: **8.100 A** Distance: **500.0 mm** Ambient temperature: 23±1 °C

The lamp was measured independently twice at the first and second measurements. The spectral irradiance values presented in this table are the average of the four measurements.

Date of measurement: First Measurement 1: 13.05.2008 from 250 nm to 2500 nm

Measurement 2: 19.05.2008 from 250 nm to 2500 nm

Second Measurement 1: 23.09.2008 from 250 nm to 800 nm

Measurement 1: 15.12.2008 from 250 nm to 2500 nm

Measurement 2: 24.12.2008 from 800 nm to 2500 nm

		Spectral Irradiance Uncertainty of BN-9101-440						
		Scale	Wavelength	Lamp Current	Alignment	Spectroradiometer responsivity stability	Repeatability (Type A)	**Combined Standard Uncertainty (k = 1)**
Wavelength (nm)	Irradiance W/(㎡ nm)		$u(\lambda)$ =0.03 nm	$u(i)$ =0.0014 A				
250	2.507E-04	0.57%	0.17%	0.22%	0.09%	0.52%	0.07%	0.83%
260	4.285E-04	0.55%	0.15%	0.18%	0.09%	0.52%	0.04%	0.80%
270	6.984E-04	0.53%	0.14%	0.18%	0.09%	0.42%	0.04%	0.72%
280	1.084E-03	0.51%	0.13%	0.18%	0.09%	0.41%	0.10%	0.70%
290	1.608E-03	0.49%	0.12%	0.19%	0.09%	0.37%	0.06%	0.67%
300	2.309E-03	0.48%	0.11%	0.17%	0.09%	0.36%	0.05%	0.64%
310	3.217E-03	0.46%	0.10%	0.17%	0.09%	0.40%	0.04%	0.65%
320	4.374E-03	0.45%	0.09%	0.16%	0.09%	0.37%	0.05%	0.62%
330	5.788E-03	0.44%	0.09%	0.14%	0.09%	0.31%	0.04%	0.57%
340	7.512E-03	0.43%	0.08%	0.14%	0.09%	0.30%	0.03%	0.55%
350	9.566E-03	0.41%	0.07%	0.13%	0.09%	0.21%	0.03%	0.50%
360	1.196E-02	0.40%	0.07%	0.13%	0.09%	0.25%	0.02%	0.51%
380	1.783E-02	0.38%	0.06%	0.12%	0.09%	0.21%	0.02%	0.47%
400	2.511E-02	0.37%	0.05%	0.11%	0.09%	0.20%	0.02%	0.45%
450	4.914E-02	0.33%	0.04%	0.10%	0.09%	0.22%	0.02%	0.42%
500	7.962E-02	0.30%	0.03%	0.09%	0.09%	0.17%	0.01%	0.37%
550	1.127E-01	0.28%	0.02%	0.07%	0.09%	0.15%	0.01%	0.34%
600	1.446E-01	0.26%	0.01%	0.07%	0.09%	0.15%	0.01%	0.32%
650	1.729E-01	0.24%	0.01%	0.07%	0.09%	0.18%	0.01%	0.32%
700	1.958E-01	0.23%	0.01%	0.07%	0.09%	0.15%	0.02%	0.29%
800	2.242E-01	0.21%	0.01%	0.06%	0.09%	0.26%	0.02%	0.35%
900	2.314E-01	0.19%	0.01%	0.06%	0.09%	0.29%	0.02%	0.36%
950	2.294E-01	0.18%	0.01%	0.06%	0.09%	0.30%	0.01%	0.37%
1000	2.247E-01	0.18%	0.01%	0.05%	0.09%	0.29%	0.01%	0.36%
1100	2.097E-01	0.17%	0.01%	0.05%	0.09%	0.40%	0.05%	0.45%
1200	1.903E-01	0.16%	0.01%	0.05%	0.09%	0.39%	0.01%	0.43%
1300	1.703E-01	0.15%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1500	1.327E-01	0.14%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1600	1.163E-01	0.14%	0.01%	0.03%	0.09%	0.32%	0.01%	0.36%
1700	1.015E-01	0.14%	0.01%	0.03%	0.09%	0.36%	0.07%	0.40%
2000	6.820E-02	0.13%	0.01%	0.03%	0.09%	0.30%	0.07%	0.35%
2100	5.976E-02	0.13%	0.01%	0.03%	0.09%	0.59%	0.09%	0.62%
2300	4.619E-02	0.13%	0.01%	0.03%	0.09%	0.66%	0.14%	0.69%
2400	4.054E-02	0.13%	0.01%	0.03%	0.09%	0.70%	0.23%	0.75%
2500	3.611E-02	0.13%	0.01%	0.03%	0.09%	0.63%	0.49%	0.81%

A.1.2 Reference Number of artifact: BN-9101-441

Current: **8.100 A** Distance: **500.0 mm** Ambient temperature: 23±1 °C

The lamp was measured independently twice at the first and second measurements. The spectral irradiance values presented in this table are the average of the four measurements.

Date of measurement: First Measurement 1: 20.05.2008 from 250 nm to 2500 nm

Measurement 2: 27.05.2008 from 250 nm to 2500 nm

Second Measurement 1: 16.12.2008 from 250 nm to 2500 nm

Measurement 2: 26.12.2008 from 250 nm to 2500 nm

		Spectral Irradiance Uncertainty of BN-9101-441						
		Scale	Wavelength	Lamp Current	Alignment	Spectroradiometer responsivity stability	Repeatability (Type A)	**Combined Standard Uncertainty (k = 1)**
Wavelength (nm)	Irradiance W/(㎡ nm)		$u(\lambda)$ =0.03 nm	$u(i)$ =0.0014 A				
250	1.913E-04	0.57%	0.17%	0.22%	0.09%	0.52%	0.08%	0.83%
260	3.323E-04	0.55%	0.15%	0.18%	0.09%	0.52%	0.04%	0.80%
270	5.508E-04	0.53%	0.14%	0.18%	0.09%	0.42%	0.09%	0.72%
280	8.649E-04	0.51%	0.13%	0.18%	0.09%	0.41%	0.12%	0.71%
290	1.294E-03	0.49%	0.12%	0.19%	0.09%	0.37%	0.07%	0.67%
300	1.875E-03	0.48%	0.11%	0.17%	0.09%	0.36%	0.06%	0.64%
310	2.632E-03	0.46%	0.10%	0.17%	0.09%	0.40%	0.05%	0.65%
320	3.597E-03	0.45%	0.09%	0.16%	0.09%	0.37%	0.05%	0.62%
330	4.790E-03	0.44%	0.09%	0.14%	0.09%	0.31%	0.04%	0.57%
340	6.254E-03	0.43%	0.08%	0.14%	0.09%	0.30%	0.04%	0.55%
350	8.003E-03	0.41%	0.07%	0.13%	0.09%	0.21%	0.03%	0.50%
360	1.005E-02	0.40%	0.07%	0.13%	0.09%	0.25%	0.03%	0.51%
380	1.513E-02	0.38%	0.06%	0.12%	0.09%	0.21%	0.02%	0.47%
400	2.149E-02	0.37%	0.05%	0.11%	0.09%	0.20%	0.02%	0.45%
450	4.279E-02	0.33%	0.04%	0.10%	0.09%	0.22%	0.01%	0.42%
500	7.027E-02	0.30%	0.03%	0.09%	0.09%	0.17%	0.01%	0.37%
550	1.005E-01	0.28%	0.02%	0.07%	0.09%	0.15%	0.01%	0.34%
600	1.302E-01	0.26%	0.01%	0.07%	0.09%	0.15%	0.01%	0.32%
650	1.568E-01	0.24%	0.01%	0.07%	0.09%	0.18%	0.01%	0.32%
700	1.787E-01	0.23%	0.01%	0.07%	0.09%	0.15%	0.02%	0.29%
800	2.066E-01	0.21%	0.01%	0.06%	0.09%	0.26%	0.02%	0.35%
900	2.152E-01	0.19%	0.01%	0.06%	0.09%	0.29%	0.02%	0.36%
950	2.139E-01	0.18%	0.01%	0.06%	0.09%	0.30%	0.01%	0.37%
1000	2.102E-01	0.18%	0.01%	0.05%	0.09%	0.29%	0.01%	0.36%
1100	1.970E-01	0.17%	0.01%	0.05%	0.09%	0.40%	0.01%	0.45%
1200	1.790E-01	0.16%	0.01%	0.05%	0.09%	0.39%	0.01%	0.43%
1300	1.605E-01	0.15%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1500	1.255E-01	0.14%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1600	1.101E-01	0.14%	0.01%	0.03%	0.09%	0.32%	0.01%	0.36%
1700	9.569E-02	0.14%	0.01%	0.03%	0.09%	0.36%	0.05%	0.40%
2000	6.467E-02	0.13%	0.01%	0.03%	0.09%	0.30%	0.07%	0.35%
2100	5.684E-02	0.13%	0.01%	0.03%	0.09%	0.59%	0.10%	0.62%
2300	4.410E-02	0.13%	0.01%	0.03%	0.09%	0.66%	0.16%	0.69%
2400	3.919E-02	0.13%	0.01%	0.03%	0.09%	0.70%	0.29%	0.78%
2500	3.459E-02	0.13%	0.01%	0.03%	0.09%	0.63%	0.45%	0.79%

