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Final Report on the EURAMET.PR-K1.a-2009 Comparison of Spectral Irradiance 250 nm - 2500 nm

TERESA GOODMAN[1], WILLIAM SERVANTES[1], EMMA WOOLLIAMS[1], PETER SPERFELD[2], MIHAI SIMIONESCU[3], PETER BLATTNER[4], STEFAN KÄLLBERG[5], BORIS KHLEVNOY[6], PAUL DEKKER[7]

1 National Physical Laboratory (NPL), UK
2 Physikalisch-Technische Bundesanstalt (PTB), Germany
3 National Institute of Metrology of Romania (INM-RO), Romania
4 Federal Office of Metrology (METAS), Switzerland
5 SP Technical Research Institute of Sweden (SP), Sweden
6 All Russian Institute for Optical and Physical Measurements (VNIIOFI), Russia
7 VSL Dutch Metrology Institute (VSL), The Netherlands

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Final Report on the EURAMET.PR-K1.a-2009 Comparison of Spectral Irradiance 250 nm to 2500 nm

Teresa Goodman[1], William Servantes[1], Emma Woolliams[1],
Peter Sperfeld[2], Mihai Simionescu[3], Peter Blattner[4], Stefan Källberg[5],
Boris Khlevnoy[6], Paul Dekker[7]

1 National Physical Laboratory (NPL), UK
2 Physikalisch-Technische Bundesanstalt (PTB), Germany
3 National Institute of Metrology of Romania (INM-RO), Romania
4 Federal Office of Metrology (METAS), Switzerland
5 SP Technical Research Institute of Sweden (SP), Sweden
6 All Russian Institute for Optical and Physical Measurements (VNIIOFI), Russia
7 VSL Dutch Metrology Institute (VSL), The Netherlands

ABSTRACT

This report gives the results of the EURAMET.PR-K1.a-2009 Comparison of Spectral Irradiance over the wavelength range 250 nm - 2500 nm. Seven laboratories took part, including the pilot. In general the results are consistent, with a few exceptions as explained in the report.

The EURAMET.PR-K1.a Key Comparison detailed in this report was carried out to establish the degrees of equivalence for the participating European laboratories with respect to the Key Comparison Reference Value (KCRV) of the CCPR-K1.a Key Comparison. The EURAMET.PR-K1.a Key Comparison was piloted by the National Physical Laboratory (NPL), who also acted as pilot for the CCPR-K1.a Key Comparison; a further linkage to the KCRV of

the CCPR-K1.a Key Comparison was provided through the participation of the Physikalisch-Technische Bundesanstalt (PTB) in both comparisons. The other participants were: National Institute of Metrology of Romania (INM-RO), Federal Office of Metrology (METAS), SP Technical Research Institute of Sweden (SP), All Russian Institute for Optical and Physical Measurements (VNIIOFI) and VSL Dutch Metrology Institute (VSL).

Measurements were made by each laboratory at 44 designated wavelengths, or a subset of these wavelengths. The link laboratories made measurements at all 44 wavelengths. For the purposes of analysis each wavelength has been treated independently, as for the CCPR K1.a comparison.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by Stephanie Bell, Science Area Leader

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1. INTRODUCTION

The Mutual Recognition Arrangement (MRA) was signed in 1999 with the objectives of establishing the degree of equivalence of national measurement standards and providing for the mutual recognition of calibration and measurement certificates issued by National Metrology Institutes (NMIs). Under the MRA the equivalence of national measurement standards maintained by the NMIs is determined by a set of Key Comparisons which are chosen and organised by the Consultative Committees of the International Committee for Weights and Measures (CIPM), working closely with the Regional Metrology Organisations (RMOs). The Consultative Committee for Photometry and Radiometry (CCPR) identified several Key Comparisons at its meeting in March 1997. One of these was the CCPR Key Comparison K1.a for spectral irradiance in the spectral region 250 nm to 2500 nm, which was carried out between 2000 and 2005 and published in January 2006 [1].

The EURAMET.PR-K1.a Key Comparison detailed in this report was carried out to establish the degrees of equivalence for the participating European laboratories with respect to the Key Comparison Reference Value (KCRV) of the CCPR-K1.a Key Comparison. The EURAMET.PR-K1.a Key Comparison was piloted by the National Physical Laboratory (NPL), who also acted as pilot for the CCPR-K1.a Key Comparison; a further linkage to the KCRV of the CCPR-K1.a Key Comparison was provided through the participation of the Physikalisch-Technische Bundesanstalt (PTB) in both comparisons. The All Russian Institute for Optical and Physical Measurements (VNIIOFI) was also a participant in both comparisons, but did not act as a link laboratory since a new scale had been realised at this laboratory since the original (CCPR) comparison.

The Pre-Draft A report for the comparison was circulated for review by participants in July 2012 and all responses to the small number of issues arising from the report were received by the coordinator by the end of January 2013. The review by participants covered the following points, as laid out in the CCPR guidelines for the preparation of comparison reports (Pre-Draft A stage):

- Review of uncertainty budgets
- Review of relative data
- Review and approval of method to be used for analysis of results and linkage to CCPR K1.a Key Comparison.

Each participant was also sent (in parallel with the Pre-Draft A report) a copy of their individual reported values as received by the pilot, for verification and correction of any errors.

Following the circulation of the Pre-Draft A report and individual reported values, a small number of corrections were made to the data and uncertainties, following identification of errors. In addition, one laboratory decided to withdraw from the comparison, as a result of equipment failure, and another participant withdrew results for one lamp, due to significant inconsistency with the results for their other two lamps. These changes are detailed in the Appendix.

The Draft A report was circulated to participants in November 2013 and the final version was agreed in February 2014. As a result of the comparison, Technical Research Institute of Sweden (SP) identified an error their measurements: the wrong reference plane was used when setting the distance for the intercomparison lamps. This problem was identified after the Draft A report had been issued and therefore the results given in this report (including the DoE values for SP) have not been corrected for this error, although it is mentioned in all relevant parts of the report.

2. ORGANISATION

2.1 PARTICIPANTS

Table 1. Participants' details

	Contact person	Institute	Contact details	Short version
Pilot	Teresa Goodman and William Servantes	**National Physical Laboratory** Hampton Road Middlesex TW11 0LW United Kingdom	+44 20 8943 6863 teresa.goodman@npl.co.uk and william.servantes@npl.co.uk	NPL
Additional link to CCPR	Peter Sperfeld and Sven Pape	**Physikalisch-Technische Bundesanstalt** 4.11 Spectroradiometry Bundesallee 100 D 38116 Braunschweig Germany	+49 531 592 4144 Peter.Sperfeld@ptb.de and Sven.pape@ptb.de	PTB
Participants	Mihai Simionescu	**National Institute of Metrology of Romania** Vitan Barzesti Street, Nr. 11 Sector IV Bucharest Romania	+4021 334 50 60 mihai.simionescu@inm.ro metrologia_ro@yahoo.com	INM-RO
	Peter Blattner	**Federal Office of Metrology** *Correspondence:* Lindenweg 50 3003 Bern-Wabern Switzerland *Shipment:* Lindenweg 50 3084 Wabern Switzerland	+41 31 32 33 340 peter.blattner@metas.ch	METAS
	Stefan Källberg	**SP Technical Research Institute of Sweden** Brinellgatan 4 504 62 BORÅS Sweden	+46105165626 Stefan.kallberg@sp.se	SP
	Boris Khlevnoy	**All Russian Institute for Optical and Physical Measurements** Ozernaya 46 119361 Moscow Russia	+7 495 437 29 88 Khlevnoy-m4@vniiofi.ru	VNIIOFI
	Paul Dekker	**VSL Dutch Metrology Institute** Thijsseweg 11 2629 JA Delft The Netherlands	+31 15 2691500 PDekker@vsl.nl	VSL

An additional participant, the Laboratory for Photometry of the Directorate of Measures and Precious Metals (DMDM), Serbia, had originally planned to take part but withdrew from the comparison due to technical problems.

2.2 FORM OF COMPARISON

The form of the comparison, and the link to the CCPR comparison, are shown in Figure 1. Like the CCPR comparison, the EURAMET comparison was organised as a star comparison, with each participant measuring a different set of three lamps and the pilot laboratory, NPL, measuring all the lamps. Measurements were taken in the sequence Participant – Pilot – Participant.

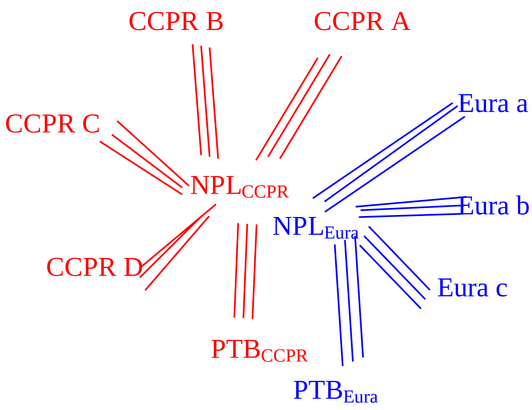

Figure 1. Star-arrangement of the comparison. The lines represent different lamps. The two link laboratories, PTB and NPL are shown twice to exaggerate and emphasise that there may be drift in the measurement scale of each laboratory since the CCPR comparison.

The pilot (NPL) and one participant (PTB) acted as link laboratories to the CCPR comparison. Four lamps were measured to provide this linkage, two of which had also been used in the CCPR comparison. Several years have passed since the CCPR comparison and in that time both laboratories have moved into new buildings and upgraded their measurement facilities. As a result both NMIs have new uncertainty budgets. NPL has a systematic offset in spectral irradiance scales between the two comparisons, the magnitude of which has been determined at each wavelength, within a known uncertainty, by independent experiments. PTB's scale has been validated to have been stable with respect to their uncertainties (see also Section 4).

Measurements were made by each laboratory at 44 designated wavelengths, or a subset of these wavelengths. The link laboratories made measurements at all 44 wavelengths. For the purposes of analysis each wavelength has been treated independently, as for the CCPR K1.a comparison.

3. ANALYSIS APPROACH

3.1 PURPOSE OF THE ANALYSIS

The purpose of the analysis is to provide unilateral Degrees of Equivalence (DoEs) between each participant in the EURAMET comparison and the defined Key Comparison Reference Value (KCRV) of the CCPR comparison. These DoEs must be consistent with the measured values obtained during the two comparisons. A linkage between the comparisons is provided by NPL, the pilot laboratory in both comparisons, and PTB, a participant in both comparisons.

3.2 THE ANALYSIS MODEL USED FOR THE COMPARISON

For the purposes of analysis, the comparison can be considered as a series of bilateral comparisons between the pilot (NPL) and the participant, with each wavelength being treated independently. The results of each bilateral comparison are then linked to the KCRV (established during the CCPR comparison) through the measurements of the two link laboratories, so that unilateral DoEs can be determined.

The spectral irradiance assigned by NMI i to lamp j at wavelength λ during measurement round r is $X_{i,j,r}(\lambda)$. In the absence of lamp drift, the results from each measurement round can be averaged to give

$X_{i,j}(\lambda)$. These measured values differ from the 'true' spectral irradiance of this lamp at this wavelength, $E_j(\lambda)$ due to:

- The systematic scale offset factor $S_i(\lambda)$ for NMI i at wavelength λ, which can also be expressed as $1+D_i(\lambda)$ where $D_i(\lambda)$ is the unilateral DoE for that NMI at that wavelength. The value of $D_i(\lambda)$ is nominally zero and (provided uncertainties have been fully evaluated) will be smaller than the stated uncertainty of that NMI at that wavelength.
- Random effects that occur during the measurements by NMI i at wavelength λ, particularly lamp reproducibility but also including other random influences such as the stability of the lamp current during measurement. These effects are described by the multiplicative factor $R_i(\lambda)$, which has the value one at all wavelengths and an associated uncertainty $u_{R,i}(\lambda)$, which is the stated random uncertainty for NMI i as a function of wavelength.

Thus, written mathematically, the measurement equation for a single participant's measurement of lamp j (averaged over both measurement rounds) is:

$$X_{i,j}(\lambda) = E_j(\lambda) \cdot S_i(\lambda) \cdot R_i(\lambda) \quad (1)$$

The aim of the comparison is to determine the systematic factors $S_i(\lambda)$, and hence $D_i(\lambda)$, for each participant NMI in a way that is consistent with the KCRV of the CCPR comparison.

The link to the CCPR comparison comes through the two link laboratories, NPL and PTB. As for the participant NMIs, the values measured by the link laboratories differ from the 'true' spectral irradiance values due to systematic scale offset effects and random effects. For these laboratories, however, prior information regarding the magnitude of the scale offset is available from the CCPR comparison results. The CCPR comparison defined the unilateral DoE, $D_{i,\text{CCPR}}(\lambda)$, of each link laboratory from the systematic scale offset factor determined during the comparison, $S_{i,\text{CCPR}}(\lambda)$:

$$D_{i,\text{CCPR}}(\lambda) = S_{i,\text{CCPR}}(\lambda) - 1 \quad (2)$$

A multiplicative factor, $C_i(\lambda)$, can be introduced to allow for any change in the scale of the link laboratories★ since the CCPR comparison, so that the systematic factor for the EURAMET comparison, $S_{i,\text{EU}}(\lambda)$, can be related to the systematic factor for the CCPR comparison, through:

$$S_{i,\text{EU}}(\lambda) = S_{i,\text{CCPR}}(\lambda) \cdot C_i(\lambda) \quad (3)$$

Note that $C_i(\lambda)$, and its associated uncertainty, has been determined experimentally by the two link laboratories through their own measurements. Section 4 provides the values for $C_i(\lambda)$ and discusses tests performed during this comparison to confirm the validity of these values and the associated uncertainties.

Thus the measurement equation for each of the link laboratories is:

$$X_{i,j}(\lambda) = E_j(\lambda) \cdot S_{i,\text{CCPR}}(\lambda) \cdot C_i(\lambda) \cdot R_i(\lambda) \quad (4)$$

The pilot laboratory, NPL, measured all of the lamps used in this comparison. Assuming that there is no change in the spectral irradiance of each lamp during the course of the comparison# (beyond that accounted for by random variations), we have the relationship:

★ See Section 4 for further detail. In practice, it is known that NPL's scale has changed, by a known amount and with a corresponding known uncertainty at each measurement point. For PTB there is no scale change, confirmed within the corresponding measurement uncertainty.

If analysis of the results for any lamp indicates a change in spectral irradiance during the comparison, this can be allowed for through an additional multiplicative factor. However this proved to be unnecessary (see Section 5).

$$E_j(\lambda) = \frac{x_{i,j}(\lambda)}{S_i(\lambda)\cdot R_i(\lambda)} = \frac{x_{\mathrm{NPL},j}(\lambda)}{S_{\mathrm{NPL,CCPR}}(\lambda)\cdot C_{\mathrm{NPL}}(\lambda)\cdot R_{\mathrm{NPL}}(\lambda)} \tag{5}$$

or

$$S_i(\lambda) = \frac{x_{i,j}(\lambda)}{x_{\mathrm{NPL},j}(\lambda)}\cdot S_{\mathrm{NPL,CCPR}}(\lambda)\cdot C_{\mathrm{NPL}}(\lambda)\cdot\frac{R_{\mathrm{NPL}}(\lambda)}{R_i(\lambda)} \tag{6}$$

This enables the scale offset factor for NMI i to be directly determined. The second link laboratory, PTB, did not measure any of the other participants' lamps. Thus it is not possible to establish a direct relationship between PTB and the participants in the same way as for NPL. However the 4 lamps measured by NPL and PTB allow a 'link factor', $F(\lambda)$, to be calculated, given by:

$$F(\lambda) = \frac{\bar{X}_{\mathrm{NPL}}(\lambda)}{\bar{X}_{\mathrm{PTB}}(\lambda)} \tag{7}$$

where $\bar{X}_{\mathrm{PTB}}(\lambda)$ represents the mean measurement of the 4 lamps by PTB and $\bar{X}_{\mathrm{NPL}}(\lambda)$ is the mean measurement of the 4 lamps by NPL. This factor can be applied to Equation 6 to obtain the scale offset factors for participant laboratory i, $S_i'(\lambda)$, that would have been obtained if PTB had measured all lamps i.e.

$$S_i'(\lambda) = F(\lambda)\cdot\frac{x_{i,j}(\lambda)}{x_{\mathrm{NPL},j}(\lambda)}\cdot S_{\mathrm{PTB,CCPR}}(\lambda)\cdot C_{\mathrm{PTB}}(\lambda)\cdot\frac{R_{\mathrm{PTB}}(\lambda)}{R_i(\lambda)} \tag{8}$$

The weighted mean of these 2 scale factors is given by Equation 9 below; subtracting one from this mean factor allows the unilateral DoE for participant i to be determined, using both link laboratories.

$$\bar{S}_i(\lambda) = \frac{x_{i,j}(\lambda)}{x_{\mathrm{NPL},j}(\lambda)\cdot R_i(\lambda)}\cdot[w_{NPL}(\lambda)\cdot S_{\mathrm{NPL,CCPR}}(\lambda)\cdot C_{\mathrm{NPL}}(\lambda)\cdot R_{\mathrm{NPL}}(\lambda) + w_{\mathrm{PTB}}(\lambda)\cdot F(\lambda)\cdot S_{\mathrm{PTB,CCPR}}(\lambda)\cdot C_{\mathrm{PTB}}(\lambda)\cdot R_{\mathrm{PTB}}(\lambda)] \tag{9}$$

where $w_{\mathrm{NPL}}(\lambda)$ and $w_{\mathrm{PTB}}(\lambda)$ are the weights assigned to NPL and PTB respectively. The weights are proportional to the inverse square of the uncertainty associated with the quality of the link provided by each laboratory to the CCPR KCRV and are subject to the constraint $w_{\mathrm{NPL}}(\lambda) + w_{\mathrm{PTB}}(\lambda) = 1$. The quality of the link depends on the random effects for the CCPR and EURAMET comparisons and the scale stability factor $C_i(\lambda)$. Thus the uncertainty associated with the quality of the link provided by NPL, $u_{\mathrm{NPL,link}}(\lambda)$, is given by:

$$u^2_{\mathrm{NPL,link}}(\lambda) = u^2_{\mathrm{NPL,R,CCPR}}(\lambda) + u^2_{\mathrm{NPL,R,EUR}}(\lambda) + u^2_{\mathrm{C,NPL}}(\lambda) \tag{10}$$

The value of the link factor, $F(\lambda)$, also provides a check on how well the results from this EURAMET comparison agree with those from the CCPR comparison for the two link laboratories. If the two comparisons are consistent with one another, then the value of $F(\lambda)$ should differ from the bilateral DoE for NPL compared with PTB determined during the CCPR-K1.a comparison (after making due allowance for the known change in NPL's scale) by less than the combined random measurement uncertainty for NPL and PTB. If this condition is satisfied, then this confirms that neither NPL's nor PTB's scale has changed relative to the other since the CCPR comparison (except for the known change in NPL's scale), within the random uncertainties associated with each scale. This is discussed further in Section 4.3.

3.3 UNCERTAINTIES ASSOCIATED WITH THE COMPARISON

The standard uncertainty associated with the unilateral DoE for each participant, $u(D_i(\lambda))$, is determined from the uncertainties associated with each element in Equation 9 and can be expressed as follows:

$$u^2(D_i(\lambda)) = [u_i^2(\lambda)]$$
$$+[u_{\mathrm{K}}^2(\lambda) + w_{\mathrm{NPL}}^2(\lambda)\cdot u_{\mathrm{NPL,R,CCPR}}^2(\lambda) + w_{\mathrm{PTB}}^2(\lambda)\cdot u_{\mathrm{PTB,R,CCPR}}^2(\lambda) + u_{\mathrm{T,CCPR}}^2(\lambda)]$$
$$+[w_{\mathrm{NPL}}^2(\lambda)\cdot u_{\mathrm{C,NPL}}^2(\lambda) + w_{\mathrm{PTB}}^2(\lambda)\cdot u_{\mathrm{C,PTB}}^2(\lambda)]$$
$$+[w_{\mathrm{NPL}}^2(\lambda)\cdot u_{\mathrm{NPL,R,EU}}^2(\lambda) + w_{\mathrm{PTB}}^2(\lambda)\cdot u_{\mathrm{PTB,R,EU}}^2(\lambda) + u_{\mathrm{T,EU}}^2(\lambda)] \quad (11)$$

The full derivation of this expression is not given here. It was determined following the approach described in Appendix A of [2], making adjustments to account for the fact that NPL was the pilot laboratory for both comparisons. Note that this has been simplified to ignore the correlation between the KCRV and the systematic factors of NPL and PTB (a simplification that slightly changes the weight for the term $u_{\mathrm{T,CCPR}}^2$) and the correlation introduced by the use of the link factor $F(\lambda)$ in Equation 9; these simplifications lead to a slight over-estimation of the uncertainty associated with the DoE values, but by an insignificant amount (<0.05 %).