A.1.3 Reference Number of artifact: BN-9101-442

Current: **8.100 A** Distance: **500.0 mm.** Ambient temperature: 23±1 °C

The lamp was measured independently twice at the first and second measurements. The spectral irradiance values presented in this table are the average of the four measurements.

Date of measurement: First Measurement 1: 21.05.2008 from 250 nm to 2500 nm

Measurement 2: 26.05.2008 from 250 nm to 2500 nm

Second Measurement 1: 17.12.2008 from 250 nm to 2500 nm

Measurement 2: 18.12.2008 from 250 nm to 2500 nm

		Spectral Irradiance Uncertainty of BN-9101-442						
		Scale	Wavelength	Lamp Current	Alignment	Spectroradiometer responsivity stability	Repeatability (Type A)	**Combined Standard Uncertainty (k = 1)**
Wavelength (nm)	Irradiance W/(㎡ nm)		$u(\lambda)$ =0.03 nm	$u(i)$ =0.0014 A				
250	2.615E-04	0.57%	0.17%	0.22%	0.09%	0.52%	0.06%	0.83%
260	4.468E-04	0.55%	0.15%	0.18%	0.09%	0.52%	0.04%	0.80%
270	7.291E-04	0.53%	0.14%	0.18%	0.09%	0.42%	0.04%	0.72%
280	1.128E-03	0.51%	0.13%	0.18%	0.09%	0.41%	0.14%	0.71%
290	1.672E-03	0.49%	0.12%	0.19%	0.09%	0.37%	0.07%	0.67%
300	2.400E-03	0.48%	0.11%	0.17%	0.09%	0.36%	0.05%	0.64%
310	3.336E-03	0.46%	0.10%	0.17%	0.09%	0.40%	0.04%	0.65%
320	4.519E-03	0.45%	0.09%	0.16%	0.09%	0.37%	0.05%	0.62%
330	5.976E-03	0.44%	0.09%	0.14%	0.09%	0.31%	0.05%	0.57%
340	7.739E-03	0.43%	0.08%	0.14%	0.09%	0.30%	0.03%	0.55%
350	9.835E-03	0.41%	0.07%	0.13%	0.09%	0.21%	0.03%	0.50%
360	1.229E-02	0.40%	0.07%	0.13%	0.09%	0.25%	0.02%	0.51%
380	1.828E-02	0.38%	0.06%	0.12%	0.09%	0.21%	0.02%	0.47%
400	2.569E-02	0.37%	0.05%	0.11%	0.09%	0.20%	0.02%	0.45%
450	5.007E-02	0.33%	0.04%	0.10%	0.09%	0.22%	0.01%	0.42%
500	8.083E-02	0.30%	0.03%	0.09%	0.09%	0.17%	0.01%	0.37%
550	1.141E-01	0.28%	0.02%	0.07%	0.09%	0.15%	0.01%	0.34%
600	1.461E-01	0.26%	0.01%	0.07%	0.09%	0.15%	0.01%	0.32%
650	1.744E-01	0.24%	0.01%	0.07%	0.09%	0.18%	0.01%	0.32%
700	1.972E-01	0.23%	0.01%	0.07%	0.09%	0.15%	0.02%	0.29%
800	2.251E-01	0.21%	0.01%	0.06%	0.09%	0.26%	0.02%	0.35%
900	2.325E-01	0.19%	0.01%	0.06%	0.09%	0.29%	0.01%	0.36%
950	2.304E-01	0.18%	0.01%	0.06%	0.09%	0.30%	0.01%	0.37%
1000	2.256E-01	0.18%	0.01%	0.05%	0.09%	0.29%	0.01%	0.36%
1100	2.102E-01	0.17%	0.01%	0.05%	0.09%	0.40%	0.01%	0.45%
1200	1.905E-01	0.16%	0.01%	0.05%	0.09%	0.39%	0.01%	0.43%
1300	1.703E-01	0.15%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1500	1.326E-01	0.14%	0.01%	0.03%	0.09%	0.38%	0.01%	0.42%
1600	1.161E-01	0.14%	0.01%	0.03%	0.09%	0.32%	0.01%	0.36%
1700	1.013E-01	0.14%	0.01%	0.03%	0.09%	0.36%	0.04%	0.40%
2000	6.797E-02	0.13%	0.01%	0.03%	0.09%	0.30%	0.08%	0.35%
2100	5.972E-02	0.13%	0.01%	0.03%	0.09%	0.59%	0.08%	0.62%
2300	4.600E-02	0.13%	0.01%	0.03%	0.09%	0.66%	0.12%	0.69%
2400	4.060E-02	0.13%	0.01%	0.03%	0.09%	0.70%	0.19%	0.74%
2500	3.633E-02	0.13%	0.01%	0.03%	0.09%	0.63%	0.50%	0.82%

A.2. VNIIOFI measurement data

A.2.1 Reference Number of artifact: BN-9101-440

Current: **8.100 A** Distance: **500.0 mm.** Ambient temperature: 22±1 °C

The lamp was measured independently (after realignment) two times. The spectral irradiance values presented in this table are the average of the two measurements except two wavelengths 1700 nm and 2500 nm, which are closer to the first measurements.

Date of measurement: First 02.06.2008 for spectral range 400 nm to 2500 nm
and 03.06.2008 for spectral range 250 nm to 400 nm

Second 07.06.2008

Wavelength	Spectral Irradiance	Uncertainty (k = 1)	Wavelength	Spectral Irradiance	Uncertainty (k = 1)
nm	W m^{-2} nm^{-1}	%	nm	W m^{-2} nm^{-1}	%
250	2.5071E-04	1.50	650	1.7279E-01	0.29
260	4.2639E-04	1.08	700	1.9563E-01	0.27
270	7.0101E-04	0.90	800	2.2389E-01	0.25
280	1.0850E-03	0.80	900	2.3145E-01	0.23
290	1.6115E-03	0.73	950	2.2958E-01	0.23
300	2.3120E-03	0.68	1000	2.2494E-01	0.22
310	3.2273E-03	0.64	1100	2.1018E-01	0.24
320	4.3758E-03	0.61	1200	1.9123E-01	0.26
330	5.8000E-03	0.58	1300	1.7104E-01	0.26
340	7.5364E-03	0.55	1500	1.3281E-01	0.28
350	9.5812E-03	0.53	1600	1.1641E-01	0.28
360	1.1976E-02	0.51	1700	1.0182E-01	0.30
380	1.7808E-02	0.47	2000	6.8078E-02	0.40
400	2.5132E-02	0.45	2100	5.9432E-02	0.46
450	4.9212E-02	0.40	2300	4.5904E-02	0.62
500	7.9653E-02	0.36	2400	4.0526E-02	0.75
550	1.1272E-01	0.33	2500	3.5917E-02	0.89
600	1.4471E-01	0.31			

A.2.2 Reference Number of artifact: BN-9101-441

Current: **8.100 A** Distance: **500.0 mm.** Ambient temperature: 22±1 °C

The lamp was measured independently (after realignment) three times. The spectral irradiance values presented in this table are the average of the three measurements.