The analysis also ignores correlations due to traceability (if applicable) between participants in this comparison and participants in the CCPR comparison, and hence the uncertainty associated with the DoE is slightly over-estimated for those cases (see Appendices for details of traceability routes for individual participants). Unlike the CCPR comparison, this EURAMET comparison is effectively analysed as a series of independent bilateral comparisons between individual participants and the link laboratories. Additionally, the KCRV is that of the CCPR comparison and is not calculated for the EURAMET comparison participants. This means that correlations between EURAMET-only participants are not important. Correlations caused by a participant obtaining traceability from one of the link laboratories (or any other participant of the CCPR comparison) do have a small effect, but only for the participant involved and not for others. The effect is small because it only involves stable systematic effects, not random or transfer effects, and is further reduced by the fact that there are two laboratories providing the link to the CCPR KCRV. In principle, participants obtaining traceability from one of the link laboratories would be expected to obtain a value closer to the KCRV than otherwise, and therefore the uncertainty associated with the DoE should be (marginally) reduced. However, it is standard practice to treat scales as independent and to test them as independent scales, which is the approach taken for this comparison.

There are four principle components to the uncertainty calculation, indicated by the square brackets in Equation 11:

a) Uncertainties associated with non-link laboratory measurement results

- $u_i(\lambda)$ is the declared total relative standard uncertainty of the participant laboratory for a single lamp i.e. it is the uncertainty associated with $X_{i,j}(\lambda)$ in Equation 9. This includes uncertainties due to both correlated (systematic) and uncorrelated (random) effects for that participant laboratory.

b) Key comparison effects

- $u_{\mathrm{K}}(\lambda)$ is the relative standard uncertainty associated with the KCRV, as given in the CCPR-K1.a report.
- $w_{\mathrm{NPL}}(\lambda)$ and $w_{\mathrm{PTB}}(\lambda)$ are the weights assigned to the measurements made by the link laboratories (NPL or PTB) determined as described previously (see Section 3.2).

- $u_{\mathrm{NPL,R,CCPR}}(\lambda)$ and $u_{\mathrm{PTB,R,CCPR}}(\lambda)$ are the relative standard uncertainties associated with uncorrelated effects (random uncertainty) for the link laboratories (NPL or PTB) during the CCPR-K1.a comparison, as given in the CCPR-K1.a report.
- $u_{\mathrm{T,CCPR}}(\lambda)$ is the relative transfer uncertainty from the CCPR-K1.a comparison, i.e. it is the lamp instability factor determined during the CCPR-K1.a comparison, as given in the CCPR-K1.a report.

Note that these four contributions together give the uncertainties associated with $[S_{\mathrm{NPL,CCPR}}(\lambda)/X_{\mathrm{NPL}}(\lambda)]$ and $[F(\lambda)\cdot S_{\mathrm{PTB,CCPR}}(\lambda)/X_{\mathrm{NPL}}(\lambda)]$ in Equation 9. They are tabulated in Table 2 below.

c) Linking quality

- $u_{\mathrm{C,NPL}}(\lambda)$ and $u_{\mathrm{C,PTB}}(\lambda)$ are the relative standard uncertainties associated with the factors $C_{\mathrm{NPL}}(\lambda)$ and $C_{\mathrm{PTB}}(\lambda)$ respectively in Equation 9, which allow for the change in the scales maintained by the link laboratories (NPL or PTB) since the CCPR-K1.a comparison, as detailed in Section 4 and tabulated in Tables 11 and 17.

d) Bilateral comparison effects

- $u_{\mathrm{NPL,R,EU}}(\lambda)$ and $u_{\mathrm{PTB,R,EU}}(\lambda)$ are the relative standard uncertainties associated with uncorrelated effects (random uncertainty) of the link laboratories (NPL or PTB) during the EURAMET comparison, as detailed in Sections 6 and 7, i.e. they are the uncertainties associated with $R_{\mathrm{NPL}}(\lambda)$ and $R_{\mathrm{PTB}}(\lambda)$ in Equation 9.
- $u_{\mathrm{T,EU}}(\lambda)$ is relative transfer uncertainty associated with the EURAMET comparison, i.e. it is the lamp instability factor determined during this comparison, as discussed in Section 5. This is essentially also the uncertainty associated with $R_i(\lambda)$ in Equation 9, excluding those components (such as lamp power supply stability) which are specific to each individual laboratory and are included in the participant laboratory measurement uncertainty $u_i(\lambda)$ or in the random uncertainties of the link laboratories, $u_{\mathrm{NPL,R,EU}}(\lambda)$ and $u_{\mathrm{PTB,R,EU}}(\lambda)$.

Table 2. Uncertainties arising from CCPR-K1.a Key Comparison effects

Wavelength / nm	KCRV uncertainty (k = 1)	NPL weight	PTB weight	NPL uncorrelated CCPR-K1.a (k = 1)	PTB uncorrelated CCPR-K1.a (k = 1)	CCPR lamp instability factor (k = 1)
250	0.43 %	0.271	0.729	0.77 %	0.58 %	0.40 %
260	0.36 %	0.276	0.724	0.77 %	0.57 %	0.24 %
270	0.34 %	0.273	0.727	0.78 %	0.57 %	0.16 %
280	0.32 %	0.291	0.709	0.78 %	0.56 %	0.27 %
290	0.30 %	0.294	0.706	0.78 %	0.56 %	0.25 %
300	0.26 %	0.308	0.692	0.78 %	0.56 %	0.26 %
310	0.24 %	0.242	0.758	0.78 %	0.47 %	0.30 %
320	0.23 %	0.232	0.768	0.82 %	0.47 %	0.27 %
330	0.22 %	0.233	0.767	0.86 %	0.47 %	0.24 %
340	0.22 %	0.238	0.762	0.82 %	0.47 %	0.23 %
350	0.21 %	0.225	0.775	0.78 %	0.47 %	0.22 %
360	0.21 %	0.189	0.811	0.16 %	0.40 %	0.20 %
370	0.21 %	0.179	0.821	0.22 %	0.40 %	0.19 %
380	0.21 %	0.176	0.824	0.21 %	0.40 %	0.18 %
390	0.21 %	0.175	0.825	0.22 %	0.40 %	0.17 %
400	0.19 %	0.178	0.822	0.18 %	0.40 %	0.18 %
450	0.15 %	0.351	0.649	0.17 %	0.35 %	0.22 %
500	0.15 %	0.371	0.629	0.17 %	0.33 %	0.20 %
550	0.14 %	0.380	0.620	0.16 %	0.33 %	0.20 %
555	0.14 %	0.380	0.620	0.16 %	0.33 %	0.20 %

Wavelength / nm	KCRV uncertainty (k = 1)	NPL weight	PTB weight	NPL uncorrelated CCPR-K1.a (k = 1)	PTB uncorrelated CCPR-K1.a (k = 1)	CCPR lamp instability factor (k = 1)
600	0.14 %	0.385	0.615	0.11 %	0.33 %	0.18 %
650	0.14 %	0.417	0.583	0.12 %	0.35 %	0.16 %
700	0.14 %	0.423	0.577	0.14 %	0.35 %	0.14 %
750	0.12 %	0.426	0.574	0.12 %	0.35 %	0.13 %
800	0.12 %	0.428	0.572	0.11 %	0.36 %	0.13 %
850	0.12 %	0.536	0.464	0.10 %	0.28 %	0.18 %
900	0.10 %	0.543	0.457	0.12 %	0.28 %	0.14 %
950	0.12 %	0.569	0.431	0.13 %	0.28 %	0.15 %
1000	0.12 %	0.574	0.426	0.12 %	0.28 %	0.14 %
1100	0.15 %	0.719	0.281	0.15 %	0.43 %	0.11 %
1200	0.17 %	0.722	0.278	0.26 %	0.43 %	0.09 %
1300	0.17 %	0.740	0.260	0.20 %	0.43 %	0.09 %
1400	0.22 %	0.724	0.276	0.65 %	1.00 %	0.11 %
1500	0.23 %	0.953	0.047	0.22 %	1.00 %	0.10 %
1600	0.24 %	0.958	0.042	0.28 %	1.00 %	0.08 %
1700	0.26 %	0.820	0.180	0.39 %	1.00 %	0.05 %
1800	0.28 %	0.814	0.186	0.36 %	1.00 %	0.09 %
1900	0.29 %	0.814	0.186	0.41 %	1.02 %	0.15 %
2000	0.27 %	0.794	0.206	0.49 %	1.02 %	0.16 %
2100	0.29 %	0.818	0.182	0.38 %	1.21 %	0.14 %
2200	0.30 %	0.833	0.167	0.39 %	1.22 %	0.07 %
2300	0.29 %	0.828	0.172	0.42 %	1.21 %	0.00 %
2400	0.36 %	0.807	0.193	0.51 %	1.19 %	0.00 %
2500	0.39 %	0.841	0.159	0.41 %	1.21 %	0.30 %

4. STABILITY OF LINK LABORATORY SCALES

NPL and PTB provide the link to the CCPR comparison. Equations 6 and 8 give the link between the scale factor determined for the participant laboratory during this EURAMET comparison and the scale factor determined for NPL or PTB respectively during the CCPR comparison. The quality of the link is dependent on the knowledge of $C_i(\lambda)$, the multiplicative 'scale change term' for each link laboratory and thus the uncertainty associated with this term must be well known. Note that in the case of NPL, where there is a known change in scale since the CCPR comparison that is allowed for by $C_{\mathrm{NPL}}(\lambda)$, the link to the CCPR comparison is through the NPL_{2003} scale.

4.1 STABILITY OF NPL SCALE

NPL upgraded the SRIPS★ facility between 2003 and 2010 (see Section A.1 for further details), leading to a systematic change in the NPL spectral irradiance scale. The magnitude of this change was determined using 10 reference lamps (3 Polaron type and 7 FEL type) which were measured in 2003, or shortly afterwards, and again in 2010/2011. The results for the individual lamps, and for the mean of all 10 lamps, are given in Figure 2. There is a spread of values around the mean, as shown by the standard deviation of the differences between 2003 and 2010 values in Figure 3 for all lamps (red curve), FEL lamps only (blue) and Polaron lamps only (green). Figure 3 also shows the 'expected standard deviation from the uncertainty budget' (purple curve). This is determined by combining in quadrature the three standard uncertainties associated with:

- random effects for the 2010 scale
- random effects for the 2003 scale

★ Spectral radiance and irradiance primary scales facility – the facility used for realisation of the primary spectral irradiance scale at NPL.

- the 'artefact stability factor' introduced for the CCPR-K1.a comparison.

Systematic effects are ignored since they are, by definition, common for all lamps and are the origin of the systematic offset shown by the mean curve in Figure 2.

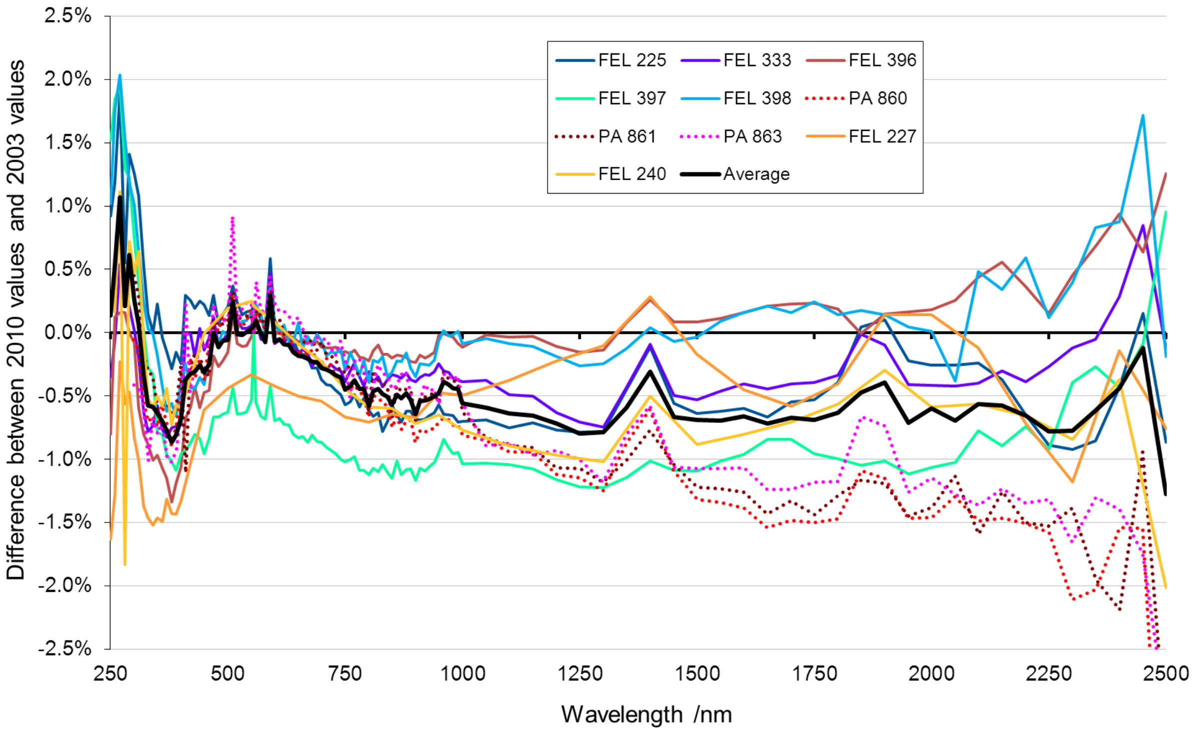

Figure 2. Difference between spectral irradiance values assigned by NPL in 2003 and 2010, and mean difference for all lamps.

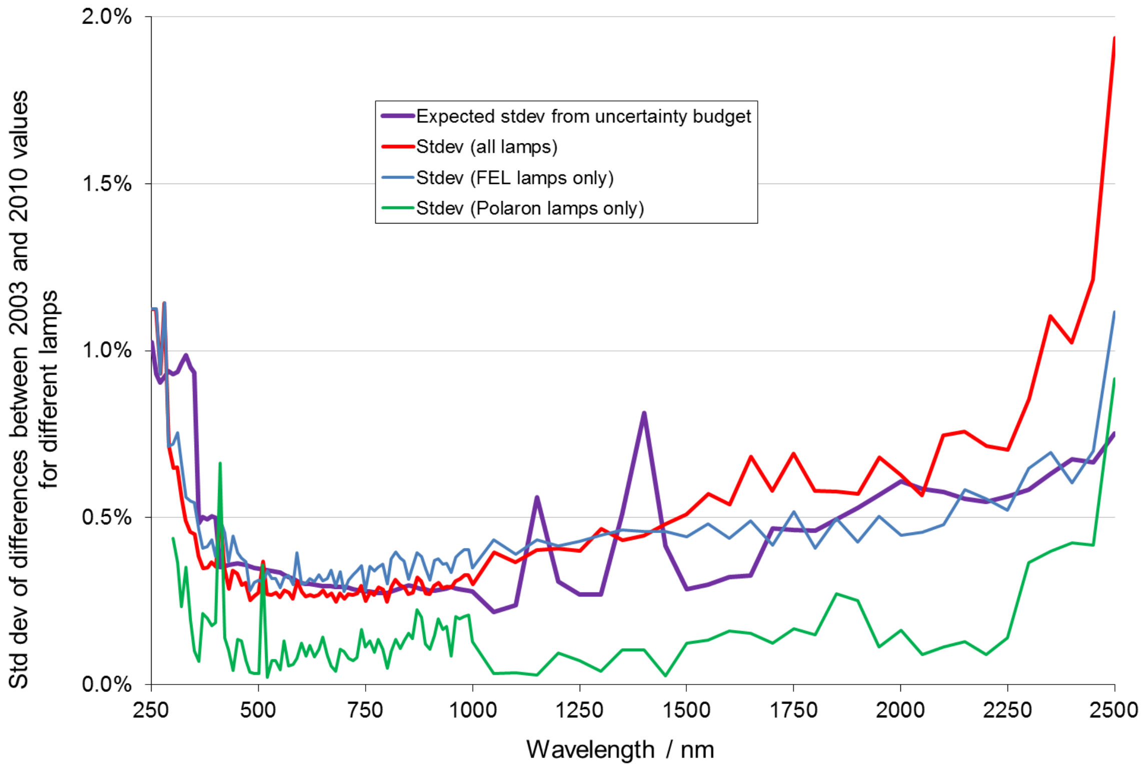

Figure 3. Standard deviation (red) and expected standard deviation (blue) of the results for different lamps in Figure 2.

Figure 3 shows that in the UV and visible spectral regions there is good agreement between the observed and expected standard deviations. In the IR the agreement between all lamps is reasonable, but not quite as good as expected. However if the FEL lamps and the Polaron lamps are analysed separately, the standard deviations of each type are seen to be in line with the expected standard deviations. Detailed examination indicates that the increased standard deviation when all lamps are included is due to a systematic difference between the two types of lamp as measured on SRIPS in 2003; this systematic difference is fully accounted for in the uncertainty budgets.

For the purposes of the EURAMET.PR-K1.a comparison, $C_{NPL}(\lambda)$ is given by the mean (black) curve in Figure 2 and its associated uncertainty $u_{C,NPL}(\lambda)$ is given by the higher value (on a wavelength-by-wavelength basis) of the two curves in Figure 3, divided by the square root of the number of lamps used to obtain this curve. The values for $C_{NPL}(\lambda)$ and $u_{C,NPL}(\lambda)$ are tabulated in Table 11 (Section A.1.1).

4.2 STABILITY OF PTB SCALE

PTB has several reference standard lamps that were measured in 2002, as part of the CCPR-K1.a comparison, and that have been remeasured on an annual basis since 2006. PTB have observed no noticeable systematic drift from year to year. The differences between the measurements made in any subsequent year and the 2002 data are random, with a standard deviation that is well within the uncertainty associated with a single measurement (see Figure 4 for example).

Therefore the best estimate of $C_{PTB}(\lambda)$ is $C_{PTB}(\lambda) = 1$. The associated uncertainty in $C_{PTB}(\lambda)$, $u_{C,PTB}(\lambda)$ is taken to be given by the uncertainty arising from random (uncorrelated) effects for any individual measurement at PTB – see Table 17 in Section A.2.4.

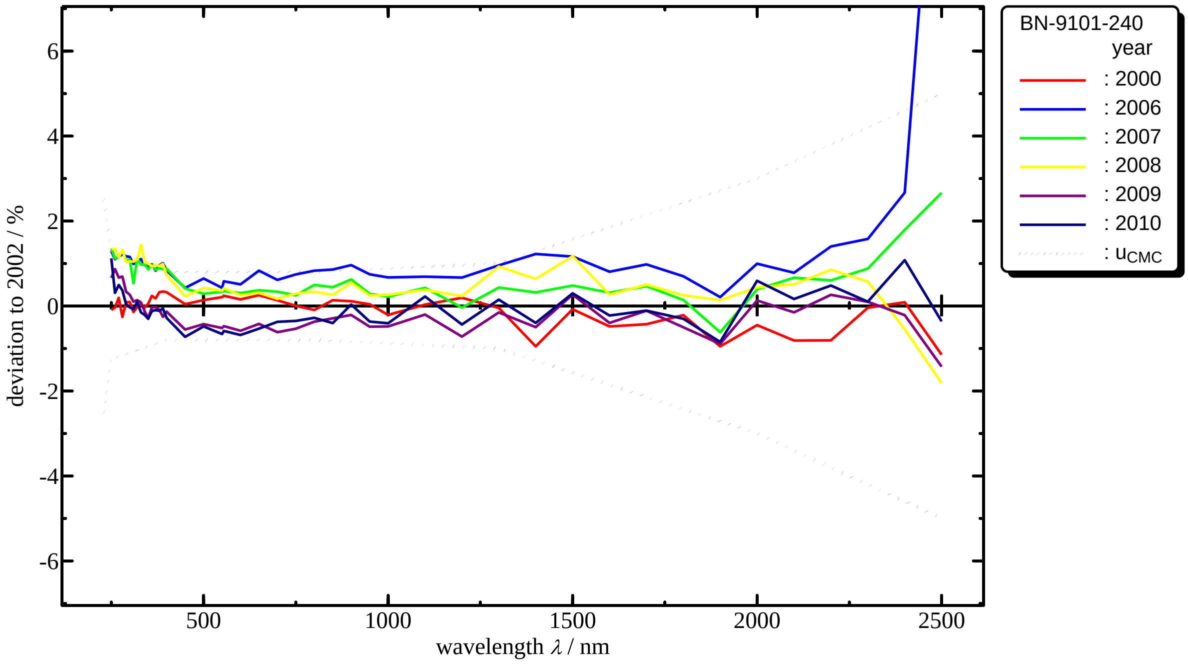

Figure 4. Exemplary validation of independent spectral irradiance realizations compared to the 2002 measurements (CCPR K1.a): Repeated calibration of lamp BN-9101-240.