Date of measurement: First 03.06.2008
Second 09.06.2008
Third 10.06.2008 for spectral range 350 nm to 2500 nm
and 11.06.2008 for spectral range 250 nm to 350 nm

Wavelength	Spectral Irradiance	Uncertainty (*k* = 1)	Wavelength	Spectral Irradiance	Uncertainty (*k* = 1)
nm	W m^{-2} nm^{-1}	%	nm	W m^{-2} nm^{-1}	%
250	1.9061E-04	1.50	650	1.5670E-01	0.29
260	3.3386E-04	1.08	700	1.7853E-01	0.27
270	5.5441E-04	0.90	800	2.0629E-01	0.25
280	8.6940E-04	0.80	900	2.1487E-01	0.23
290	1.3006E-03	0.73	950	2.1369E-01	0.23
300	1.8817E-03	0.68	1000	2.0992E-01	0.22
310	2.6452E-03	0.64	1100	1.9697E-01	0.24
320	3.6089E-03	0.61	1200	1.7971E-01	0.26
330	4.8171E-03	0.58	1300	1.6116E-01	0.26
340	6.2817E-03	0.55	1500	1.2563E-01	0.28
350	8.0284E-03	0.53	1600	1.1023E-01	0.28
360	1.0075E-02	0.51	1700	9.6527E-02	0.30
380	1.5136E-02	0.47	2000	6.4633E-02	0.40
400	2.1525E-02	0.45	2100	5.6541E-02	0.46
450	4.2876E-02	0.40	2300	4.3640E-02	0.62
500	7.0339E-02	0.36	2400	3.8624E-02	0.75
550	1.0054E-01	0.33	2500	3.4171E-02	0.89
600	1.3024E-01	0.31			

A.2.3 Reference Number of artifact: BN-9101-442

Current: **8.100 A** Distance: **500.0 mm** Ambient temperature: 22±1 °C

The lamp was measured independently (after realignment) two times. The spectral irradiance values presented in this table are the average of the two measurements.

Date of measurement: First 04.06.2008
Second 09.06.2008 for spectral range 250 nm to 400 nm
and 10.06.2008 for spectral range 400 nm to 2500 nm

Wavelength	Spectral Irradiance	Uncertainty (k = 1)	Wavelength	Spectral Irradiance	Uncertainty (k = 1)
nm	W m^{-2} nm^{-1}	%	nm	W m^{-2} nm^{-1}	%
250	2.5946E-04	1.50	650	1.7393E-01	0.29
260	4.4572E-04	1.08	700	1.9668E-01	0.27
270	7.2918E-04	0.90	800	2.2456E-01	0.25
280	1.1313E-03	0.80	900	2.3185E-01	0.23
290	1.6776E-03	0.73	950	2.2975E-01	0.23
300	2.3984E-03	0.68	1000	2.2505E-01	0.22
310	3.3520E-03	0.64	1100	2.1009E-01	0.24
320	4.5331E-03	0.61	1200	1.9101E-01	0.26
330	5.9880E-03	0.58	1300	1.7079E-01	0.26
340	7.7682E-03	0.55	1500	1.3267E-01	0.28
350	9.8571E-03	0.53	1600	1.1622E-01	0.28
360	1.2295E-02	0.51	1700	1.0173E-01	0.30
380	1.8250E-02	0.47	2000	6.7777E-02	0.40
400	2.5691E-02	0.45	2100	5.9318E-02	0.46
450	5.0092E-02	0.40	2300	4.6033E-02	0.62
500	8.0768E-02	0.36	2400	4.0604E-02	0.75
550	1.1402E-01	0.33	2500	3.5798E-02	0.89
600	1.4593E-01	0.31			

Appendix B. Record of lamp burn hours

B.1. Record of lamp burn hours at KRISS

B.1.1. Reference Number of artifact: BN-9101-440 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage (average) V	Operator initials
				per day	Total		
13/05/2008	11:37	Measurement 250 nm – 2500 nm	17:00	5h23'	5h23'	114.65	DJS
19/05/2008	9:40	Measurement 250 nm – 2500 nm	14:50	5h10'	10h33'	114.79	DJS
23/09/2008	10:30	Measurement 250 nm – 800 nm	15:11	4h41'	19h56'	114.70	DJS
15/12/2008	12:07	Measurement 250 nm – 2500 nm	16:45	4h38'	15h11'	114.89	DJS
24/12/2008	11:07	Measurement 800 nm – 2500 nm	14:25	3h18'	23h14'	114.90	DJS

B.1.2. Reference Number of artifact: BN-9101-441 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage (average) V	Operator initials
				per day	Total		
20/05/2008	8:40	Measurement 250 nm – 2500 nm	16:41	8h01'	8h01'	112.6	DJS
27/05/2008	9:25	Measurement 250 nm – 2500 nm	14:55	7h30'	15h31'	112.5	DJS
16/12/2008	11:02	Measurement 250 nm – 2500 nm	15:34	4h32'	20h03'	113.1	DJS
22/12/2008	12:56	Measurement 250 nm – 2500 nm	17:46	4h50'	24h53'	113.1	DJS

B.1.3. Reference Number of artifact: BN-9101-442 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage (average) V	Operator initials
				per day	Total		
21/05/2008	12:50	Measurement 250 nm – 2500 nm	17:15	4h25'	4h45'	114.7	DJS
26/05/2008	9:30	Measurement 250 nm – 2500 nm	16:25	6h55'	11h40'	114.4	DJS
17/12/2008	11:11	Measurement 250 nm – 2500 nm	15:38	4h27'	16h07'	115.0	DJS
18/12/2008	11:03	Measurement 250 nm – 2500 nm	16:16	5h13'	21h20'	115.0	DJS

B.2. Record of lamp burn hours at VNIIOFI

B.2.1. Reference Number of artifact: BN-9101-440 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage, V	Operator initials
				per day	Total		
02/06/2008	11:40	Measurement 400 nm – 2500 nm	16:25	4h45'	4h45'	114.88	SSK
03/06/2008	8:50	Measurement 250 nm – 400 nm at the same alignment than on 02/06/2008.	11:10	2h20'	7h05'	114.92 114.94	SSK
07/06/2008	10:05	Measurement 250 nm – 2500 nm New alignment	16:45	6h40'	13h45'	115.10 114.97 114.98	SSK

B.2.2 Reference Number of artifact: BN-9101-441 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage, V	Operator initials
				per day	Total		
03/06/2008	11:45	Measurement 250 nm – 2500 nm	17:15	5h30'	5h30'	112.75 112.79	SSK
09/06/2008	9:30	Measurement 250 nm – 2500 nm New alignment	15:30	6h00'	11h30'	113.02 112.99	SSK
10/06/2008	13:20	Measurement 350 nm – 2500 nm New alignment	17:00	3h40'	15h10'	112.98 113.02	SSK
11/06/2008	8:50	Measurement 250 nm – 350 nm at the same alignment than on 10/06/2008.	11:00	2h10'	17h20'	113.01 113.03	SSK