4.3 TESTING THE STABILITY OF THE NPL AND PTB SCALES

During the EURAMET.PR-K1.a comparison, four lamps were measured by both PTB and NPL. Two of these lamps were also measured by both NMIs during the CCPR-K1.a comparison. There are two valuable ways to analyse these data, both of which are discussed below (Sections 4.3.1 and 4.3.2):

1. In terms of a bilateral comparison between PTB and NPL, comparing the results with the bilateral agreement between PTB and NPL from the CCPR-K1.a comparison.
2. In terms of the agreement between the absolute values assigned by NPL and PTB in the EURAMET comparison and those assigned by these two laboratories to the same lamps in the CCPR-K1.a comparison.

As well as testing the quality of the link of the EURAMET.PR-K1.a to the CCPR-K1.a comparison, these tests also provide a means by which to confirm the reliability of the estimate of $C_{NPL}(\lambda)$ and can be used to provide the DoE for the NPL_{2010} scale by reference to the KCRV of the CCPR-K1.a comparison.

Note that although the CCPR guidelines for Pre-Draft A reports emphasise that no information must be given that enables the absolute level of agreement between participant laboratories to be determined, in the case of the link laboratories in regional comparisons this level of agreement was already known (from the associated CCPR comparison). Since the stability of this agreement for the link laboratories between the CCPR and regional comparison was critical in ensuring the quality of the link to the CCPR comparison, it was decided that it was appropriate, and permissible, to give this information in the Pre-Draft A report; this was therefore done.

4.3.1 NPL-PTB bilateral

Figure 5 shows the results of analysing the data from the four lamps as a bilateral between NPL and PTB and comparing the results of this bilateral with the expected difference, as determined from the CCPR-K1.a comparison. If $\bar{X}_{\mathrm{NPL,EU}}(\lambda)$ and $\bar{X}_{\mathrm{PTB,EU}}(\lambda)$ are the means of the irradiance values assigned by NPL and PTB respectively to the lamps in the EURAMET comparison, and $\bar{X}_{\mathrm{NPL,CCPR}}(\lambda)$ and $\bar{X}_{\mathrm{PTB,CCPR}}(\lambda)$ are the means of the irradiance values assigned by NPL and PTB respectively to the lamps in the CCPR comparison, then Figure 5 presents:

- Green curve: $\bar{X}_{\mathrm{NPL,EU}}(\lambda)/\bar{X}_{\mathrm{PTB,EU}}(\lambda)$ (Note this is the link factor $F(\lambda)$ defined in Equation 7.)
- Blue curve: $[\bar{X}_{\mathrm{NPL,CCPR}}(\lambda) \cdot C_{\mathrm{NPL}}(\lambda)]/[\bar{X}_{\mathrm{PTB,CCPR}}(\lambda) \cdot C_{\mathrm{PTB}}(\lambda)]$ (Note this is the bilateral agreement between NPL and PTB from the CCPR comparison, corrected for the change in the NPL scale since that comparison.)
- Black dotted curves: associated uncertainty i.e. the quadrature sum of the random uncertainties for NPL and PTB and the CCPR comparison artefact stability factor (all at k=1).

If the change in the NPL scale, as described by $C_{NPL}(\lambda)$, is the only cause of the change in the difference between NPL and PTB in the EURAMET comparison and that in the CCPR comparison, then the green and blue curves in Figure 5 should agree within the random uncertainties, i.e. the difference between the two curves should be smaller than the limits indicted by the black dotted curves. This difference is plotted in Figure 6 and confirms that (except at the shortest wavelengths where it appears the uncertainties may have been underestimated) the agreement between the NPL and PTB scales determined during the EURAMET comparison is as expected on the basis of the results of the CCPR-K1.a comparison.

The fact that the bilateral DoE values for the two comparisons differ by less than the combined random measurement uncertainty provides confirmation that the two comparisons are consistent with one another. Thus NPL and PTB can be considered equivalent as comparison links; the best link to the CCPR comparison is provided by using data from both link laboratories, as described in Section 3.2. Furthermore, this analysis confirms that the values determined by NPL for the change in the NPL spectral irradiance scale between 2003 and 2010, $C_{NPL}(\lambda)$, are consistent with the expected results, and are therefore reliable.

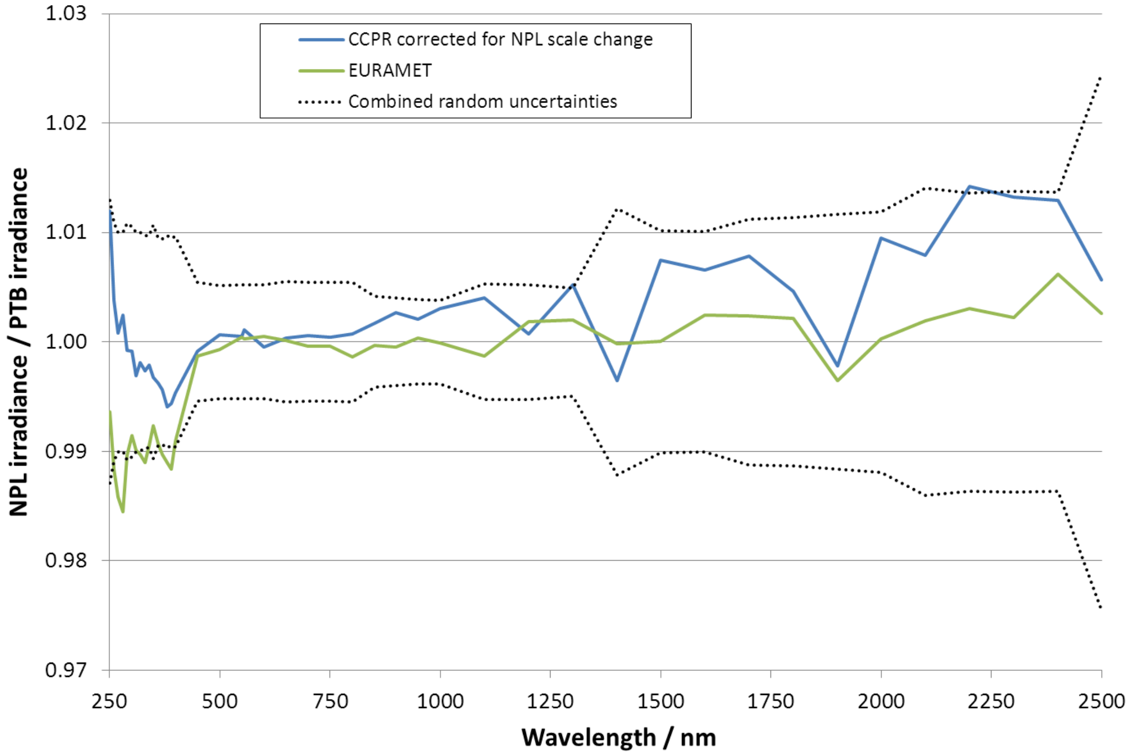

Figure 5. Bilateral agreement between NPL and PTB, as determined from EURAMET.PR-K1.a comparison results (green curve) and from CCPR-K1.a comparison after allowing for the subsequent change in the NPL scale (blue curve). Black dotted curve is combined random effects (*k*=1).

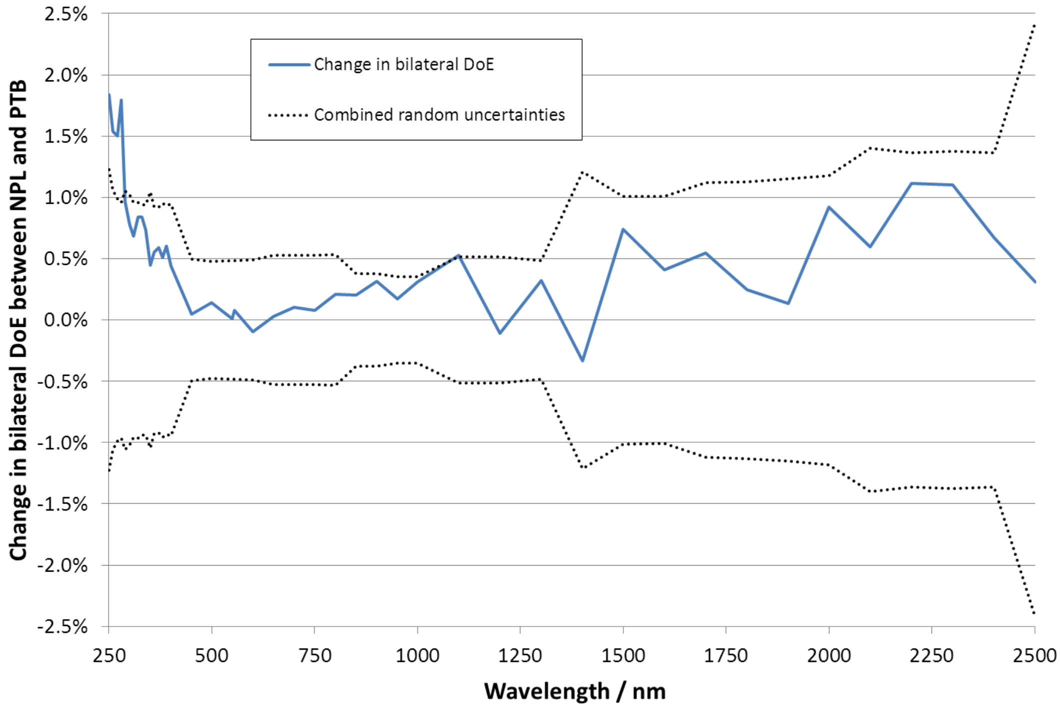

Figure 6. Change in bilateral agreement between NPL and PTB, after allowing for the known change in the NPL scale. Black dotted curve is combined random effects (*k*=1).

4.3.2 Absolute irradiance values

Two lamps, FEL 227 and FEL 240, were measured by both NPL and PTB during the course of both the CCPR-K1.a and EURAMET.PR-K1.a comparisons. Figure 7 shows the ratios of the absolute spectral irradiance values assigned by each laboratory to each of these lamps during each comparison, allowing for the known shift in the NPL scale. The black dotted curve shows the quadrature sum of the random uncertainties for NPL and PTB and the artefact stability factor determined during the CCPR comparison (all standard uncertainties, i.e. k=1).

Figure 7 indicates that the absolute values assigned by each laboratory to FEL lamps 227 and 240 have not changed significantly (by more than the combined random effects) between the two comparisons, after allowing for the known change in the NPL scale. This is not an unexpected conclusion, based on the fact that the level of agreement between NPL and PTB has not changed between the two comparisons (see Section 4.3.1). However it also serves to exclude the (remote) possibility that the scales maintained by NPL and PTB have drifted between the two comparisons by a similar, but unsuspected, amount. In other words, Figure 7 confirms the stability of the NPL_{2003} and PTB spectral irradiance scales and validates the quality of the link provided by these two NMIs to the KCRV of the CCPR-K1.a comparison.

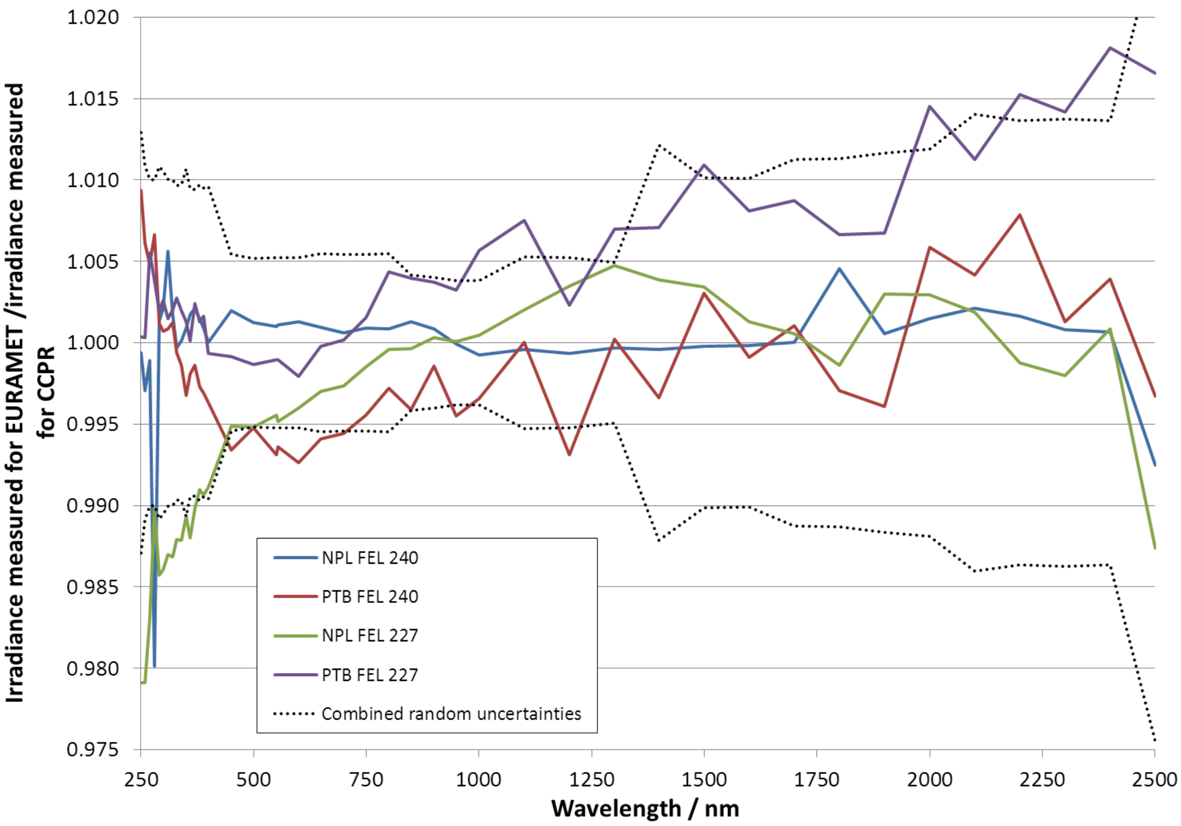

Figure 7. Ratio of spectral irradiance values assigned by NPL and PTB to FEL lamps 227 and 240 in both comparisons, allowing for the known change in the NPL scale. Black dotted curve is combined random effects (k=1).

5. RESULTS OF ANALYSIS OF PARTICIPANT DATA

The results of the measurements carried out by each participant NMI have been analysed in terms of:

1. The absolute results for each participant.

2. The stability of the lamps for each participant before and after transportation to the pilot laboratory (NPL).
3. The internal consistency of all the lamps measured at each participant's laboratory.
4. The resultant unilateral degrees of equivalence.

Results for each participant are given in Sections 5.1 to 5.6. Absolute results for each lamp, as measured by the participant and the pilot (NPL), are presented in both tabular and graphical form; the NPL results are as measured against the 2010 scale. The stability of the lamps was evaluated by calculating the ratios between the values assigned to each lamp by the relevant participant before transport to NPL and the values assigned on their return to the participant laboratory. The internal consistency of the lamps measured by each participant was determined by calculating the ratios between the values assigned to each lamp by the relevant participant to the values assigned to the same lamp by the pilot, and normalising these values to the mean participant-to-pilot ratio for all the lamps measured by that participant i.e. by plotting:

$$Z_{i,j} - Z_i \quad (12)$$

where

$$Z_{i,j} = \frac{x_{i,j}}{x_{\mathrm{NPL},j}} \quad (13)$$

and Z_i is the mean value of $Z_{i,j}$ for all the lamps measured by that participant.

Graphs showing the stability and internal consistency of the lamps are presented for each participant (including the second link laboratory, PTB). Where combined uncertainties are shown, these are based on the information provided by the participants and the uncertainty budget for the pilot (NPL), and also include the (random / uncorrelated) artefact stability factor introduced during the CCPR-K1.a comparison. The results show that in most cases the bilateral ratios (NPL-to-participant) for each individual lamp agree well (i.e. to within the combined random uncertainties) with the mean ratio for that participant. This suggests that there is no need to introduce an additional 'artefact stability factor' for this comparison; the factor determined for during the CCPR-K1.a comparison appears to apply for this comparison also.

The resultant unilateral DoE values and associated uncertainties are presented in Section 5.7 and show the degrees of equivalence between the spectral irradiance scales for each participant and the CCPR-K1.a KCRV. DoE values and uncertainties are also given for the NPL_{2010} scale in this Section.

5.1 RESULTS FOR PTB, GERMANY

PTB, Germany, made measurements over the full wavelength range. Four lamps were measured, three in the sequence NPL-PTB-NPL-PTB and the fourth in the sequence PTB-NPL-PTB. There is no evidence of any significant drift in any of the lamps during the course of the comparison and the consistency between lamps is good.

Table 3. Absolute results for PTB, Germany

LAMP FEL 196			
Wavelength / nm	**PTB Run 1**	**NPL**	**PTB Run 2**
250	1.297E-04	1.277E-04	1.288E-04
260	2.283E-04	2.244E-04	2.270E-04
270	3.838E-04	3.758E-04	3.804E-04
280	6.073E-04	5.948E-04	6.031E-04

LAMP FEL 196			
Wavelength / nm	**PTB Run 1**	**NPL**	**PTB Run 2**
290	9.216E-04	9.052E-04	9.180E-04
300	1.349E-03	1.332E-03	1.344E-03
310	1.917E-03	1.889E-03	1.910E-03
320	2.647E-03	2.606E-03	2.638E-03
330	3.569E-03	3.506E-03	3.553E-03
340	4.701E-03	4.631E-03	4.684E-03
350	6.063E-03	5.998E-03	6.053E-03
360	7.688E-03	7.572E-03	7.651E-03
370	9.581E-03	9.429E-03	9.555E-03
380	1.176E-02	1.157E-02	1.174E-02
390	1.422E-02	1.398E-02	1.422E-02
400	1.698E-02	1.671E-02	1.691E-02
450	3.490E-02	3.462E-02	3.479E-02
500	5.875E-02	5.843E-02	5.863E-02
550	8.580E-02	8.541E-02	8.547E-02
555	8.858E-02	8.820E-02	8.835E-02
600	1.130E-01	1.126E-01	1.128E-01
650	1.383E-01	1.376E-01	1.378E-01
700	1.592E-01	1.586E-01	1.592E-01
750	1.758E-01	1.751E-01	1.757E-01
800	1.873E-01	1.866E-01	1.873E-01
850	1.946E-01	1.937E-01	1.940E-01
900	1.975E-01	1.968E-01	1.975E-01
950	1.974E-01	1.968E-01	1.972E-01
1000	1.944E-01	1.941E-01	1.948E-01
1100	1.834E-01	1.827E-01	1.834E-01
1200	1.671E-01	1.673E-01	1.677E-01
1300	1.501E-01	1.504E-01	1.504E-01
1400	1.346E-01	1.342E-01	1.341E-01
1500	1.177E-01	1.175E-01	1.178E-01
1600	1.030E-01	1.031E-01	1.030E-01
1700	9.015E-02	9.010E-02	9.009E-02
1800	7.887E-02	7.881E-02	7.884E-02
1900	6.962E-02	6.916E-02	6.930E-02
2000	6.036E-02	6.017E-02	6.021E-02
2100	5.269E-02	5.276E-02	5.273E-02
2200	4.640E-02	4.629E-02	4.631E-02
2300	4.068E-02	4.064E-02	4.074E-02
2400	3.571E-02	3.597E-02	3.598E-02
2500	3.129E-02	3.158E-02	3.153E-02

LAMP FEL 197				
Wavelength / nm	**NPL run 1**	**PTB Run 1**	**NPL run 2**	**PTB Run 2**
250	1.251E-04	1.263E-04	1.251E-04	1.256E-04
260	2.199E-04	2.225E-04	2.198E-04	2.213E-04
270	3.678E-04	3.727E-04	3.664E-04	3.712E-04
280	5.798E-04	5.879E-04	5.779E-04	5.863E-04
290	8.861E-04	8.947E-04	8.855E-04	8.925E-04
300	1.300E-03	1.311E-03	1.298E-03	1.308E-03
310	1.850E-03	1.872E-03	1.850E-03	1.864E-03
320	2.543E-03	2.569E-03	2.538E-03	2.563E-03
330	3.424E-03	3.457E-03	3.419E-03	3.451E-03
340	4.517E-03	4.553E-03	4.502E-03	4.543E-03
350	5.845E-03	5.870E-03	5.822E-03	5.871E-03
360	7.383E-03	7.443E-03	7.376E-03	7.436E-03
370	9.196E-03	9.275E-03	9.186E-03	9.253E-03
380	1.127E-02	1.136E-02	1.126E-02	1.137E-02
390	1.363E-02	1.376E-02	1.363E-02	1.376E-02
400	1.630E-02	1.641E-02	1.627E-02	1.637E-02
450	3.371E-02	3.371E-02	3.371E-02	3.363E-02
500	5.683E-02	5.680E-02	5.681E-02	5.666E-02
550	8.296E-02	8.290E-02	8.296E-02	8.270E-02
555	8.563E-02	8.553E-02	8.562E-02	8.542E-02
600	1.095E-01	1.091E-01	1.094E-01	1.091E-01
650	1.336E-01	1.334E-01	1.336E-01	1.332E-01
700	1.540E-01	1.539E-01	1.541E-01	1.539E-01
750	1.700E-01	1.697E-01	1.700E-01	1.697E-01
800	1.811E-01	1.812E-01	1.814E-01	1.810E-01
850	1.884E-01	1.880E-01	1.879E-01	1.880E-01
900	1.913E-01	1.910E-01	1.913E-01	1.911E-01
950	1.913E-01	1.908E-01	1.913E-01	1.909E-01
1000	1.886E-01	1.880E-01	1.884E-01	1.882E-01
1100	1.777E-01	1.771E-01	1.776E-01	1.779E-01
1200	1.627E-01	1.618E-01	1.625E-01	1.621E-01
1300	1.462E-01	1.454E-01	1.460E-01	1.456E-01
1400	1.305E-01	1.302E-01	1.300E-01	1.299E-01
1500	1.142E-01	1.140E-01	1.142E-01	1.139E-01
1600	1.001E-01	9.971E-02	1.002E-01	9.974E-02
1700	8.768E-02	8.718E-02	8.757E-02	8.724E-02
1800	7.663E-02	7.628E-02	7.664E-02	7.639E-02
1900	6.725E-02	6.737E-02	6.719E-02	6.729E-02
2000	5.854E-02	5.836E-02	5.857E-02	5.836E-02
2100	5.135E-02	5.097E-02	5.124E-02	5.113E-02
2200	4.503E-02	4.474E-02	4.509E-02	4.470E-02
2300	3.957E-02	3.932E-02	3.942E-02	3.948E-02
2400	3.492E-02	3.434E-02	3.486E-02	3.411E-02
2500	3.075E-02	2.999E-02	3.065E-02	2.958E-02

LAMP FEL 227				
Wavelength / nm	**NPL run 1**	**PTB Run 1**	**NPL run 2**	**PTB Run 2**
250	1.281E-04	1.297E-04	1.286E-04	1.285E-04
260	2.248E-04	2.294E-04	2.255E-04	2.274E-04
270	3.771E-04	3.849E-04	3.771E-04	3.837E-04
280	5.964E-04	6.089E-04	5.979E-04	6.062E-04
290	9.097E-04	9.239E-04	9.099E-04	9.216E-04
300	1.333E-03	1.354E-03	1.334E-03	1.351E-03
310	1.895E-03	1.926E-03	1.900E-03	1.920E-03
320	2.614E-03	2.657E-03	2.618E-03	2.650E-03
330	3.524E-03	3.586E-03	3.527E-03	3.572E-03
340	4.644E-03	4.721E-03	4.652E-03	4.706E-03
350	6.000E-03	6.088E-03	6.016E-03	6.085E-03
360	7.600E-03	7.721E-03	7.597E-03	7.697E-03
370	9.484E-03	9.623E-03	9.467E-03	9.619E-03
380	1.162E-02	1.180E-02	1.163E-02	1.180E-02
390	1.404E-02	1.428E-02	1.407E-02	1.427E-02
400	1.677E-02	1.704E-02	1.682E-02	1.698E-02
450	3.478E-02	3.501E-02	3.485E-02	3.494E-02
500	5.853E-02	5.887E-02	5.866E-02	5.879E-02
550	8.549E-02	8.597E-02	8.566E-02	8.582E-02
555	8.824E-02	8.868E-02	8.838E-02	8.859E-02
600	1.126E-01	1.132E-01	1.127E-01	1.129E-01
650	1.375E-01	1.384E-01	1.378E-01	1.379E-01
700	1.587E-01	1.594E-01	1.588E-01	1.592E-01
750	1.750E-01	1.759E-01	1.753E-01	1.760E-01
800	1.866E-01	1.877E-01	1.870E-01	1.880E-01
850	1.938E-01	1.950E-01	1.940E-01	1.947E-01
900	1.968E-01	1.979E-01	1.972E-01	1.977E-01
950	1.970E-01	1.978E-01	1.972E-01	1.980E-01
1000	1.940E-01	1.949E-01	1.942E-01	1.954E-01
1100	1.828E-01	1.838E-01	1.831E-01	1.843E-01
1200	1.674E-01	1.677E-01	1.676E-01	1.682E-01
1300	1.504E-01	1.508E-01	1.506E-01	1.510E-01
1400	1.340E-01	1.349E-01	1.342E-01	1.352E-01
1500	1.176E-01	1.183E-01	1.177E-01	1.182E-01
1600	1.030E-01	1.034E-01	1.033E-01	1.034E-01
1700	9.015E-02	9.048E-02	9.035E-02	9.050E-02
1800	7.889E-02	7.921E-02	7.868E-02	7.937E-02
1900	6.917E-02	6.980E-02	6.933E-02	7.001E-02
2000	6.033E-02	6.053E-02	6.037E-02	6.067E-02
2100	5.279E-02	5.306E-02	5.289E-02	5.315E-02
2200	4.632E-02	4.653E-02	4.634E-02	4.633E-02
2300	4.069E-02	4.088E-02	4.083E-02	4.079E-02
2400	3.590E-02	3.604E-02	3.602E-02	3.642E-02
2500	3.162E-02	3.181E-02	3.081E-02	3.206E-02

LAMP FEL 240				
Wavelength / nm	**NPL run 1**	**PTB Run 1**	**NPL run 2**	**PTB Run 2**
250	1.696E-04	1.700E-04	1.702E-04	1.708E-04
260	2.936E-04	2.982E-04	2.956E-04	2.965E-04
270	4.878E-04	4.934E-04	4.885E-04	4.926E-04
280	7.454E-04	7.590E-04	7.490E-04	7.565E-04
290	1.157E-03	1.166E-03	1.161E-03	1.163E-03
300	1.684E-03	1.696E-03	1.690E-03	1.691E-03
310	2.388E-03	2.406E-03	2.395E-03	2.402E-03
320	3.261E-03	3.280E-03	3.266E-03	3.279E-03
330	4.355E-03	4.389E-03	4.363E-03	4.378E-03
340	5.705E-03	5.742E-03	5.729E-03	5.736E-03
350	7.335E-03	7.366E-03	7.356E-03	7.364E-03
360	9.240E-03	9.300E-03	9.287E-03	9.292E-03
370	1.147E-02	1.154E-02	1.149E-02	1.153E-02
380	1.396E-02	1.407E-02	1.402E-02	1.407E-02
390	1.683E-02	1.692E-02	1.685E-02	1.695E-02
400	2.000E-02	2.013E-02	2.005E-02	2.010E-02
450	4.064E-02	4.057E-02	4.073E-02	4.050E-02
500	6.742E-02	6.725E-02	6.751E-02	6.721E-02
550	9.726E-02	9.684E-02	9.735E-02	9.671E-02
555	1.002E-01	9.986E-02	1.005E-01	9.975E-02
600	1.268E-01	1.263E-01	1.270E-01	1.261E-01
650	1.534E-01	1.530E-01	1.537E-01	1.528E-01
700	1.757E-01	1.748E-01	1.759E-01	1.752E-01
750	1.925E-01	1.917E-01	1.928E-01	1.920E-01
800	2.041E-01	2.034E-01	2.043E-01	2.036E-01
850	2.109E-01	2.101E-01	2.113E-01	2.099E-01
900	2.133E-01	2.123E-01	2.136E-01	2.128E-01
950	2.125E-01	2.113E-01	2.127E-01	2.115E-01
1000	2.085E-01	2.073E-01	2.086E-01	2.075E-01
1100	1.952E-01	1.942E-01	1.955E-01	1.951E-01
1200	1.778E-01	1.765E-01	1.779E-01	1.770E-01
1300	1.591E-01	1.579E-01	1.591E-01	1.584E-01
1400	1.413E-01	1.404E-01	1.412E-01	1.406E-01
1500	1.235E-01	1.229E-01	1.235E-01	1.230E-01
1600	1.080E-01	1.071E-01	1.080E-01	1.073E-01
1700	9.434E-02	9.358E-02	9.419E-02	9.358E-02
1800	8.242E-02	8.164E-02	8.287E-02	8.180E-02
1900	7.212E-02	7.187E-02	7.179E-02	7.191E-02
2000	6.276E-02	6.233E-02	6.265E-02	6.262E-02
2100	5.489E-02	5.440E-02	5.483E-02	5.457E-02
2200	4.810E-02	4.762E-02	4.802E-02	4.772E-02
2300	4.223E-02	4.180E-02	4.220E-02	4.180E-02
2400	3.733E-02	3.664E-02	3.714E-02	3.711E-02
2500	3.224E-02	3.212E-02	3.227E-02	3.247E-02

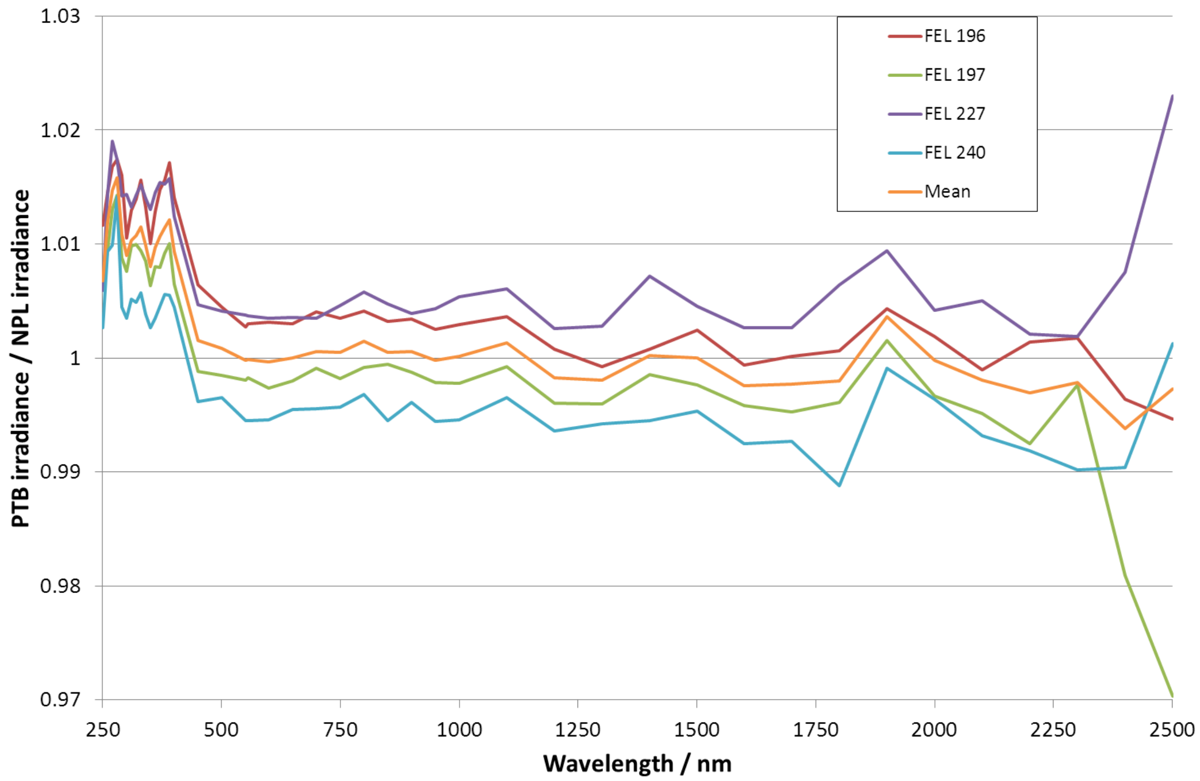

Figure 8. Comparison between irradiance values measured by NPL and by PTB, Germany.

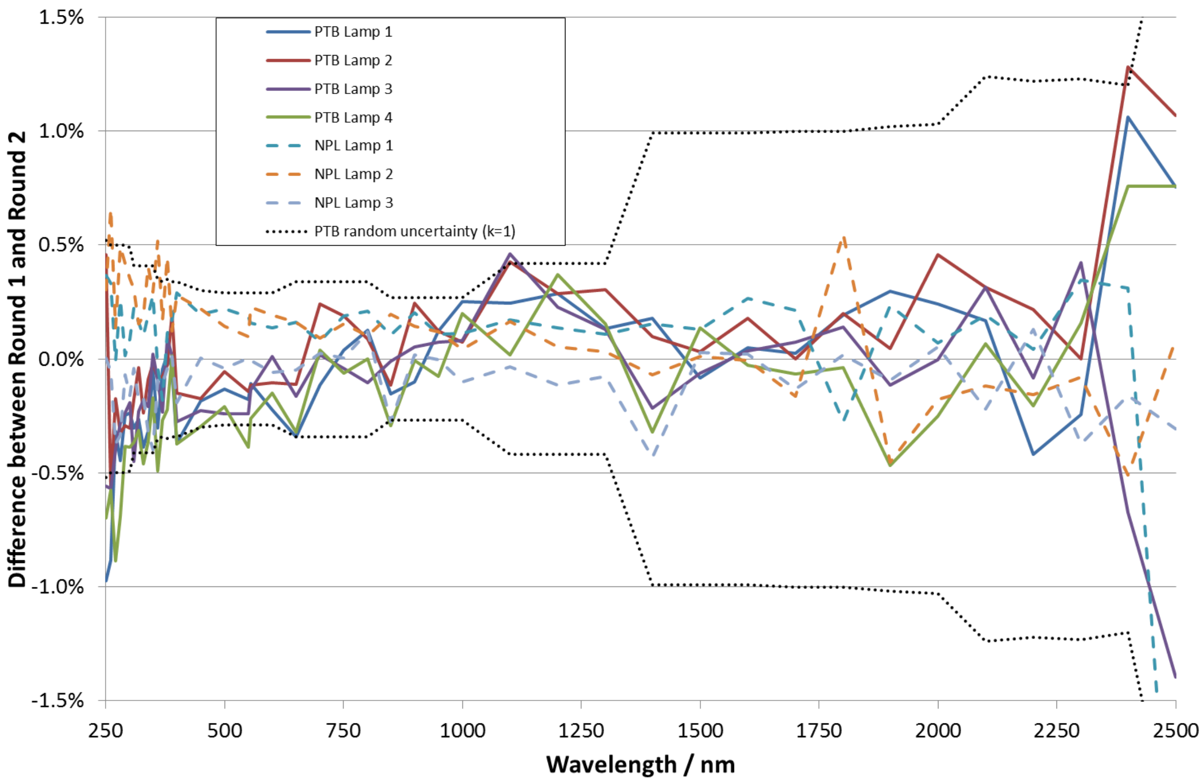

Figure 9. Agreement between first and second round measurements for PTB, Germany.

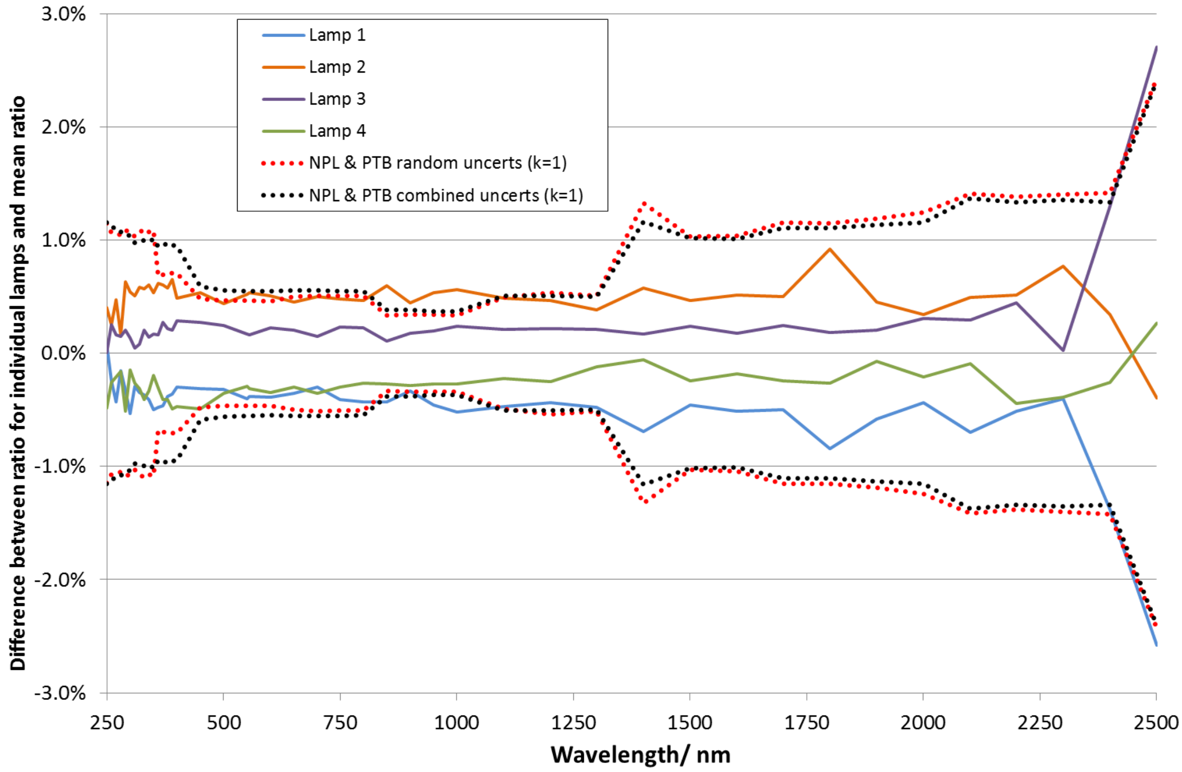

Figure 10. Difference between ratios of values assigned to each lamp by PTB, Germany to values assigned to the same lamp by NPL and mean PTB-to-NPL ratio for all lamps measured by PTB (see Eq. 12 and 13).

5.2 RESULTS FOR INM, ROMANIA

INM, Romania, made measurements over a subset of the full range, at 50 nm intervals from 400 nm to 900 nm and 555 nm only. There is no evidence of any significant drift in any of the lamps during the course of the comparison; the consistency between lamps is moderate (slightly outside uncertainties).