B.2.3 . Reference Number of artifact: BN-9101-442 Current: 8.100 A

Date dd/mm/yyyy	Switch-on Local Time	Activity (Test, Alignment, Measure)	Switch-off Local Time	Burn Hrs		Voltage, V	Operator initials
				per day	Total		
04/06/2008	10:05	Measurement 250 nm – 2500 nm	16:20	6h15'	6h15'	114.71 114.74	SSK
09/06/2008	15:55	Measurement 250 nm – 400 nm New alignment	17:50	1h55'	8h10'	114.84 114.85	SSK
10/06/2008	9:00	Measurement 400 nm – 2500 nm at the same alignment than on 09/06/2008.	13:00	4h00'	12h10'	114.83 114.87	SSK

Appendix C. Unilateral and bilateral DoEs and their uncertainties in bilateral comparison

C.1. Definition of the KCRV and unilateral DoE, and their uncertainties

Definitions of CCPR KCRV, unilateral, and bilateral Degree of Equivalence (DoE) and their uncertainties defined in the CCPR K1.a final report were used in this report to keep the consistency. The symbols and uncertainties described in this report are used according to *Guide to the Expression of Uncertainty in Measurement* (GUM). Even though equations related to uncertainties were not shown in the CCPR K1.a final report, some uncertainty derivations such as the uncertainty of the CCPR KCRV and uncertainties of unilateral and bilateral DoEs are shown here to explain the uncertainty derivation of KRISS DoE obtained from this bilateral comparison. We tried to calculate the KRISS DoE and its uncertainty using only the final results reported in the CCPR K1.a comparison report, such as the unilateral DoE and its uncertainty, and the spectral irradiance measurement uncertainty of the linking NMI (VNIIOFI) available in the CCPR K1.a final report, without further calculations that should have been presented in the final report of the CCPR K1.a comparison, such as the KCRV and its uncertainty, or weights of the linking NMI.

C.1.1. Definition of CCPR KCRV of spectral irradiance in the CCPR K1.a final report and its uncertainty

The CCPR KCRV of the spectral irradiance of the CCPR K1.a comparison was defined for the generalized weighted geometric mean of systematic factors to meet the constraint as Eq (17-26) of the CCPR K1.a final report.

$$\prod_i s_i^{w_i} = 1. \qquad \text{(17-26) of the CCPR K1.a final report}$$

In Eq (17-26), s_i is the value of the systematic factor S_i, which is defined as the ratio of the spectral irradiance measured by the NMI i to the KCRV, expressed as

$$E_i^l = E^l \cdot S_i \qquad \text{(17-3) of the CCPR K1.a final report}$$

where E_i^l is the NMI i measurement scale realization of the spectral irradiance lamp l, and E^l is the spectral irradiance of the lamp that is the CCPR KCRV of the spectral irradiance, X_{ref} of the lamp l. w_i is the weight of the NMI i defined as below.

$$w_i = u^{-2}(x_i)/W \qquad \text{(17-15) of the CCPR K1.a final report}$$

$$W = \sum_j u^{-2}(x_j) \qquad \text{(17-16) of the CCPR K1.a final report}$$

where $u(x_i)$ is the standard uncertainty of the spectral irradiance measurement of the NMI i.

The superscription l is eliminated in the following for simplicity, except for the KCRV to avoid confusion with an exponential function.

Eq (17-26) of in the CCPR K1.a final report can be written as

$$\begin{aligned}\prod_i s_i^{w_i} &= \left(\frac{e_1}{e_l}\right)^{w_1} \cdot \left(\frac{e_2}{e_l}\right)^{w_2} \cdot \cdots \left(\frac{e_n}{e_l}\right)^{w_n} \\ &= \frac{e_1^{w_1} \cdot e_2^{w_2} \cdot \cdots \cdot e_n^{w_n}}{e_l^{w_1+w_2+\cdots+w_n}} \\ &= \frac{e_1^{w_1} \cdot e_2^{w_2} \cdot \cdots \cdot e_n^{w_n}}{e_l} \\ &= 1\end{aligned} \quad . \tag{C1}$$

From Eq (C1), the value of the KCRV $e_l \left(= x_{\text{ref,KC}} \right)$ can be expressed as below.

$$\begin{aligned}e_l &= x_{\text{ref,KC}} \\ &= e_1^{w_1} \cdot e_2^{w_2} \cdot \cdots \cdot e_n^{w_n}\end{aligned} \tag{C2}$$

where $x_{\text{ref,KC}}$ means the value of the KCRV of the spectral irradiance determined by the CCPR K1.a key comparison, and the addition of KC in the subscription is only to show that the value of the KCRV was determined for the lamps used in the key comparison.

The standard uncertainty of the $x_{\text{ref,KC}}$ can be calculated using Eq (C2) and uncertainty propagation law as below.

$$\begin{aligned}u^2\left(x_{\text{ref, KC}}\right) &= \left(\frac{\partial x_{\text{ref, KC}}}{\partial e_1}\right)^2 \cdot u^2(e_1) + \left(\frac{\partial x_{\text{ref, KC}}}{\partial e_2}\right)^2 \cdot u^2(e_2) + \cdots + \left(\frac{\partial x_{\text{ref, KC}}}{\partial e_n}\right)^2 \cdot u^2(e_n) \\ &= x_{\text{ref, KC}}^2 \cdot \left\{ w_1 \cdot \frac{u(e_1)}{e_1} \right\}^2 + x_{\text{ref, KC}}^2 \cdot \left\{ w_2 \cdot \frac{u(e_2)}{e_2} \right\}^2 + \cdots + x_{\text{ref, KC}}^2 \cdot \left\{ w_n \cdot \frac{u(e_n)}{e_n} \right\}^2 \\ &= x_{\text{ref, KC}}^2 \cdot \left\{ w_1 \cdot u_{\text{rel}}^2(e_1) \right\}^2 + x_{\text{ref}}^2 \cdot \left\{ w_2 \cdot u_{\text{rel}}^2(e_2) \right\}^2 + \cdots + x_{\text{ref}}^2 \cdot \left\{ w_n \cdot u_{\text{rel}}^2(e_n) \right\}^2\end{aligned} \quad . \tag{C3}$$

The relative standard uncertainty $u_{\text{rel}}^2\left(x_{\text{ref, KC}}\right)$ is given by Eq (C4).

$$\begin{aligned}u_{\text{rel}}^2\left(x_{\text{ref,KC}}\right) &= \frac{u^2\left(x_{\text{ref,KC}}\right)}{x_{ref}^2} \\ &= w_1^2 \cdot u_{\text{rel}}^2(e_1) + w_2^2 \cdot u_{\text{rel}}^2(e_2) + \cdots + w_n^2 \cdot u_{\text{rel}}^2(e_n)\end{aligned} \quad . \tag{C4}$$

C.1.2. Definition of unilateral DoE in the CCPR K1.a final report and its uncertainty

The unilateral DoE of an NMI i was defined as the difference (expressed as a percentage) between systematic factor S_i and unity in 17.3.2 of the CCPR K1.a final report. In the CCPR K1.a final report, however, the uncertainty associated with lamp instability $u(\delta_i)$ was introduced for the model to matche the data, but the additional uncertainties were not included in the calculation of the KCRV (page 296 of 396 in the CCPR K1.a final report).

Hence, the effect of artifact instability δ_i is added to the uncertainty of each NMI in the calculation of uncertainties of DoEs in the following, but the uncertainty of the KCRV expressed by Eq (C4) is used without a change.

The unilateral DoE of the NMI i was defined by Eq (17-21) of the CCPR K1.a final report.