Table 4. Absolute results for INM, Romania

LAMP FEL 472			
Wavelength / nm	**INM Run 1**	**NPL**	**INM Run 2**
400	2.490E-02	2.404E-02	2.470E-02
450	4.860E-02	4.736E-02	4.850E-02
500	8.180E-02	7.744E-02	8.170E-02
550	1.120E-01	1.097E-01	1.119E-01
555	1.152E-01	1.134E-01	1.151E-01
600	1.441E-01	1.413E-01	1.439E-01
650	1.724E-01	1.692E-01	1.722E-01
700	1.955E-01	1.916E-01	1.952E-01
750	2.127E-01	2.086E-01	2.124E-01
800	2.244E-01	2.194E-01	2.241E-01
850	2.307E-01	2.257E-01	2.304E-01
900	2.322E-01	2.274E-01	2.319E-01

LAMP FEL 473			
Wavelength / nm	**INM Run 1**	**NPL**	**INM Run 2**
400	2.520E-02	2.420E-02	2.540E-02
450	5.100E-02	4.791E-02	5.120E-02
500	7.990E-02	7.765E-02	8.020E-02
550	1.132E-01	1.099E-01	1.135E-01
555	1.164E-01	1.132E-01	1.166E-01
600	1.446E-01	1.411E-01	1.447E-01
650	1.728E-01	1.686E-01	1.729E-01
700	1.958E-01	1.908E-01	1.959E-01
750	2.128E-01	2.072E-01	2.129E-01
800	2.246E-01	2.182E-01	2.248E-01
850	2.309E-01	2.244E-01	2.312E-01
900	2.323E-01	2.253E-01	2.325E-01

LAMP FEL 474			
Wavelength / nm	**INM Run 1**	**NPL**	**INM Run 2**
400	2.440E-02	2.337E-02	2.460E-02
450	4.960E-02	4.621E-02	4.970E-02
500	7.800E-02	7.486E-02	7.830E-02
550	1.107E-01	1.061E-01	1.109E-01
555	1.139E-01	1.092E-01	1.142E-01
600	1.428E-01	1.363E-01	1.431E-01
650	1.716E-01	1.629E-01	1.719E-01
700	1.948E-01	1.845E-01	1.951E-01
750	2.121E-01	2.005E-01	2.126E-01
800	2.238E-01	2.111E-01	2.242E-01
850	2.302E-01	2.168E-01	2.307E-01
900	2.322E-01	2.185E-01	2.328E-01

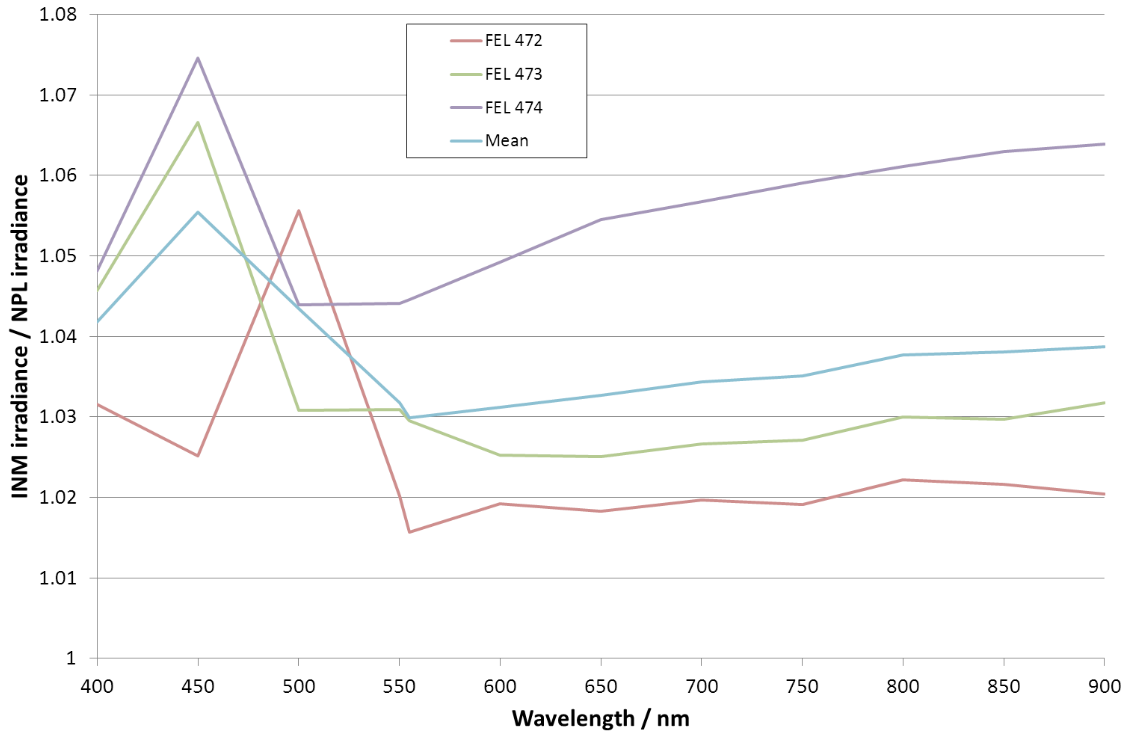

Figure 11. Comparison between irradiance values measured by NPL and by INM, Romania.

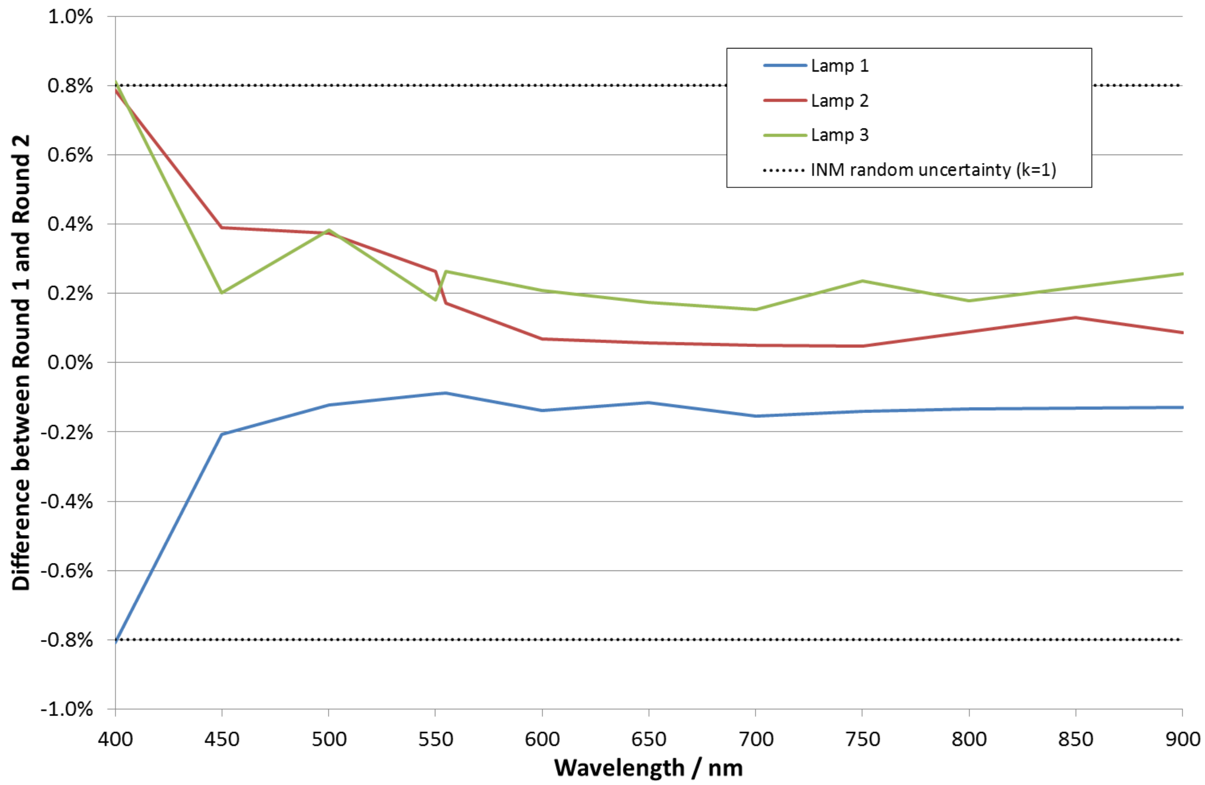

Figure 12. Agreement between first and second round measurements for INM, Romania.

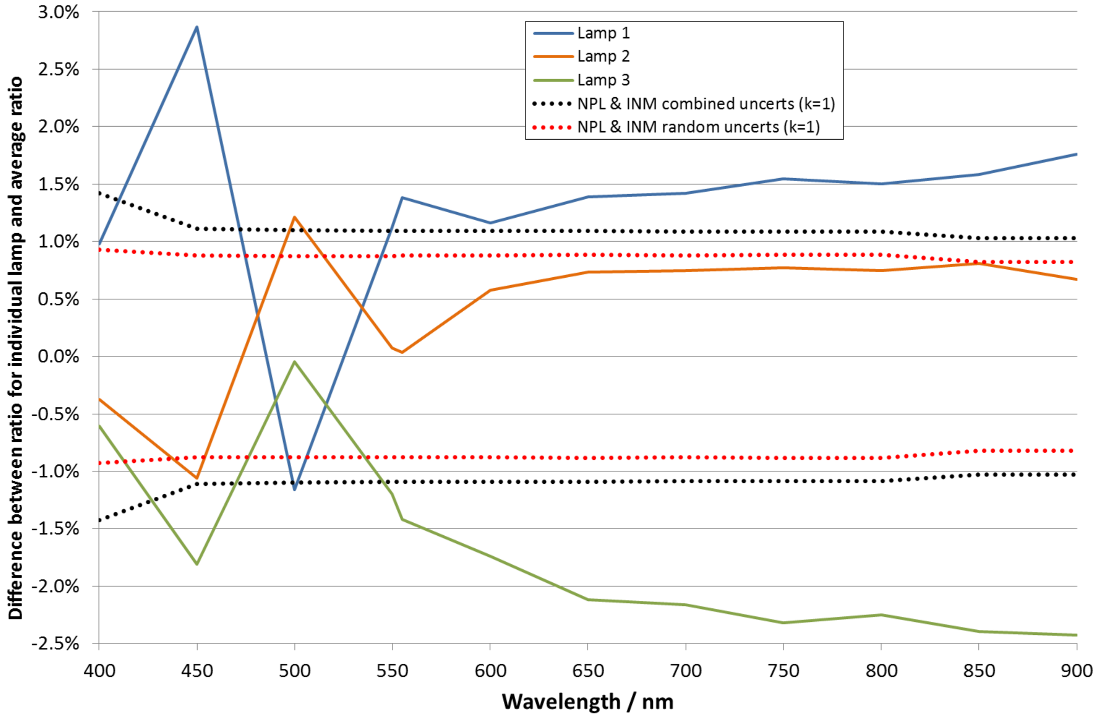

Figure 13. Difference between ratios of values assigned to each lamp by INM, Romania, to values assigned to same lamp by NPL and mean INM-to-NPL ratio for all lamps measured by INM (see Eq. 12 and 13).

5.3 RESULTS FOR METAS, SWITZERLAND

METAS, Switzerland, made measurements over a subset of the full range, at 10 nm intervals between 250 nm and 400 nm, 50 nm intervals from 400 nm to 1000 nm, 555 nm and 1100 nm. Although the agreement between the first and second round of measurements for one of the lamps is not as good as expected (the difference between the two sets of results is considerably larger than the random uncertainty associated with the measurements), the consistency between all three lamps is good; this suggests that this lamp may have drifted during the course of the comparison but in such a way that the drift was accounted for by averaging the two sets of measurements.

Table 5. Absolute results for METAS, Switzerland

LAMP FEL 388			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
250	2.960E-04	3.019E-04	2.968E-04
260	4.991E-04	5.137E-04	4.943E-04
270	8.040E-04	8.313E-04	8.062E-04
280	1.249E-03	1.279E-03	1.245E-03
290	1.845E-03	1.889E-03	1.845E-03
300	2.640E-03	2.694E-03	2.633E-03
310	3.664E-03	3.729E-03	3.671E-03
320	4.971E-03	5.015E-03	4.950E-03
330	6.530E-03	6.590E-03	6.508E-03
340	8.421E-03	8.519E-03	8.383E-03
350	1.071E-02	1.078E-02	1.068E-02

LAMP FEL 388			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
360	1.331E-02	1.337E-02	1.328E-02
370	1.631E-02	1.637E-02	1.629E-02
380	1.970E-02	1.975E-02	1.963E-02
390	2.343E-02	2.349E-02	2.336E-02
400	2.748E-02	2.764E-02	2.745E-02
450	5.331E-02	5.370E-02	5.312E-02
500	8.504E-02	8.563E-02	8.456E-02
550	1.186E-01	1.195E-01	1.181E-01
555	1.220E-01	1.230E-01	1.215E-01
600	1.510E-01	1.519E-01	1.504E-01
650	1.790E-01	1.801E-01	1.782E-01
700	2.016E-01	2.024E-01	2.009E-01
750	2.179E-01	2.185E-01	2.172E-01
800	2.288E-01	2.288E-01	2.277E-01
850	2.342E-01	2.345E-01	2.331E-01
900	2.351E-01	2.347E-01	2.340E-01
950	2.321E-01	2.319E-01	2.308E-01
1000	2.266E-01	2.261E-01	2.253E-01
1100	2.106E-01	2.101E-01	2.094E-01

LAMP FEL 389			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
250	2.626E-04	2.645E-04	2.601E-04
260	4.429E-04	4.516E-04	4.374E-04
270	7.189E-04	7.354E-04	7.157E-04
280	1.124E-03	1.137E-03	1.111E-03
290	1.666E-03	1.689E-03	1.653E-03
300	2.395E-03	2.417E-03	2.368E-03
310	3.331E-03	3.350E-03	3.296E-03
320	4.532E-03	4.528E-03	4.498E-03
330	5.975E-03	5.970E-03	5.919E-03
340	7.730E-03	7.731E-03	7.635E-03
350	9.862E-03	9.808E-03	9.764E-03
360	1.229E-02	1.223E-02	1.217E-02
370	1.511E-02	1.500E-02	1.498E-02
380	1.828E-02	1.814E-02	1.810E-02
390	2.178E-02	2.165E-02	2.158E-02
400	2.560E-02	2.546E-02	2.542E-02
450	5.016E-02	4.987E-02	4.968E-02
500	8.062E-02	8.020E-02	7.982E-02
550	1.132E-01	1.128E-01	1.123E-01
555	1.165E-01	1.160E-01	1.156E-01

LAMP FEL 389			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
600	1.448E-01	1.442E-01	1.437E-01
650	1.726E-01	1.717E-01	1.712E-01
700	1.950E-01	1.938E-01	1.936E-01
750	2.115E-01	2.101E-01	2.101E-01
800	2.227E-01	2.207E-01	2.210E-01
850	2.285E-01	2.263E-01	2.268E-01
900	2.299E-01	2.276E-01	2.282E-01
950	2.274E-01	2.255E-01	2.255E-01
1000	2.223E-01	2.204E-01	2.204E-01
1100	2.070E-01	2.054E-01	2.054E-01

LAMP FEL 390			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
250	2.569E-04	2.604E-04	2.554E-04
260	4.307E-04	4.458E-04	4.320E-04
270	7.040E-04	7.264E-04	7.069E-04
280	1.099E-03	1.122E-03	1.098E-03
290	1.631E-03	1.668E-03	1.634E-03
300	2.346E-03	2.389E-03	2.340E-03
310	3.261E-03	3.310E-03	3.258E-03
320	4.437E-03	4.471E-03	4.454E-03
330	5.846E-03	5.897E-03	5.840E-03
340	7.565E-03	7.634E-03	7.547E-03
350	9.641E-03	9.682E-03	9.639E-03
360	1.201E-02	1.207E-02	1.201E-02
370	1.476E-02	1.477E-02	1.476E-02
380	1.786E-02	1.786E-02	1.783E-02
390	2.128E-02	2.131E-02	2.127E-02
400	2.500E-02	2.512E-02	2.504E-02
450	4.891E-02	4.906E-02	4.886E-02
500	7.861E-02	7.881E-02	7.842E-02
550	1.102E-01	1.108E-01	1.102E-01
555	1.135E-01	1.140E-01	1.134E-01
600	1.410E-01	1.415E-01	1.410E-01
650	1.681E-01	1.683E-01	1.679E-01
700	1.900E-01	1.901E-01	1.900E-01
750	2.060E-01	2.061E-01	2.062E-01
800	2.171E-01	2.167E-01	2.170E-01
850	2.230E-01	2.223E-01	2.229E-01
900	2.243E-01	2.234E-01	2.243E-01
950	2.221E-01	2.215E-01	2.219E-01
1000	2.173E-01	2.166E-01	2.171E-01

LAMP FEL 390			
Wavelength / nm	**METAS Run 1**	**NPL**	**METAS Run 2**
1100	2.028E-01	2.022E-01	2.026E-01

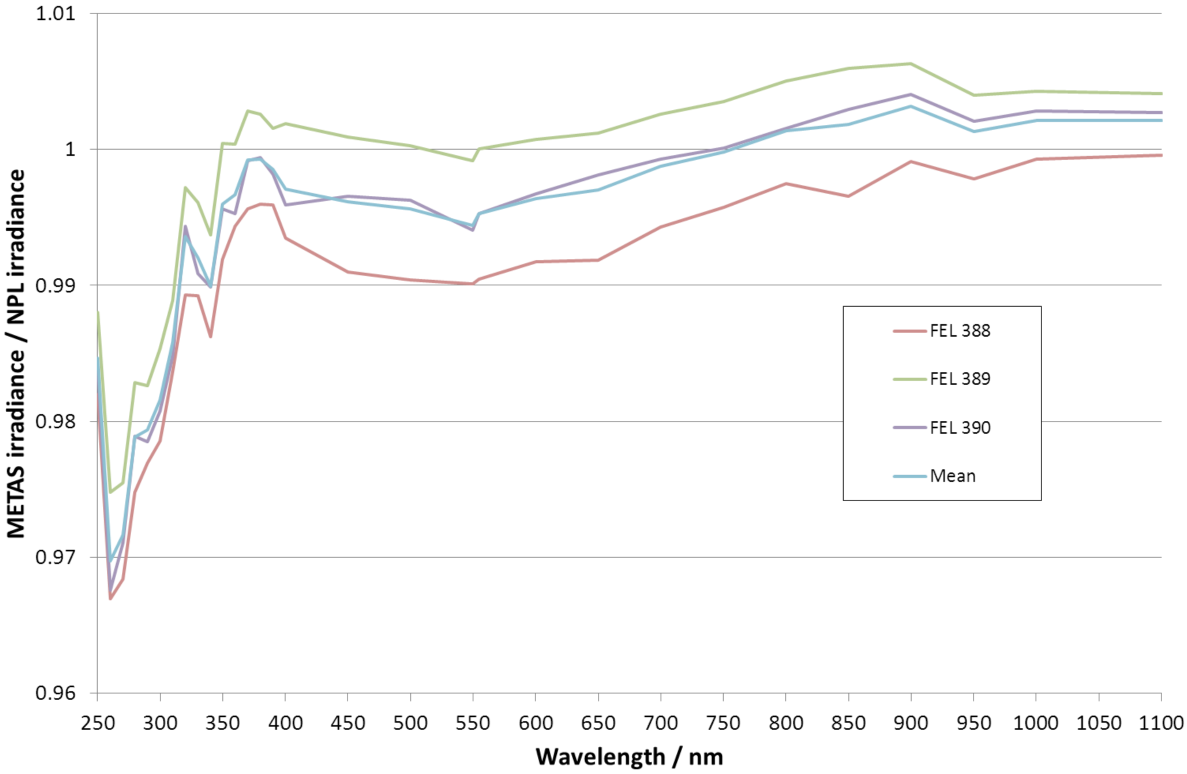

Figure 14. Comparison between irradiance values measured by NPL and by METAS, Switzerland.

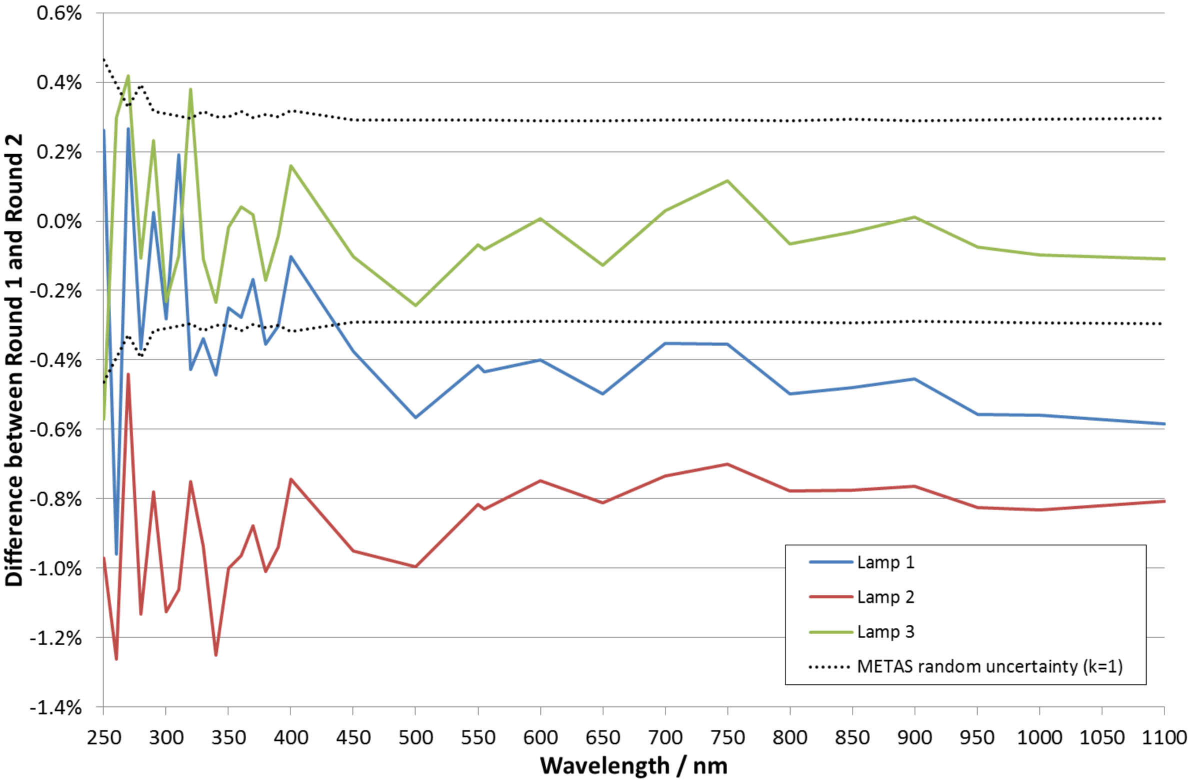

Figure 15. Agreement between first and second round measurements for METAS, Switzerland.

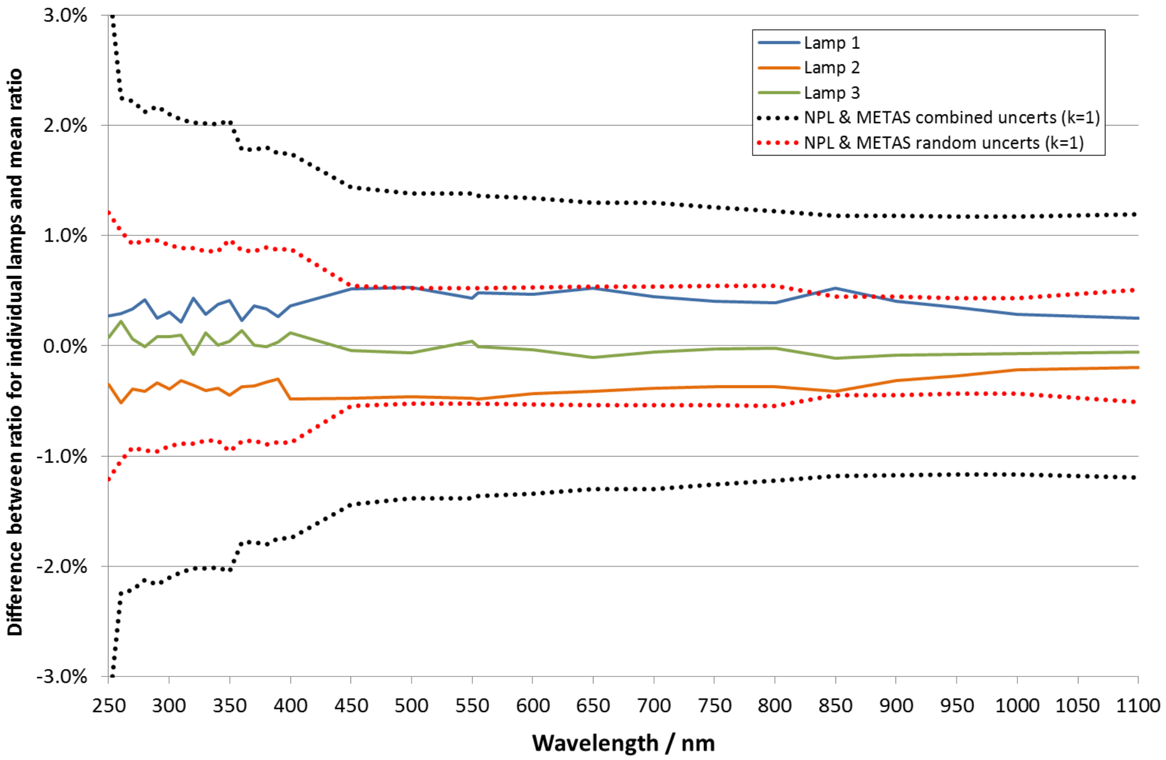

Figure 16. Difference between ratios of values assigned to each lamp by METAS, Switzerland, to values assigned to the same lamp by NPL and mean METAS-to-NPL ratio for all lamps measured by METAS (see Eq. 12 and 13).

5.4 RESULTS FOR SP, SWEDEN

SP, Sweden, made measurements over the full wavelength range of the comparison. There is no evidence of any significant drift in any of the lamps during the course of the comparison and the consistency between lamps is good.

As a result of the comparison, SP identified an error their measurements. The wrong reference plane was used when setting the distance for the intercomparison lamps at SP: instead of using the front plate of the lamp mount, as specified in the protocol, SP used the plane of the alignment jig containing the crosshair. This meant that measurements were made at a distance that was 6 mm less than that used at NPL, and resulted in irradiance values that were about 2.3 % higher than would be obtained using the correct distance. This problem was identified after the Draft A report had been issued and therefore the results given in this report (including the DoE values for SP) have not been corrected for this error.

Table 6. Absolute results for SP, Sweden.

LAMP PTB-SL-135			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
250	1.374E-04	1.327E-04	1.373E-04
260	2.408E-04	2.316E-04	2.413E-04
270	4.018E-04	3.869E-04	4.020E-04
280	6.375E-04	6.093E-04	6.396E-04
290	9.668E-04	9.318E-04	9.663E-04
300	1.415E-03	1.365E-03	1.418E-03
310	2.007E-03	1.944E-03	2.011E-03
320	2.766E-03	2.661E-03	2.775E-03
330	3.716E-03	3.583E-03	3.720E-03
340	4.886E-03	4.718E-03	4.884E-03
350	6.287E-03	6.098E-03	6.289E-03
360	7.941E-03	7.700E-03	7.957E-03
370	9.875E-03	9.594E-03	9.895E-03
380	1.208E-02	1.177E-02	1.211E-02
390	1.459E-02	1.421E-02	1.462E-02
400	1.740E-02	1.697E-02	1.743E-02
450	3.579E-02	3.502E-02	3.585E-02
500	6.029E-02	5.883E-02	6.035E-02
550	8.795E-02	8.578E-02	8.817E-02
555	9.079E-02	8.851E-02	9.100E-02
600	1.156E-01	1.128E-01	1.159E-01
650	1.406E-01	1.376E-01	1.409E-01
700	1.613E-01	1.583E-01	1.616E-01
750	1.776E-01	1.745E-01	1.777E-01
800	1.900E-01	1.859E-01	1.900E-01
850	1.972E-01	1.928E-01	1.981E-01
900	2.002E-01	1.957E-01	2.007E-01
950	2.008E-01	1.955E-01	2.006E-01
1000	1.977E-01	1.924E-01	1.979E-01

LAMP PTB-SL-135			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
1100	1.865E-01	1.810E-01	1.861E-01
1200	1.717E-01	1.655E-01	1.708E-01
1300	1.533E-01	1.485E-01	1.524E-01
1400	1.360E-01	1.320E-01	1.352E-01
1500	1.191E-01	1.158E-01	1.186E-01
1600	1.043E-01	1.014E-01	1.039E-01
1700	9.113E-02	8.860E-02	9.106E-02
1800	7.957E-02	7.752E-02	7.949E-02
1900	6.929E-02	6.792E-02	6.899E-02
2000	6.060E-02	5.913E-02	6.058E-02
2100	5.300E-02	5.179E-02	5.309E-02
2200	4.645E-02	4.538E-02	4.656E-02
2300	4.090E-02	3.993E-02	4.089E-02
2400	3.604E-02	3.529E-02	3.603E-02
2500	3.179E-02	3.084E-02	3.190E-02

LAMP SP 96-5			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
250	2.257E-04	2.163E-04	2.244E-04
260	3.898E-04	3.733E-04	3.871E-04
270	6.409E-04	6.132E-04	6.376E-04
280	1.002E-03	9.492E-04	1.000E-03
290	1.503E-03	1.443E-03	1.501E-03
300	2.172E-03	2.088E-03	2.172E-03
310	3.050E-03	2.942E-03	3.049E-03
320	4.154E-03	3.988E-03	4.150E-03
330	5.527E-03	5.299E-03	5.514E-03
340	7.189E-03	6.913E-03	7.168E-03
350	9.165E-03	8.851E-03	9.154E-03
360	1.147E-02	1.109E-02	1.146E-02
370	1.414E-02	1.364E-02	1.411E-02
380	1.716E-02	1.661E-02	1.712E-02
390	2.053E-02	1.988E-02	2.052E-02
400	2.432E-02	2.359E-02	2.427E-02
450	4.840E-02	4.729E-02	4.827E-02
500	7.946E-02	7.725E-02	7.925E-02
550	1.136E-01	1.102E-01	1.133E-01
555	1.170E-01	1.135E-01	1.167E-01
600	1.466E-01	1.423E-01	1.464E-01

LAMP SP 96-5			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
650	1.758E-01	1.709E-01	1.751E-01
700	1.986E-01	1.941E-01	1.983E-01
750	2.164E-01	2.115E-01	2.163E-01
800	2.285E-01	2.230E-01	2.290E-01
850	2.346E-01	2.293E-01	2.354E-01
900	2.369E-01	2.309E-01	2.371E-01
950	2.355E-01	2.294E-01	2.357E-01
1000	2.309E-01	2.243E-01	2.311E-01
1100	2.151E-01	2.090E-01	2.151E-01
1200	1.959E-01	1.895E-01	1.953E-01
1300	1.736E-01	1.689E-01	1.734E-01
1400	1.534E-01	1.495E-01	1.527E-01
1500	1.339E-01	1.305E-01	1.339E-01
1600	1.169E-01	1.139E-01	1.165E-01
1700	1.018E-01	9.916E-02	1.018E-01
1800	8.879E-02	8.672E-02	8.857E-02
1900	7.711E-02	7.567E-02	7.709E-02
2000	6.745E-02	6.574E-02	6.731E-02
2100	5.891E-02	5.752E-02	5.895E-02
2200	5.162E-02	5.016E-02	5.166E-02
2300	4.522E-02	4.429E-02	4.529E-02
2400	3.993E-02	3.894E-02	3.978E-02
2500	3.481E-02	3.486E-02	3.504E-02
LAMP SP 96-7			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
250	2.648E-04	2.556E-04	2.652E-04
260	4.565E-04	4.388E-04	4.548E-04
270	7.443E-04	7.172E-04	7.486E-04
280	1.157E-03	1.103E-03	1.160E-03
290	1.726E-03	1.663E-03	1.732E-03
300	2.481E-03	2.391E-03	2.491E-03
310	3.462E-03	3.349E-03	3.475E-03
320	4.691E-03	4.519E-03	4.706E-03
330	6.211E-03	5.986E-03	6.239E-03
340	8.048E-03	7.779E-03	8.080E-03
350	1.022E-02	9.893E-03	1.027E-02
360	1.276E-02	1.238E-02	1.281E-02
370	1.567E-02	1.518E-02	1.572E-02
380	1.896E-02	1.843E-02	1.903E-02
390	2.264E-02	2.204E-02	2.273E-02
400	2.672E-02	2.602E-02	2.682E-02
450	5.255E-02	5.136E-02	5.270E-02
500	8.538E-02	8.331E-02	8.564E-02

LAMP SP 96-5			
Wavelength / nm	**SP Run 1**	**NPL**	**SP Run 2**
550	1.211E-01	1.179E-01	1.215E-01
555	1.246E-01	1.213E-01	1.250E-01
600	1.552E-01	1.513E-01	1.558E-01
650	1.846E-01	1.807E-01	1.855E-01
700	2.086E-01	2.044E-01	2.094E-01
750	2.260E-01	2.218E-01	2.271E-01
800	2.395E-01	2.331E-01	2.398E-01
850	2.450E-01	2.392E-01	2.443E-01
900	2.468E-01	2.404E-01	2.460E-01
950	2.456E-01	2.380E-01	2.442E-01
1000	2.398E-01	2.322E-01	2.388E-01
1100	2.230E-01	2.157E-01	2.217E-01
1200	2.024E-01	1.950E-01	2.011E-01
1300	1.788E-01	1.733E-01	1.777E-01
1400	1.574E-01	1.531E-01	1.564E-01
1500	1.374E-01	1.333E-01	1.369E-01
1600	1.197E-01	1.162E-01	1.190E-01
1700	1.041E-01	1.010E-01	1.035E-01
1800	9.064E-02	8.792E-02	9.013E-02
1900	7.873E-02	7.670E-02	7.841E-02
2000	6.865E-02	6.667E-02	6.827E-02
2100	5.987E-02	5.819E-02	5.969E-02
2200	5.237E-02	5.089E-02	5.217E-02
2300	4.611E-02	4.468E-02	4.589E-02
2400	4.045E-02	3.932E-02	4.034E-02
2500	3.538E-02	3.399E-02	3.537E-02

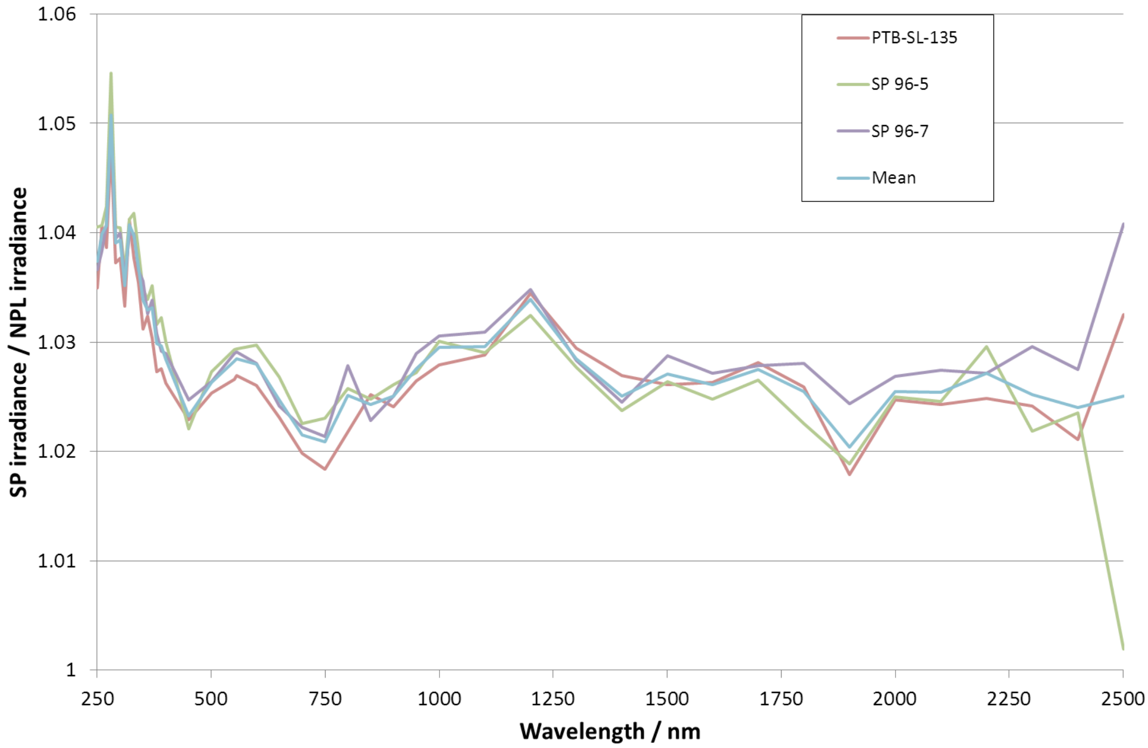

Figure 17. Comparison between irradiance values measured by NPL and by SP, Sweden.

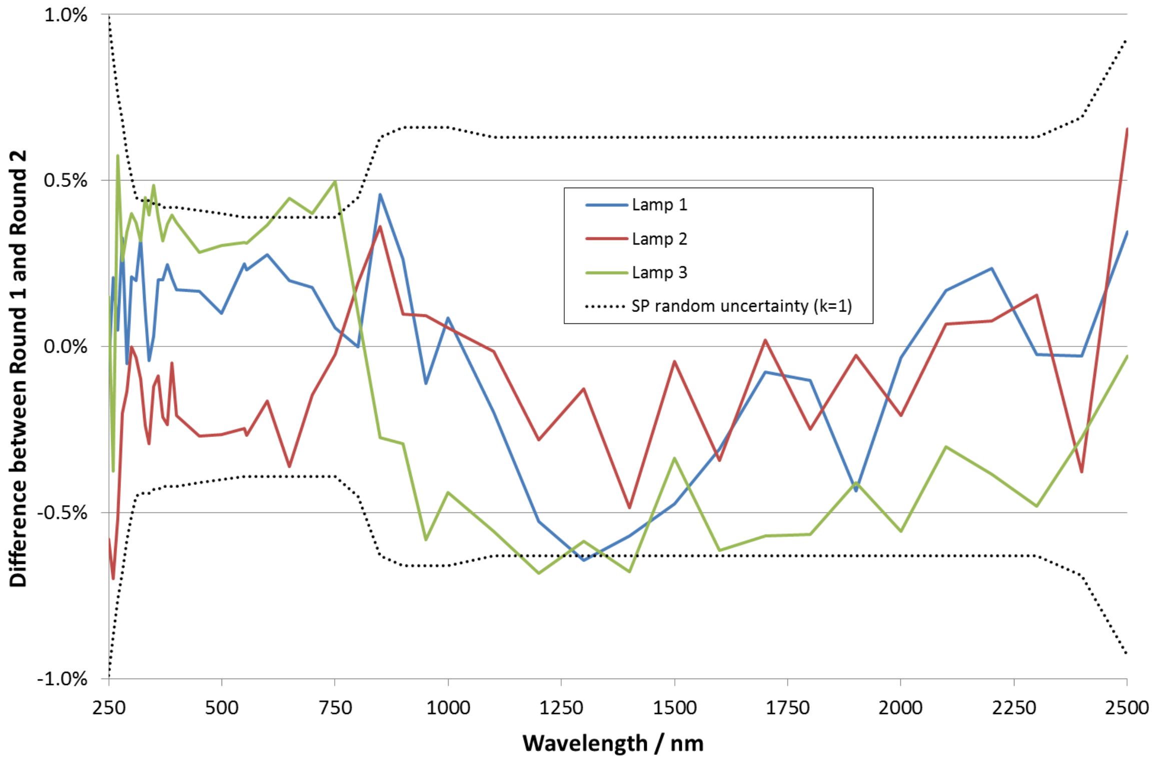

Figure 18. Agreement between first and second round measurements for SP, Sweden.