$D_i = S_i - 1$. (17-21) of the CCPR K1.a final report

It can be expressed as Eq (C5) with the KCRV and the effect of artifact instability,

$$\begin{aligned} d_i &= s_i - 1 \\ &= \left(\frac{e_i \cdot \delta_i}{x_{\text{ref,KC}}} \right) - 1 \end{aligned} \quad \text{(C5)}$$

The standard uncertainty of the unilateral DoE D_i can be derived as below.

$$\begin{aligned} u^2(d_i) &= u^2(s_i) \\ &= u^2\left(\frac{e_i \cdot \delta_i}{x_{\text{ref,KC}}} \right) \\ &= \left(\frac{\partial S_i}{\partial e_1} \right)^2 \cdot u^2(e_1) + \left(\frac{\partial S_i}{\partial e_2} \right)^2 \cdot u^2(e_2) + \cdots + \left(\frac{\partial S_i}{\partial e_i} \right)^2 \cdot u^2(e_i) + \left(\frac{\partial S_i}{\partial \delta_i} \right)^2 \cdot u^2(\delta_i) + \cdots + \left(\frac{\partial S_n}{\partial e_n} \right)^2 \cdot u^2(e_n) \\ &= \frac{e_i^2 \cdot \delta_i^2}{x_{\text{ref,KC}}^2} \cdot \left\{ w_1^2 \cdot u_{\text{rel}}^2(e_1) + \cdots + w_i^2 \cdot u_{\text{rel}}^2(e_i) + \frac{u^2(\delta_i)}{\delta_i^2} + \cdots + w_n^2 \cdot u_{\text{rel}}^2(e_n) \right\} + \frac{(1-2w_i)}{x_{\text{ref,KC}}^2} \cdot u^2(e_i) \\ &= \frac{e_i^2 \cdot \delta_i^2}{x_{\text{ref,KC}}^2} \cdot \left\{ u_{\text{rel}}^2(x_{\text{ref,KC}}) + u_{\text{rel}}^2(\delta_i) \right\} + \frac{(1-2w_i)}{x_{\text{ref}}^2} \cdot u^2(e_i) \\ &= \frac{e_i^2 \cdot \delta_i^2}{x_{\text{ref,KC}}^2} \cdot \left\{ u_{\text{rel}}^2(x_{\text{ref,KC}}) + u_{\text{rel}}^2(\delta_i) + (1-2w_i) \cdot u_{\text{rel}}^2(e_i) \right\} \end{aligned} \quad \text{(C6)}$$

where $u_{\text{rel}}(\delta_i)$ is the relative standard uncertainty associated with lamp instability introduced in the CCPR K1.a final report. Eq (C6) can be expressed with the unilateral DoE and relative standard uncertainties of the KCRV and spectral irradiance measurement of the NMI i as Eq (C7).

$$u^2(d_i) = (1 + d_i)^2 \cdot \left\{ u_{\text{rel}}^2(x_{\text{ref}}) + u_{\text{rel}}^2(\delta_i) + (1-2w_i) \cdot u_{\text{rel}}^2(e_i) \right\}. \quad \text{(C7)}$$

As can be seen in Eq (C6), the uncertainty value of DoE is the absolute value of the uncertainty of the systematic factor (it is $u(s_i)$, not $\frac{u(s_i)}{s_i}$). In other words, it means that the uncertainty of the unilateral DoE is the absolute uncertainty of DoE, not relative one. Even though the uncertainty of the unilateral DoE is usually expressed in percentage similar to a relative uncertainty in the CCPR K1.a final report, it is because the systematic factor is the ratio of the spectral irradiance measured by the NMI i to the KCRV, not because the uncertainty is a relative one. So the uncertainty of DoE should be given by Eq (C7) with DoE value, not only with relative uncertainties of the KCRV and spectral irradiance measurement of the NMI i. The expanded uncertainties(k = 2) of DoEs were given as uncertainties of unilateral DoEs in the CCPR K1.a final report. Therefore, the uncertainty of the unilateral DoE of the NMI i in the CCPR K1.a final report should be the value given by Eq (C8).

$$\begin{aligned} U(d_i) &= 2 \cdot u(d_i) \\ &= 2 \cdot (1 + d_i) \cdot \sqrt{\left\{ u_{\text{rel}}^2(x_{\text{ref}}) + u_{\text{rel}}^2(\delta_i) + (1-2w_i) \cdot u_{\text{rel}}^2(e_i) \right\}} \end{aligned}. \quad \text{(C8)}$$

If the participant NMI i was excluded in the KCRV calculation, then the uncertainty of its DoE should be given by Eq (C9).

$$U(d_i) = 2\cdot(1+d_i)\cdot\sqrt{\left\{u_{\mathrm{rel}}^2(x_{\mathrm{ref}}) + u_{\mathrm{rel}}^2(\delta_i) + u_{\mathrm{rel}}^2(e_i)\right\}}. \tag{C9}$$

C.2. Definition of the bilateral DoE in the CCPR K1.a final report and its uncertainty

The bilateral DoE between two NMIs, i and j, was defined as the Eq (17-30) of the CCPR K1.a final report.

$$D_{ij} = D_i - D_j \quad . \qquad \text{(17-30) of the CCPR K1.a final report}$$

It can be expressed with the KCRV as below.

$$\begin{aligned} d_{ij} &= \frac{e_i\cdot\delta_i}{x_{ref,KC}} - \frac{e_j\cdot\delta_j}{x_{ref,KC}} \\ &= \frac{(e_i - e_j)}{x_{ref,KC}} \\ &= \frac{e_i\cdot\delta_i - e_j\cdot\delta_j}{e_1^{w_1}\cdot e_2^{w_2}\cdots e_i^{w_i}\cdots e_j^{w_i}\cdots e_n^{w_n}} \end{aligned} \quad . \tag{C10}$$

Its standard uncertainty can be derived as below.

$$\begin{aligned} u^2(d_{ij}) =& \left\{\frac{\partial(d_{ij})}{\partial e_1}\right\}^2 u^2(e_1) + \cdots + \left\{\frac{\partial(d_{ij})}{\partial e_i}\right\}^2 u^2(e_i) + \left\{\frac{\partial(d_{ij})}{\partial \delta_i}\right\}^2 u^2(\delta_i) + \cdots + \left\{\frac{\partial(d_{ij})}{\partial e_j}\right\}^2 u^2(e_j) + \left\{\frac{\partial(d_{ij})}{\partial \delta_j}\right\}^2 u^2(\delta_j) \\ & + \cdots + \left\{\frac{\partial(D_{ij})}{\partial e_n}\right\}^2 u^2(e_n) \\ =& \left\{-\frac{(e_i\cdot\delta_i - e_j\cdot\delta_j)}{x_{\mathrm{ref,KC}}}\right\}^2\cdot w_1^2\cdot\frac{u^2(e_1)}{e_1^2} + \cdots + \left\{\frac{\delta_i}{x_{\mathrm{ref,KC}}} - \frac{(e_i\cdot\delta_i - e_j\cdot\delta_j)}{x_{\mathrm{ref,KC}}}\cdot\frac{w_i}{e_i}\right\}^2\cdot u^2(e_i) + \left(\frac{e_i}{x_{\mathrm{ref,KC}}}\right)^2\cdot u^2(\delta_i) + \cdots \\ & + \left\{\left(-\frac{\delta_j}{x_{\mathrm{ref,KC}}}\right) - \frac{(e_i\cdot\delta_i - e_j\cdot\delta_j)}{x_{\mathrm{ref,KC}}}\cdot\frac{w_j}{e_j}\right\}^2\cdot u^2(e_j) + \left(-\frac{e_j}{x_{\mathrm{ref,KC}}}\right)^2\cdot u^2(\delta_j) + \cdots + \left\{-\frac{(e_i\cdot\delta_i - e_j\cdot\delta_j)}{x_{\mathrm{ref,KC}}}\right\}^2\cdot w_n^2\cdot\frac{u^2(e_n)}{e_n^2} \\ =& \frac{e_i^2\cdot\delta_i^2}{x_{\mathrm{ref,KC}}^2}\cdot\left[u_{\mathrm{rel}}^2(x_{\mathrm{ref,KC}}) + u_{\mathrm{rel}}^2(\delta_i) + (1-2\cdot w_i)\cdot u_{\mathrm{rel}}^2(e_i)\right] + \frac{e_j^2\cdot\delta_j^2}{x_{\mathrm{ref}}^2}\cdot\left[u_{\mathrm{rel}}^2(x_{\mathrm{ref,KC}}) + u_{\mathrm{rel}}^2(\delta_j) + (1-2\cdot w_j)\cdot u_{\mathrm{rel}}^2(e_j)\right] \\ & - \frac{e_i\cdot\delta_i\cdot e_j\cdot\delta_j}{x_{\mathrm{ref,KC}}^2}\cdot\left[\left\{u_{\mathrm{rel}}^2(x_{\mathrm{ref,KC}}) + u_{\mathrm{rel}}^2(\delta_i) + (1-2\cdot w_i)\cdot u_{\mathrm{rel}}^2(e_i)\right\} - \left\{u_{\mathrm{rel}}^2(e_i) + u_{\mathrm{rel}}^2(\delta_i)\right\}\right. \\ & \left. + \left\{u_{\mathrm{rel}}^2(x_{\mathrm{ref}}) + u_{\mathrm{rel}}^2(\delta_j) + (1-2\cdot w_j)\cdot u_{\mathrm{rel}}^2(e_j)\right\} - \left\{u_{\mathrm{rel}}^2(e_j) + u_{\mathrm{rel}}^2(\delta_j)\right\}\right] \end{aligned} \quad . \tag{C11}$$