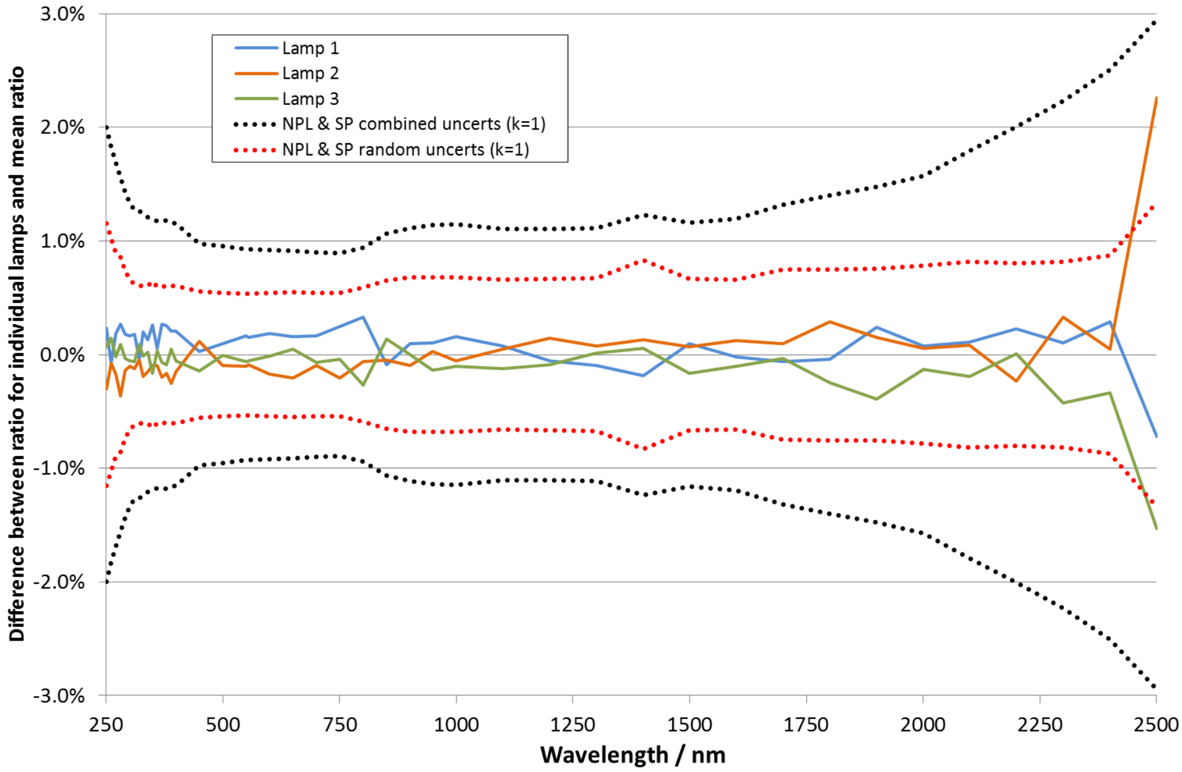

Figure 19. Difference between ratios of values assigned to each lamp by SP, Sweden, to values assigned to the same lamp by NPL and mean SP-to-NPL ratio for all lamps measured by SP (see Eq. 12 and 13).

5.5 RESULTS FOR VNIIOFI, RUSSIA

VNIIOFI, Russia, made measurements over the full wavelength range of the comparison. However due to an error in the lamp current and distance used in the first round of measurements, only results from the second round are considered. The consistency between two of the lamps was good, but results for the third lamp were removed from the comparison due to a lack of internal consistency in the results (identified during the Pre-Draft A stage – see Appendix B).

Table 7. Absolute results for VNIIOFI, Russia.

LAMP SL-218		
Wavelength / nm	**NPL**	**VNIIOFI Run 2**
250	1.620E-04	1.613E-04
260	2.832E-04	2.821E-04
270	4.685E-04	4.704E-04
280	7.066E-04	7.214E-04
290	1.119E-03	1.117E-03
300	1.631E-03	1.630E-03
310	2.318E-03	2.323E-03
320	3.156E-03	3.160E-03
330	4.222E-03	4.242E-03
340	5.542E-03	5.573E-03
350	7.128E-03	7.154E-03

LAMP SL-219		
Wavelength / nm	**NPL**	**VNIIOFI Run 2**
250	1.615E-04	1.619E-04
260	2.817E-04	2.822E-04
270	4.673E-04	4.695E-04
280	6.793E-04	6.988E-04
290	1.116E-03	1.114E-03
300	1.633E-03	1.628E-03
310	2.326E-03	2.333E-03
320	3.159E-03	3.163E-03
330	4.235E-03	4.249E-03
340	5.560E-03	5.581E-03
350	7.166E-03	7.185E-03

LAMP SL-218		
Wavelength / nm	**NPL**	**VNIIOFI Run 2**
360	8.981E-03	9.039E-03
370	1.115E-02	1.122E-02
380	1.363E-02	1.374E-02
390	1.644E-02	1.657E-02
400	1.953E-02	1.964E-02
450	3.976E-02	3.965E-02
500	6.611E-02	6.595E-02
550	9.550E-02	9.535E-02
555	9.849E-02	9.840E-02
600	1.247E-01	1.246E-01
650	1.511E-01	1.510E-01
700	1.731E-01	1.733E-01
750	1.898E-01	1.899E-01
800	2.013E-01	2.017E-01
850	2.082E-01	2.082E-01
900	2.107E-01	2.110E-01
950	2.100E-01	2.102E-01
1000	2.061E-01	2.064E-01
1100	1.933E-01	1.939E-01
1200	1.760E-01	1.768E-01
1300	1.575E-01	1.582E-01
1400	1.400E-01	1.398E-01
1500	1.224E-01	1.229E-01
1600	1.071E-01	1.075E-01
1700	9.346E-02	9.373E-02
1800	8.163E-02	8.180E-02
1900	7.150E-02	7.140E-02
2000	6.230E-02	6.190E-02
2100	5.445E-02	5.410E-02
2200	4.785E-02	4.760E-02
2300	4.182E-02	4.203E-02
2400	3.697E-02	3.699E-02
2500	3.226E-02	3.225E-02

LAMP SL-219		
Wavelength / nm	**NPL**	**VNIIOFI Run 2**
360	9.027E-03	9.085E-03
370	1.122E-02	1.127E-02
380	1.370E-02	1.381E-02
390	1.651E-02	1.669E-02
400	1.965E-02	1.977E-02
450	4.017E-02	4.004E-02
500	6.677E-02	6.671E-02
550	9.654E-02	9.648E-02
555	9.960E-02	9.956E-02
600	1.262E-01	1.262E-01
650	1.531E-01	1.531E-01
700	1.754E-01	1.755E-01
750	1.926E-01	1.928E-01
800	2.044E-01	2.047E-01
850	2.112E-01	2.114E-01
900	2.140E-01	2.143E-01
950	2.134E-01	2.134E-01
1000	2.094E-01	2.098E-01
1100	1.965E-01	1.971E-01
1200	1.790E-01	1.797E-01
1300	1.602E-01	1.610E-01
1400	1.423E-01	1.424E-01
1500	1.245E-01	1.251E-01
1600	1.089E-01	1.095E-01
1700	9.504E-02	9.530E-02
1800	8.363E-02	8.336E-02
1900	7.255E-02	7.273E-02
2000	6.321E-02	6.279E-02
2100	5.536E-02	5.537E-02
2200	4.858E-02	4.839E-02
2300	4.273E-02	4.267E-02
2400	3.760E-02	3.752E-02
2500	3.280E-02	3.302E-02

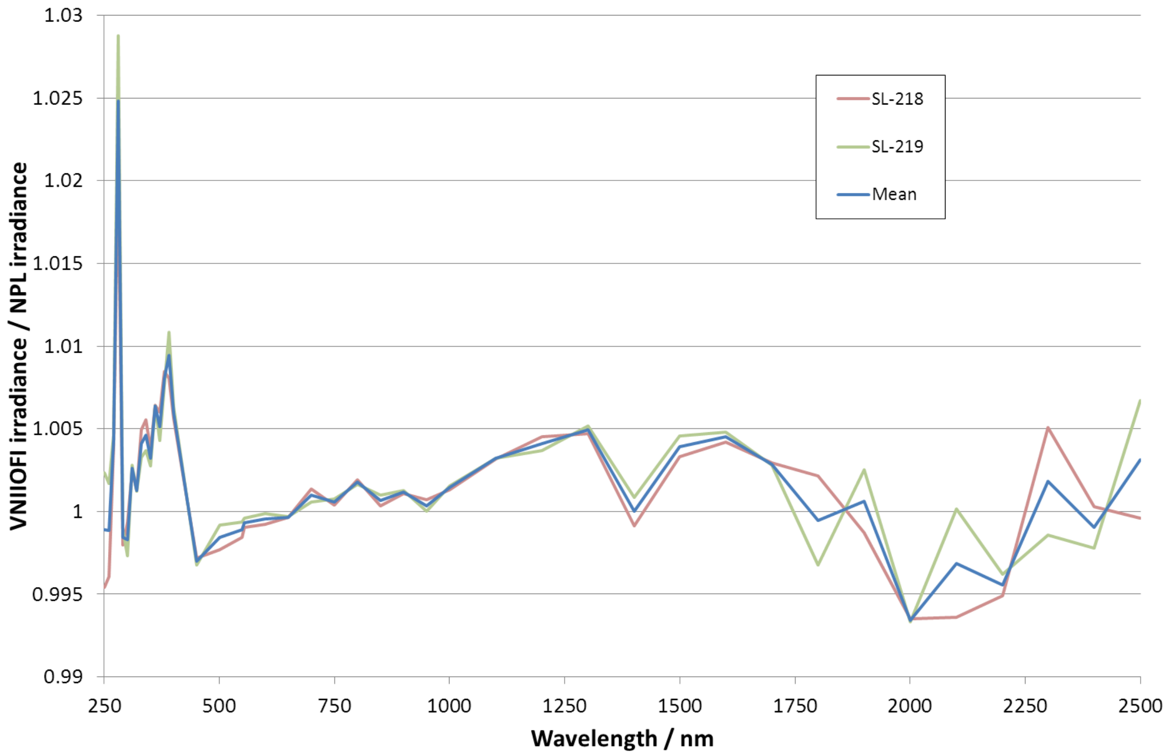

Figure 20. Comparison between irradiance values measured by NPL and by VNIIOFI, Russia.

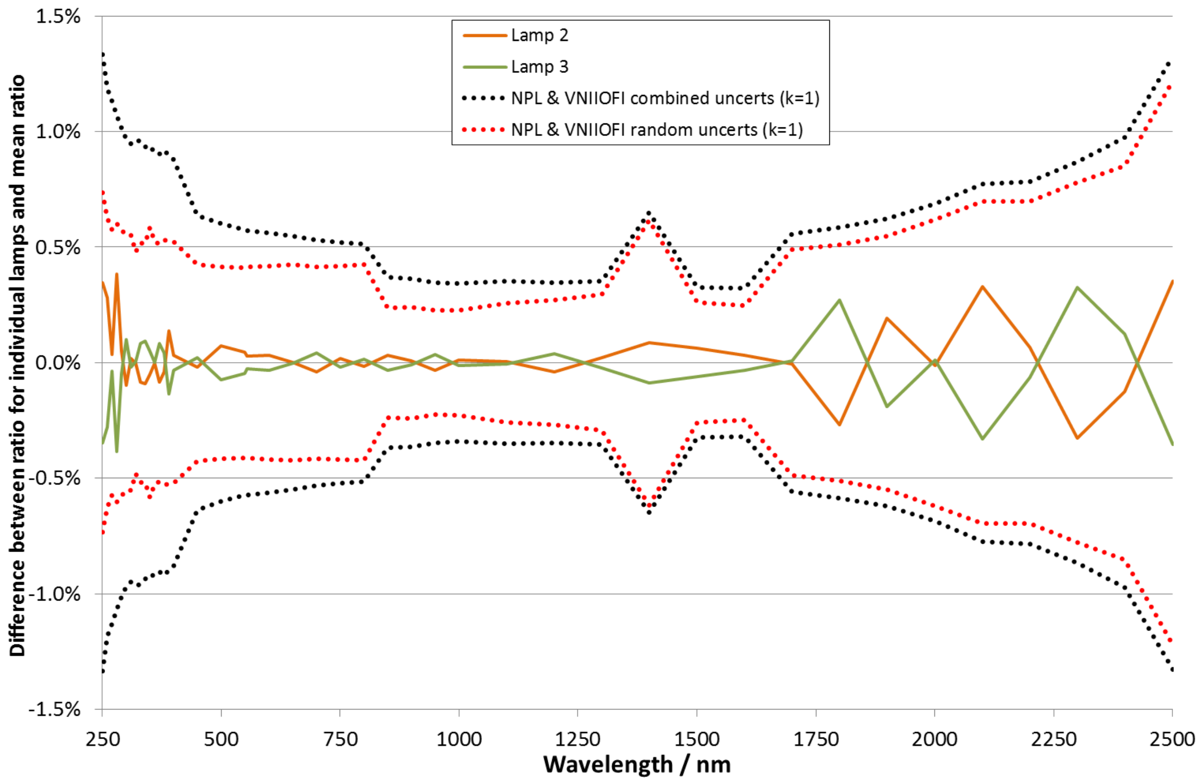

Figure 21. Difference between ratios of values assigned to each lamp by VNIIOFI to values assigned to the same lamp by NPL and mean VNIIOFI-to-NPL ratio for two of the lamps measured by VNIIOFI (results for a third lamp have been excluded due to poor internal consistency between this lamp and the other two, identified at the Pre-Draft A stage of the comparison).

5.6 RESULTS FOR VSL, THE NETHERLANDS

VSL, The Netherlands, made measurements over a subset of the full range, at 10 nm intervals between 250 nm and 400 nm, 50 nm intervals from 400 nm to 1000 nm, 100 nm intervals from 1000 nm to 2000 nm, and 555 nm. There is no evidence of any significant drift in any of the lamps during the course of the comparison and the consistency between lamps is good.

Table 8. Absolute results for VSL, The Netherlands

LAMP FEL 266			
Wavelength / nm	**VSL Run 1**	**NPL**	**VSL Run 2**
250	1.149E-04	1.159E-04	1.144E-04
260	2.043E-04	2.032E-04	2.027E-04
270	3.426E-04	3.400E-04	3.391E-04
280	5.434E-04	5.405E-04	5.396E-04
290	8.271E-04	8.263E-04	8.221E-04
300	1.215E-03	1.218E-03	1.209E-03
310	1.728E-03	1.731E-03	1.716E-03
320	2.394E-03	2.393E-03	2.381E-03
330	3.242E-03	3.227E-03	3.226E-03
340	4.274E-03	4.269E-03	4.252E-03
350	5.523E-03	5.529E-03	5.513E-03
360	6.984E-03	7.024E-03	6.943E-03
370	8.728E-03	8.764E-03	8.681E-03
380	1.072E-02	1.076E-02	1.061E-02
390	1.297E-02	1.302E-02	1.292E-02
400	1.543E-02	1.558E-02	1.551E-02
450	3.223E-02	3.253E-02	3.240E-02
500	5.482E-02	5.502E-02	5.468E-02
550	8.033E-02	8.069E-02	8.032E-02
555	8.291E-02	8.337E-02	8.293E-02
600	1.0596E-01	1.067E-01	1.063E-01
650	1.2991E-01	1.306E-01	1.305E-01
700	1.5012E-01	1.510E-01	1.504E-01
750	1.6612E-01	1.669E-01	1.662E-01
800	1.7765E-01	1.782E-01	1.778E-01
850	1.8453E-01	1.852E-01	1.851E-01
900	1.8697E-01	1.884E-01	1.889E-01
950	1.8691E-01	1.884E-01	1.886E-01
1000	1.8436E-01	1.857E-01	1.863E-01
1100	1.762E-01	1.753E-01	1.743E-01
1200	1.602E-01	1.603E-01	1.606E-01
1300	1.433E-01	1.440E-01	1.442E-01
1400	1.270E-01	1.283E-01	1.285E-01
1500	1.128E-01	1.125E-01	1.121E-01
1600	9.830E-02	9.865E-02	9.890E-02
1700	8.600E-02	8.629E-02	8.550E-02
1800	7.520E-02	7.569E-02	7.440E-02
1900	6.610E-02	6.610E-02	6.590E-02
2000	5.670E-02	5.759E-02	5.780E-02

LAMP FEL 310			
Wavelength / nm	**VSL Run 1**	**NPL**	**VSL Run 2**
250	1.495E-04	1.503E-04	1.486E-04
260	2.607E-04	2.629E-04	2.613E-04
270	4.370E-04	4.362E-04	4.342E-04
280	6.876E-04	6.894E-04	6.845E-04
290	1.037E-03	1.046E-03	1.034E-03
300	1.511E-03	1.530E-03	1.511E-03
310	2.134E-03	2.161E-03	2.130E-03
320	2.938E-03	2.966E-03	2.935E-03
330	3.961E-03	3.981E-03	3.952E-03
340	5.190E-03	5.238E-03	5.182E-03
350	6.676E-03	6.750E-03	6.687E-03
360	8.391E-03	8.537E-03	8.379E-03
370	1.044E-02	1.059E-02	1.043E-02
380	1.279E-02	1.294E-02	1.272E-02
390	1.539E-02	1.562E-02	1.540E-02
400	1.824E-02	1.862E-02	1.843E-02
450	3.748E-02	3.815E-02	3.784E-02
500	6.300E-02	6.370E-02	6.295E-02
550	9.119E-02	9.229E-02	9.139E-02
555	9.396E-02	9.521E-02	9.429E-02
600	1.191E-01	1.209E-01	1.199E-01
650	1.448E-01	1.468E-01	1.459E-01
700	1.662E-01	1.685E-01	1.670E-01
750	1.828E-01	1.851E-01	1.834E-01
800	1.945E-01	1.967E-01	1.954E-01
850	2.007E-01	2.038E-01	2.019E-01
900	2.026E-01	2.062E-01	2.051E-01
950	2.017E-01	2.056E-01	2.036E-01
1000	1.980E-01	2.020E-01	2.008E-01
1100	1.872E-01	1.896E-01	1.873E-01
1200	1.710E-01	1.728E-01	1.716E-01
1300	1.526E-01	1.548E-01	1.533E-01
1400	1.343E-01	1.375E-01	1.340E-01
1500	1.194E-01	1.204E-01	1.188E-01
1600	1.040E-01	1.053E-01	1.037E-01
1700	9.030E-02	9.178E-02	9.130E-02
1800	7.890E-02	8.014E-02	7.850E-02
1900	6.920E-02	7.014E-02	6.780E-02
2000	6.000E-02	6.102E-02	6.040E-02

LAMP FEL 312			
Wavelength / nm	**VSL Run 1**	**NPL**	**VSL Run 2**
250	1.580E-04	1.565E-04	1.547E-04
260	2.752E-04	2.737E-04	2.722E-04
270	4.596E-04	4.543E-04	4.523E-04
280	7.200E-04	7.161E-04	7.125E-04
290	1.087E-03	1.085E-03	1.075E-03
300	1.583E-03	1.585E-03	1.570E-03
310	2.231E-03	2.236E-03	2.208E-03
320	3.070E-03	3.069E-03	3.042E-03
330	4.128E-03	4.104E-03	4.089E-03
340	5.407E-03	5.396E-03	5.354E-03
350	6.940E-03	6.956E-03	6.901E-03
360	8.725E-03	8.773E-03	8.635E-03
370	1.084E-02	1.088E-02	1.074E-02
380	1.324E-02	1.326E-02	1.315E-02
390	1.593E-02	1.596E-02	1.582E-02
400	1.886E-02	1.902E-02	1.887E-02
450	3.857E-02	3.885E-02	3.863E-02
500	6.458E-02	6.465E-02	6.418E-02
550	9.332E-02	9.353E-02	9.305E-02
555	9.616E-02	9.650E-02	9.594E-02
600	1.217E-01	1.223E-01	1.218E-01
650	1.479E-01	1.483E-01	1.481E-01
700	1.695E-01	1.701E-01	1.694E-01
750	1.861E-01	1.867E-01	1.857E-01
800	1.977E-01	1.981E-01	1.974E-01
850	2.041E-01	2.048E-01	2.039E-01
900	2.060E-01	2.076E-01	2.071E-01
950	2.049E-01	2.068E-01	2.056E-01
1000	2.009E-01	2.031E-01	2.025E-01
1100	1.890E-01	1.905E-01	1.889E-01
1200	1.722E-01	1.736E-01	1.723E-01
1300	1.538E-01	1.554E-01	1.550E-01
1400	1.356E-01	1.377E-01	1.365E-01
1500	1.198E-01	1.207E-01	1.204E-01
1600	1.055E-01	1.056E-01	1.055E-01
1700	9.150E-02	9.212E-02	9.160E-02
1800	7.990E-02	8.051E-02	7.920E-02
1900	7.000E-02	7.040E-02	6.980E-02
2000	5.980E-02	6.122E-02	6.070E-02

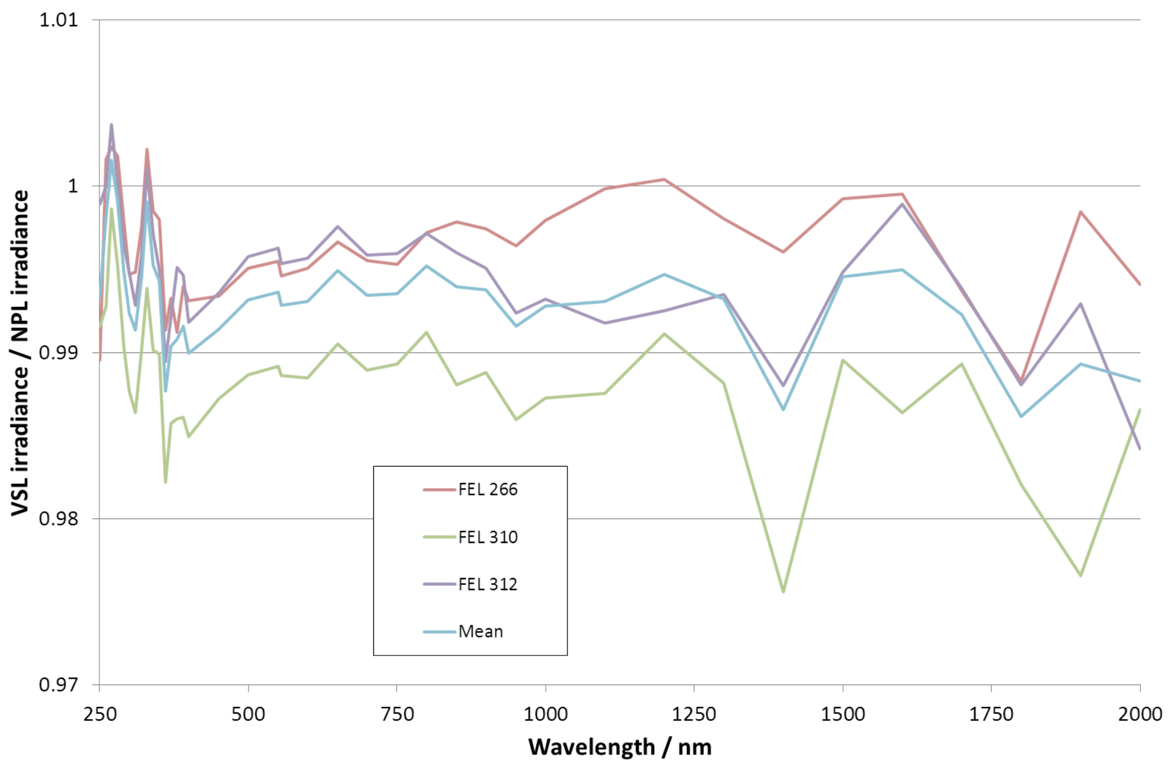

Figure 22. Comparison between irradiance values measured by NPL and by VSL, The Netherlands.