Eq (C11) can be expressed as Eq (C12) with DoEs and their uncertainties of the two NMIs, i and j.

$$\begin{aligned} u^2(d_{ij}) = u^2(d_i) + u^2(d_j) - (1+d_i)\cdot(1+d_j)\cdot & \left[\left\{\frac{u^2(d_i)}{(1+d_i)^2} - \left\{u_{\mathrm{rel}}^2(e_i) + u_{\mathrm{rel}}^2(\delta_i)\right\}\right\}\right. \\ & \left. + \left\{\frac{u^2(d_j)}{(1+d_j)^2} - \left\{u_{\mathrm{rel}}^2(e_j) + u_{\mathrm{rel}}^2(\delta_j)\right\}\right\}\right] \end{aligned} \quad . \tag{C12}$$

The uncertainty of the bilateral DoE can be given by Eq (C13) with the expanded uncertainty listed in the CCPR K1.a final report.

$$U(d_{ij}) = 2\cdot\left\{\frac{U(d_i)}{2}\right\}^2 + \left\{\frac{U(d_j)}{2}\right\}^2 - (1+d_i)\cdot(1+d_j)\cdot\left[\left\{\left(\frac{U(d_i)}{2\cdot(1+d_i)}\right)^2 - \left\{u_{\mathrm{rel}}^2(e_i)+u_{\mathrm{rel}}^2(\delta_i)\right\}\right\} + \left\{\left(\frac{U(d_j)}{2\cdot(1+d_j)}\right)^2 - \left\{u_{\mathrm{rel}}^2(e_j)+u_{\mathrm{rel}}^2(\delta_j)\right\}\right\}\right] \quad \text{(C13)}$$

C.3. Unilateral DoE and its uncertainty of an NMI α linked to the KCRV through the bilateral comparison with a linking NMI i

C.3.1. Definition of unilateral DoE of the linked NMI α

In order for the unilateral DoE of the linked NMI α to have the same definition of unilateral DoE defined in the CCPR K1.a final report, it should be defined as Eq (C14).

$$D_{\alpha(i)} = S_\alpha - 1$$
$$d_{\alpha(i)} = \frac{e_\alpha}{x_{\mathrm{ref,BC}}} - 1 \quad \text{(C14)}$$

where e_α is the spectral irradiance of the transfer lamp measured by the linked NMI α, S_α is the systematic factor of the linked NMI α defined as the ratio between the spectral irradiance measured by the NMI and the KCRV for the lamp. $x_{\mathrm{ref,BC}}$ is equivalent to the KCRV of the spectral irradiance for the transfer standard lamps used in the bilateral comparison; it should be deduced from the DoE of the linking NMI i and the spectral irradiance measured by the linking NMI i at the bilateral comparison; but it does not mean that the KCRV was determined by the bilateral comparison.
The DoE of the linking NMI i given by Eq (C5) can be written as

$$d_i = s_{i,\mathrm{KC}} - 1$$
$$= \frac{e_{i,\mathrm{KC}}\cdot\delta_i}{x_{\mathrm{ref,KC}}} - 1 \quad \text{(C15)}$$

where $e_{i,\mathrm{KC}}$ and $x_{\mathrm{ref,KC}}$ are the same meaning as in Eq (C5). Under the assumption that the systematic factor of the linking NMI i is the same at the CCPR K1.a as at the bilateral comparison, the DoE of the linking NMI i can be expressed as below.

$$d_i = s_{i,\mathrm{BC}} - 1$$
$$= \frac{e_{i,\mathrm{BC}}}{x_{\mathrm{ref,\,BC}}} - 1 \quad . \quad \text{(C16)}$$

From Eq (C15) and Eq (C16), $x_{ref,BC}$ can be expressed as

$$x_{\mathrm{ref,\,BC}} = \frac{e_{i,\mathrm{BC}}}{(1+d_i)}$$
$$= e_{i,\mathrm{BC}}\cdot\frac{x_{\mathrm{ref,\,KC}}}{e_{i,\mathrm{KC}}\cdot\delta_i} \quad \text{(C17)}$$

where $e_{i,\mathrm{BC}}$ is the spectral irradiance of the transfer standard lamp used for the bilateral comparison measured by the linking NMI i.

Using Eq (C14) and (C17), the unilateral DoE of the linked NMI α can be expressed as Eq (C18).

$$\begin{aligned} d_{\alpha(i)} &= \frac{e_\alpha}{x_{\mathrm{ref,BC}}} - 1 \\ &= \frac{e_\alpha}{e_{i,\mathrm{BC}}} \cdot \frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}} - 1 \\ &= r \cdot (1 + d_i) - 1 \end{aligned} \tag{C18}$$

where r is the ratio of the spectral irradiances measured by the linked NMI α to that measured by the linking NMI i for the bilateral comparison.

C.3.2. Uncertainty of the unilateral DoE of the linked NMI α

Uncertainty of the unilateral DoE of the linked NMI α can be calculated using the uncertainty propagation and Eq (C18) as below. Relative standard uncertainties of spectral irradiances measured by the linking NMI i at the CCPR K1.a comparison and at the bilateral comparison might have not only uncertainties associated with random components but also uncertainties associated with correlated components between the two comparisons. In such a case, the uncertainties at both comparisons can be written as Eq (C19).

$$\begin{aligned} u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC}}\right) &= u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,random}}\right) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{correlated}}\right) + u_{\mathrm{rel}}^2\left(\delta_i\right) \\ u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right) &= u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,random}}\right) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{correlated}}\right) \end{aligned} \tag{C19}$$

where $u_{\mathrm{rel}}(\delta_i)$ is the relative standard uncertainty associated with lamp instability introduced in the CCPR K1.a comparison.

In order to evaluate the uncertainty of the linked NMI α, the values of the link NMI measurements is denoted as below.

$$\begin{aligned} e_{i,\mathrm{KC}} &= e_{i,\mathrm{KC,random}} \cdot f_{i,\mathrm{correlated}} \\ &= e_{i,\mathrm{KC,r}} \cdot f_{i,\mathrm{c}} \qquad \text{in the calculation of } x_{\mathrm{ref}} \\ &= e_{i,\mathrm{KC,r}} \cdot f_{i,\mathrm{c}} \cdot \delta_i \qquad \text{in calculations of DoE and its uncertainty} \\ e_{i,\mathrm{BC}} &= e_{i,\mathrm{BC,random}} \cdot f_{i,\mathrm{correlated}} = e_{i,\mathrm{BC,r}} \cdot f_{i,\mathrm{c}} \end{aligned} \tag{C20}$$

where $e_{i,\mathrm{KC,random}}\left(= e_{i,\mathrm{KC,r}}\right)$ and $e_{i,\mathrm{BC,random}}\left(= e_{i,\mathrm{BC,r}}\right)$ are spectral irradiances with uncertainties associated with random components at the CCPR Key comparison and at the bilateral comparison, respectively, and $f_{i,\mathrm{c}}$ is the factor with an uncertainty associated with the correlated components between the two comparisons.

From Eq (C18), the standard uncertainty of the unilateral DoE of the linked NMI α can be given by

$$
\begin{aligned}
u^2\left(d_{\alpha(i)}\right) &= \left\{\left(\frac{\partial d_{\alpha(i)}}{\partial e_1}\right)^2 \cdot u^2(e_1) + \cdots + \left(\frac{\partial d_i}{\partial e_{i,\mathrm{KC,r}}}\right)^2 \cdot u^2\left(e_{i,\mathrm{KC,r}}\right) + \left(\frac{\partial d_i}{\partial f_{i,\mathrm{c}}}\right)^2 \cdot u^2\left(f_{i,\mathrm{c}}\right) + \left(\frac{\partial d_{\alpha(i)}}{\partial \delta_i}\right)^2 \cdot u^2(\delta_i) + \cdots + \left(\frac{\partial d_{\alpha(i)}}{\partial e_n}\right)^2 \cdot u^2(e_n)\right\} \\
&\quad + \left\{\left(\frac{\partial d_{\alpha(i)}}{\partial e_\alpha}\right)^2 \cdot u^2(e_\alpha) + \left(\frac{\partial d_{\alpha(i)}}{\partial e_{i,\mathrm{BC,r}}}\right)^2 \cdot u^2\left(e_{i,\mathrm{BC,r}}\right)\right\} \\
&= \left(r \cdot \frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}} \cdot \frac{w_1}{e_1}\right)^2 \cdot u^2(e_1) + \cdots + r^2 \cdot \delta_i^2 \cdot \left(\frac{f_{i,\mathrm{KC,c}}}{x_{\mathrm{ref,KC}}} - \frac{f_{i,\mathrm{KC,c}} \cdot w_i}{x_{\mathrm{ref,KC}}}\right)^2 \cdot u^2\left(e_{i,\mathrm{KC,r}}\right) + \left(r \cdot \frac{e_{i,\mathrm{KC,r}} \cdot f_{i,\mathrm{KC,c}}}{x_{\mathrm{ref,KC}}}\right)^2 \cdot u^2(\delta_i) \\
&\quad + \left\{- w_i \cdot r \cdot \frac{e_{i,\mathrm{KC,r}} \cdot \delta_i}{x_{\mathrm{ref,KC}}}\right\}^2 \cdot u^2\left(f_{i,\mathrm{c}}\right) + \cdots + \left(r \cdot \frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}} \cdot \frac{w_n}{e_n}\right)^2 \cdot u^2(e_n) + \left(\frac{1}{e_{i,\mathrm{BC,r}} \cdot f_{i,\mathrm{BC,c}}} \cdot \frac{e_{i,\mathrm{KC,r}} \cdot f_{i,\mathrm{KC,c}} \cdot \delta_i}{x_{\mathrm{ref,KC}}}\right)^2 \cdot u^2(e_\alpha) \\
&\quad + \left(-\frac{1}{e_{i,\mathrm{BC,r}}^2} \cdot \frac{e_\alpha}{f_{i,\mathrm{BC,c}}}\right)^2 \cdot \left(\frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}}\right)^2 \cdot u^2\left(e_{i,\mathrm{BC,r}}\right) \\
&= r^2 \cdot \left(\frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}}\right)^2 \cdot \left\{w_1^2 \cdot u_{\mathrm{rel}}^2(e_1) + \cdots + (1-w_i)^2 \cdot u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right) + w_i^2 \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{BC,c}}\right) + \cdots + w_n^2 \cdot u_{\mathrm{rel}}^2(e_n)\right\} \\
&\quad + r^2 \cdot \left(\frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}}\right)^2 \cdot \left\{w_i^2 \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{BC,c}}\right) + u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right) + u_{\mathrm{rel}}^2(\delta_i)\right\} \\
&= r^2 \cdot \left(\frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref}}}\right)^2 \cdot \left\{\left(w_1^2 \cdot u_{\mathrm{rel}}^2(e_1) + w_2^2 \cdot u_{rel}^2(e_2) + \cdots + w_n^2 \cdot u_{\mathrm{rel}}^2(e_n)\right) + u_{\mathrm{rel}}^2(\delta_i) + (1-2w_i) \cdot u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC}}\right)\right\} \\
&\quad + r^2 \cdot \left(\frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref}}}\right)^2 \cdot \left\{u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right) - (1-2w_i) \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{c}}\right)\right\}
\end{aligned}
$$

. ... (C21)

Using Eq (C18), Eq (C21) can be expressed as Eq (C22) with the uncertainty of the unilateral DoE of the linked NMI α and relative standard uncertainties of spectral irradiance measured by both NMIs.

$$
u^2\left(d_{\alpha(i)}\right) = \left(1 + d_{\alpha(i)}\right)^2 \cdot \left\{u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right) + \frac{u^2(d_i)}{(1+d_i)^2} - (1-2w_i) \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{c}}\right)\right\}. \quad \text{(C22)}
$$

The expanded uncertainty $(k = 2)$ of the linked NMI α is given by Eq (C23).

$$
U\left(d_{\alpha(i)}\right) = 2 \cdot \left(1 + d_{\alpha(i)}\right) \cdot \sqrt{u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}} + \left\{\left(\frac{U(d_i)}{2 \cdot (1+d_i)}\right)^2 - (1-2w_i) \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{correlated}}\right)\right\}}. \quad \text{(C23)}
$$

When there is no correlated component between the two comparisons, Eq (C23) becomes

$$
U\left(d_{\alpha(i)}\right) = 2 \cdot \left(1 + d_{\alpha(i)}\right) \cdot \sqrt{u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}} + \left(\frac{U(d_i)}{2 \cdot (1+d_i)}\right)^2}. \quad \text{(C24)}
$$

When the linking NMI i was excluded in the KCRV calculation or its weight was very small, Eq (C23) becomes

$$
U\left(d_{\alpha(i)}\right) = 2 \cdot \left(1 + d_{\alpha(i)}\right) \cdot \sqrt{u_{\mathrm{rel}}^2(e_\alpha) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC}}\right)_{\mathrm{random}} + \left\{\left(\frac{U(d_i)}{2 \cdot (1+d_i)}\right)^2 - u_{\mathrm{rel}}^2\left(f_{i,\mathrm{correlated}}\right)\right\}}. \quad \text{(C25)}
$$

C.4. Bilateral DoE and its uncertainty between the linked NMI α and other NMI j participated in the CCPR K1.a comparison

Bilateral DoE between the NMI α and an NMI j is given by Eq (C26) according to its definition defined in the CCPR K1.a final report.

$$D_{\alpha j} = D_{\alpha(i)} - D_j \quad . \tag{C26}$$

Eq (C26) can be expressed as below using Eq (C18).

$$\begin{aligned} d_{\alpha j} &= r \cdot \frac{e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}} - \frac{e_j \cdot \delta_j}{x_{\mathrm{ref,KC}}} \\ &= \frac{\dfrac{e_\alpha}{e_{i,\mathrm{BC,r}}} \cdot e_{i,\mathrm{KC,r}} \cdot \delta_i - e_j \cdot \delta_j}{e_1^{w_1} \cdot e_2^{w_2} \cdots \left(e_{i,\mathrm{KC,r}} \cdot f_{i,\mathrm{c}}\right)^{w_i} \cdots e_j^{w_j} \cdots e_n^{w_n}} \end{aligned} \quad . \tag{C27}$$

The standard uncertainty of the bilateral DoE can be calculated as below.

$$\begin{aligned} u^2\left(d_{\alpha j}\right) =& \left[\left\{ \frac{\partial\left(d_{\alpha j}\right)}{\partial e_1} \right\}^2 u^2(e_1) + \left\{ \frac{\partial\left(d_{\alpha j}\right)}{\partial e_2} \right\}^2 u^2(e_2) + \cdots + \left\{ \frac{\partial\left(d_{\alpha j}\right)}{\partial e_n} \right\}^2 u^2(e_n) \right]_{i,j \text{ excluded}} + \left(\frac{\partial d_{\alpha j}}{\partial e_{i,KC,r}} \right)^2 \cdot u^2\left(e_{i,\mathrm{KC,r}}\right) \\ & + \left(\frac{\partial d_{\alpha j}}{\partial f_{i,\mathrm{c}}} \right)^2 \cdot u^2\left(f_{i,\mathrm{c}}\right) + \left(\frac{\partial d_{\alpha j}}{\partial \delta_i} \right)^2 \cdot u^2(\delta_i) + \left(\frac{\partial d_{\alpha j}}{\partial e_{i,\mathrm{BC,r}}} \right)^2 \cdot u^2\left(e_{i,\mathrm{BC,r}}\right) + \left(\frac{\partial d_{\alpha j}}{\partial e_j} \right)^2 \cdot u^2\left(e_j\right) + \left(\frac{\partial d_{\alpha j}}{\partial \delta_j} \right)^2 \cdot u^2\left(\delta_j\right) \\ & + \left(\frac{\partial d_{\alpha j}}{\partial e_\alpha} \right)^2 \cdot u^2\left(e_\alpha\right) \\ =& \left(\frac{r \cdot e_{i,\mathrm{KC}} \cdot \delta_i}{x_{\mathrm{ref,KC}}} \right)^2 \cdot \left\{ u_{\mathrm{rel}}^2\left(x_{\mathrm{ref,KC}}\right) + u_{\mathrm{rel}}^2(\delta_i) + (1 - 2w_i) \cdot u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right) + u_{\mathrm{rel}}^2\left(e_\alpha\right) \right\} \\ & + \left(\frac{e_j \cdot \delta_j}{x_{\mathrm{ref,KC}}} \right)^2 \cdot \left\{ u_{\mathrm{rel}}^2\left(x_{\mathrm{ref,KC}}\right) + u_{\mathrm{rel}}^2\left(\delta_j\right) + \left(1 - 2w_j\right) \cdot u_{\mathrm{rel}}^2\left(e_j\right) \right\} \\ & - 2 \frac{r \cdot e_{i,\mathrm{KC}} \cdot \delta_i \cdot e_j \cdot \delta_j}{x_{\mathrm{ref,KC}}^2} \cdot \left\{ u_{\mathrm{rel}}^2\left(x_{\mathrm{ref,KC}}\right) - w_i \cdot u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right) - w_j \cdot u_{\mathrm{rel}}^2\left(e_j\right) \right\} \\ =& u^2\left(d_{\alpha(i)}\right) + u^2\left(d_j\right) \\ & - \frac{r \cdot e_{i,\mathrm{KC}} \cdot \delta_i \cdot e_j \cdot \delta_j}{x_{\mathrm{ref,KC}}^2} \cdot \left[\left\{ \frac{u^2(d_i)}{(1 + d_i)^2} - (1 - 2w_i) \cdot u_{\mathrm{rel}}^2\left(f_{i,\mathrm{c}}\right) - \left\{ u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right) + u_{\mathrm{rel}}^2(\delta_i) \right\} \right\} \right. \\ & \left. + \left\{ \frac{u_l^2\left(d_j\right)}{\left(1 + d_j\right)^2} - \left\{ u_{\mathrm{rel}}^2\left(e_j\right) + u_{\mathrm{rel}}^2\left(\delta_j\right) \right\} \right\} \right] \end{aligned} \quad . \tag{C28}$$

Eq (C28) can be expressed as Eq (C29) with DoEs and their uncertainties, and relative standard uncertainties of spectral irradiance measurements of NMIs.

$$\begin{aligned} u^2\left(d_{\alpha j}\right) =& u^2\left(d_{\alpha(i)}\right) + u^2\left(d_j\right) \\ & - \left(1 + d_{\alpha(i)}\right) \cdot \left(1 + d_j\right) \cdot \left[\left\{ \frac{u^2\left(d_{\alpha(i)}\right)}{\left(1 + d_{\alpha(i)}\right)^2} - \left\{ u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right) + u_{\mathrm{rel}}^2\left(e_\alpha\right) + u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right) + u_{\mathrm{rel}}^2(\delta_i) \right\} \right\} \right. \\ & \left. + \left\{ \frac{u^2\left(d_j\right)}{\left(1 + d_j\right)^2} - \left\{ u_{\mathrm{rel}}^2\left(e_j\right) + u_{\mathrm{rel}}^2\left(\delta_j\right) \right\} \right\} \right] \end{aligned} \quad . \tag{C29}$$

The expanded uncertainty $(k=2)$ of the bilateral DoE is given by Eq (C30) with unilateral DoEs and their uncertainties.

$$U\left(d_{\alpha j}\right)=2\cdot\left[\left(\frac{U\left(d_{\alpha(i)}\right)}{2}\right)^2+\left(\frac{U\left(d_j\right)}{2}\right)^2\right.$$
$$-\left(1+d_{\alpha(i)}\right)\cdot\left(1+d_j\right)\cdot\left(\left\{\left(\frac{U\left(d_{\alpha(i)}\right)}{2\cdot\left(1+d_{\alpha(i)}\right)}\right)^2-\left\{u_{\mathrm{rel}}^2\left(e_{i,\mathrm{BC,r}}\right)+u_{\mathrm{rel}}^2\left(e_\alpha\right)+u_{\mathrm{rel}}^2\left(e_{i,\mathrm{KC,r}}\right)+u_{\mathrm{rel}}^2\left(\delta_i\right)\right\}\right\}\right. \quad . \qquad \text{(C30)}$$
$$\left.\left.+\left\{\left(\frac{U\left(d_j\right)}{2\cdot\left(1+d_j\right)}\right)^2-\left\{u_{\mathrm{rel}}^2\left(e_j\right)+u_{\mathrm{rel}}^2\left(\delta_j\right)\right\}\right\}\right)\right]^{\frac{1}{2}}$$

Appendix D. Unilateral degree of equivalence of KRISS

Unilateral degrees of equivalence of KRISS and their expanded uncertainties (k = 2)

	DoE of KRISS and uncertainties	
Wavelength	**DoE**	***U* (DoE) (*k* = 2)**
250	**-0.2%**	**4.4%**
260	**1.2%**	**3.1%**
270	**0.5%**	**2.6%**
280	**0.7%**	**2.4%**
290	**0.1%**	**2.1%**
300	**0.5%**	**2.0%**
310	**-0.3%**	**2.0%**
320	**0.1%**	**1.9%**
330	**0.0%**	**1.7%**
340	**0.0%**	**1.6%**
350	**0.3%**	**1.5%**
360	**0.5%**	**1.4%**
380	**0.7%**	**1.4%**
400	**0.4%**	**1.3%**
450	**0.2%**	**1.3%**
500	**0.4%**	**1.2%**
550	**0.4%**	**1.1%**
600	**0.3%**	**1.1%**
650	**0.4%**	**1.0%**
700	**0.5%**	**1.0%**
800	**0.8%**	**1.1%**
900	**1.0%**	**1.0%**
950	**1.0%**	**1.1%**
1000	**1.1%**	**1.1%**
1100	**1.3%**	**1.3%**
1200	**1.1%**	**1.3%**
1300	**1.2%**	**1.2%**
1500	**1.4%**	**1.3%**
1600	**1.4%**	**1.5%**
1700	**1.0%**	**1.6%**
2000	**1.6%**	**1.8%**
2100	**2.2%**	**2.2%**
2300	**1.4%**	**2.5%**
2400	**1.7%**	**3.4%**
2500	**2.5%**	**3.7%**