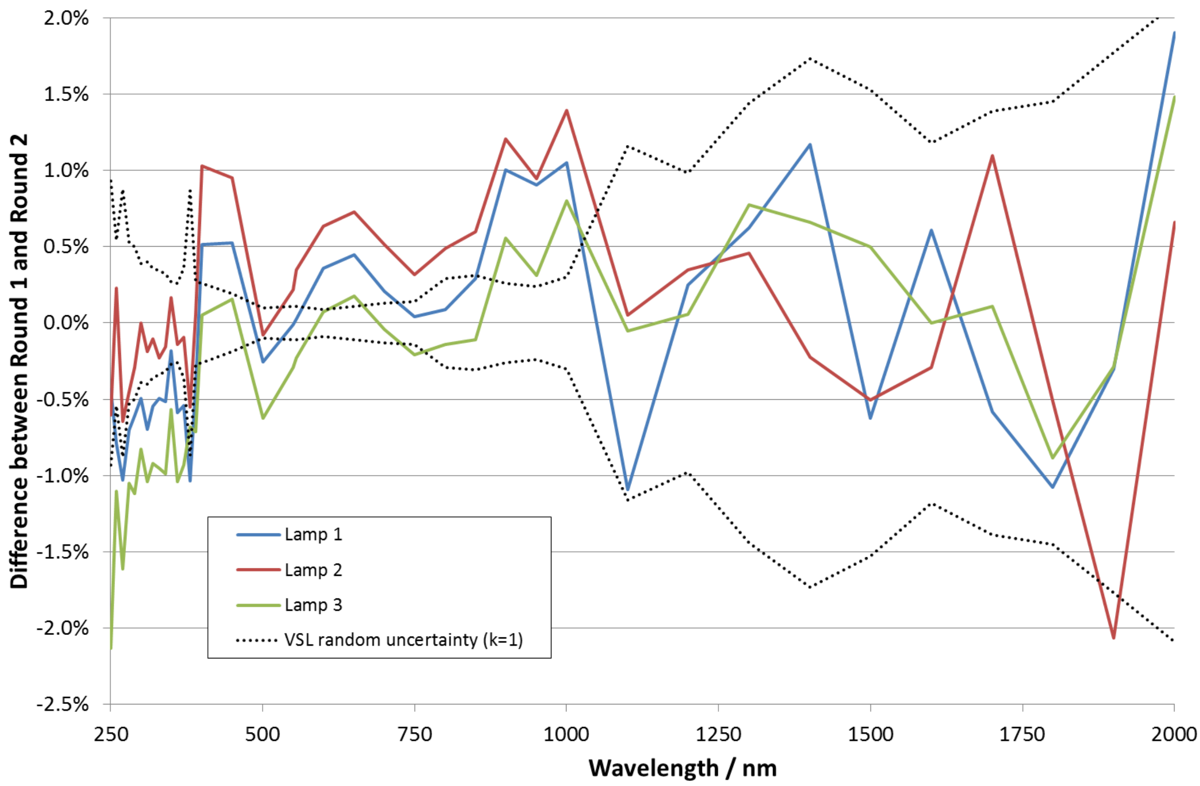

Figure 23. Agreement between first and second round measurements for VSL, The Netherlands.

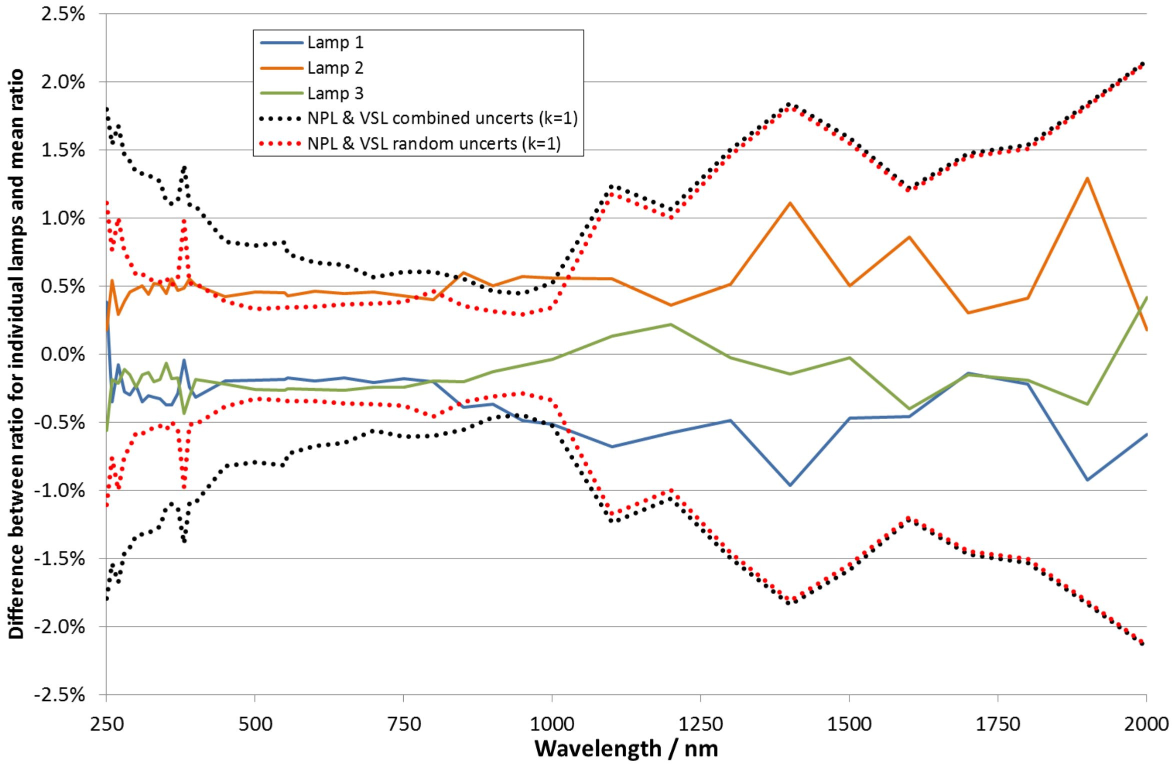

Figure 24. Difference between ratios of values assigned to each lamp by VSL, The Netherlands to values assigned to the same lamp by NPL and mean VSL-to-NPL ratio for all lamps measured by VSL (see Eq. 12 and 13).

5.7 UNILATERAL DEGREES OF EQUIVALENCE

The unilateral DoE values for the participants, i.e. the DoE for the participants to the CCPR KCRV, are given in Table 9 and Figure 25; the associated uncertainties are given in Table 10. In the case of NPL, the scale considered is that realised in 2010 (see Section 4.1). No DoE values are given in Table 9 or Figure 25 for PTB, since these were determined in the CCPR K1.a Key Comparison.

The DoE values and associated uncertainties for each individual participant are also given in Appendix C, in tabular and graphical form. For completeness, Appendix D (Table 44) gives the DoE values and uncertainties for PTB and NPL (2003 scale) as given in the report of the CCPR K1.a Key Comparison.

As a result of the comparison SP identified an error their measurements, due to incorrect distance-setting for the comparison lamps, leading to values that were approximately 2.3 % higher than would have been be obtained using the correct distance. This problem was identified after the Draft A report had been issued and therefore the results given for SP in Table 9 and Figure 25 have not been corrected for this error.

Table 9. Unilateral DoE

Wavelength / nm	NPL2010	INM-RO	METAS	SP	VNIIOFI	VSL
250	-0.76 %		-2.28 %	2.95 %	-1.00 %	-1.42 %
260	-0.74 %		-3.75 %	3.22 %	-0.73 %	-0.93 %
270	-1.02 %		-3.83 %	3.00 %	-0.64 %	-0.86 %
280	-1.76 %		-3.84 %	3.23 %	0.56 %	-1.85 %
290	-0.90 %		-2.94 %	2.98 %	-0.80 %	-1.40 %
300	-0.75 %		-2.58 %	3.16 %	-0.72 %	-1.50 %
310	-0.80 %		-2.21 %	2.69 %	-0.45 %	-1.66 %
320	-1.03 %		-1.66 %	3.00 %	-0.70 %	-1.57 %
330	-1.16 %		-1.95 %	2.77 %	-0.57 %	-1.26 %
340	-1.02 %		-2.01 %	2.63 %	-0.34 %	-1.49 %
350	-0.78 %		-1.18 %	2.58 %	-0.24 %	-1.35 %
360	-0.96 %		-1.29 %	2.30 %	-0.05 %	-2.18 %
370	-1.05 %		-1.13 %	2.23 %	-0.16 %	-2.00 %
380	-1.08 %		-1.15 %	1.88 %	0.07 %	-1.99 %
390	-1.20 %		-1.34 %	1.73 %	0.17 %	-2.03 %
400	-0.93 %	3.21 %	-1.21 %	1.89 %	0.02 %	-1.92 %
450	-0.50 %	5.01 %	-0.88 %	1.81 %	-0.34 %	-1.36 %
500	-0.39 %	3.94 %	-0.83 %	2.23 %	-0.03 %	-1.08 %
550	-0.18 %	2.98 %	-0.74 %	2.64 %	0.24 %	-0.82 %
555	-0.24 %	2.74 %	-0.71 %	2.60 %	0.16 %	-0.95 %
600	-0.27 %	2.84 %	-0.64 %	2.51 %	0.12 %	-0.97 %
650	-0.32 %	2.93 %	-0.62 %	2.14 %	-0.03 %	-0.83 %
700	-0.40 %	3.02 %	-0.53 %	1.74 %	0.02 %	-1.06 %
750	-0.33 %	3.17 %	-0.35 %	1.75 %	-0.02 %	-0.98 %
800	-0.51 %	3.24 %	-0.38 %	1.99 %	-0.17 %	-0.99 %
850	-0.27 %	3.52 %	-0.09 %	2.15 %	-0.06 %	-0.88 %
900	-0.32 %	3.53 %	-0.01 %	2.17 %	-0.08 %	-0.95 %
950	-0.15 %		-0.02 %	2.60 %	0.02 %	-0.99 %
1000	-0.22 %		0.00 %	2.73 %	0.02 %	-0.93 %
1100	-0.24 %		-0.03 %	2.71 %	0.21 %	-0.93 %
1200	-0.36 %			3.02 %	0.05 %	-0.89 %
1300	-0.35 %			2.49 %	0.17 %	-1.02 %
1400	0.39 %			2.91 %	0.38 %	-0.96 %
1500	-0.10 %			2.61 %	0.24 %	-0.64 %
1600	0.10 %			2.71 %	0.49 %	-0.41 %
1700	0.07 %			2.82 %	0.27 %	-0.70 %
1800	0.34 %			2.89 %	0.11 %	-1.06 %
1900	0.37 %			2.41 %	0.27 %	-0.71 %
2000	0.04 %			2.59 %	-0.59 %	-1.13 %
2100	0.06 %			2.60 %	-0.51 %	
2200	-0.27 %			2.44 %	-0.77 %	
2300	0.05 %			2.57 %	0.03 %	
2400	0.99 %			3.42 %	0.40 %	
2500	0.32 %			2.84 %	0.17 %	

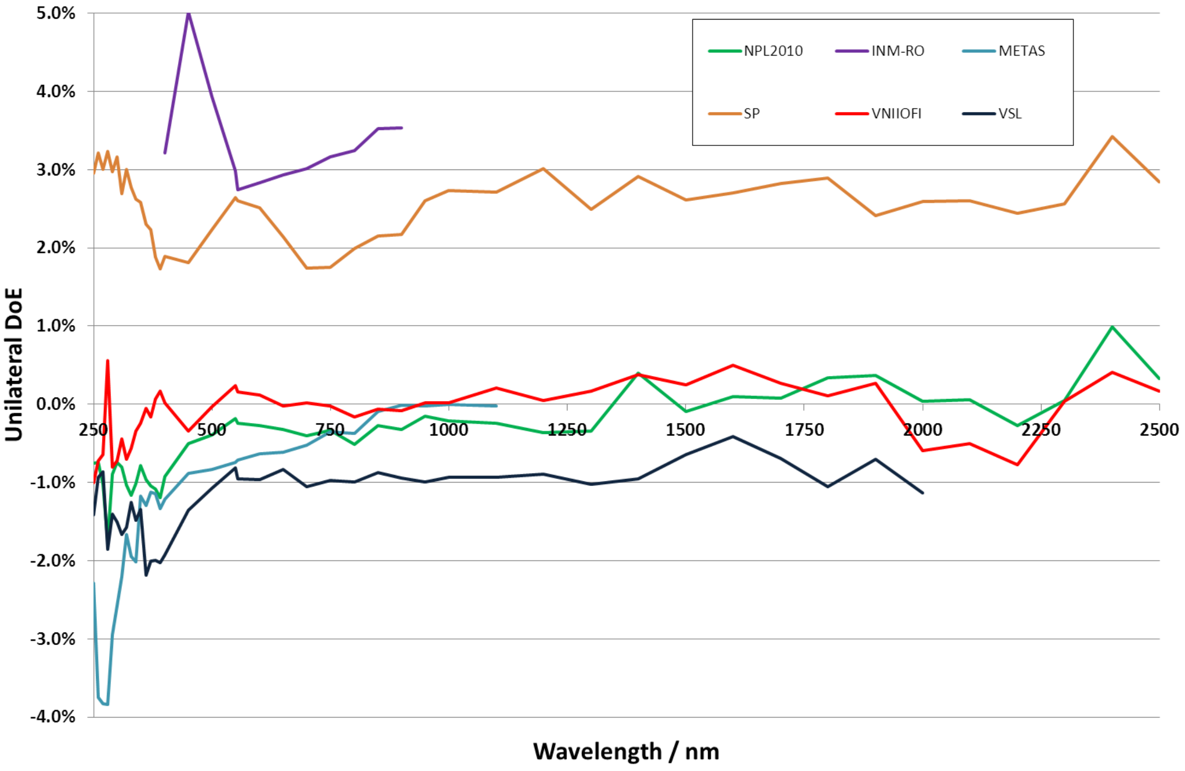

Figure 25. Unilateral DoE i.e. DoE for participants to the CCPR KCRV. Note results for NPL are for the 2010 scale and show the DoE for this scale to the CCPR KCRV.

Table 10. Uncertainty associated with unilateral DoE (*k*=2).

Wavelength / nm	NPL_{2010}	INM-RO	METAS	SP	VNIIOFI	VSL
250	2.85 %		6.52 %	4.20 %	2.91 %	3.81 %
260	2.56 %		4.24 %	3.71 %	2.42 %	3.15 %
270	2.51 %		4.18 %	3.37 %	2.19 %	3.33 %
280	2.50 %		4.07 %	3.19 %	2.19 %	2.99 %
290	2.47 %		4.11 %	2.95 %	2.10 %	2.92 %
300	2.38 %		4.01 %	2.78 %	2.04 %	2.78 %
310	2.31 %		3.89 %	2.61 %	1.94 %	2.70 %
320	2.32 %		3.79 %	2.53 %	1.89 %	2.63 %
330	2.29 %		3.77 %	2.46 %	1.84 %	2.56 %
340	2.26 %		3.76 %	2.40 %	1.80 %	2.51 %
350	2.30 %		3.76 %	2.35 %	1.77 %	2.19 %
360	2.12 %		3.19 %	2.22 %	1.59 %	2.06 %
370	2.12 %		3.18 %	2.19 %	1.55 %	2.10 %
380	2.17 %		3.18 %	2.18 %	1.54 %	2.62 %
390	2.13 %		3.09 %	2.15 %	1.50 %	2.00 %
400	2.11 %	2.70 %	3.09 %	2.15 %	1.49 %	2.00 %
450	1.40 %	2.25 %	2.85 %	1.97 %	1.29 %	1.71 %
500	1.31 %	2.22 %	2.74 %	1.92 %	1.21 %	1.65 %
550	1.29 %	2.22 %	2.74 %	1.88 %	1.17 %	1.70 %
555	1.29 %	2.22 %	2.70 %	1.88 %	1.17 %	1.53 %
600	1.26 %	2.20 %	2.64 %	1.84 %	1.13 %	1.40 %
650	1.26 %	2.21 %	2.57 %	1.85 %	1.12 %	1.38 %
700	1.23 %	2.19 %	2.56 %	1.82 %	1.08 %	1.19 %
750	1.21 %	2.18 %	2.47 %	1.79 %	1.05 %	1.26 %
800	1.21 %	2.18 %	2.40 %	1.90 %	1.03 %	1.26 %
850	0.91 %		2.35 %	2.21 %	0.92 %	1.25 %
900	0.84 %		2.33 %	2.28 %	0.85 %	1.04 %
950	0.85 %		2.34 %	2.34 %	0.87 %	1.04 %
1000	0.82 %		2.33 %	2.36 %	0.85 %	1.17 %
1100	0.90 %		2.35 %	2.28 %	0.88 %	2.54 %
1200	0.95 %			2.30 %	0.93 %	2.22 %
1300	0.90 %			2.30 %	0.90 %	3.05 %
1400	2.11 %			2.81 %	1.79 %	3.92 %
1500	0.94 %			2.43 %	0.96 %	3.25 %
1600	0.98 %			2.52 %	1.02 %	2.56 %
1700	1.60 %			2.82 %	1.41 %	3.10 %
1800	1.63 %			2.97 %	1.46 %	3.22 %
1900	1.73 %			3.16 %	1.60 %	3.83 %
2000	1.86 %			3.37 %	1.75 %	4.47 %
2100	1.96 %			3.76 %	1.84 %	
2200	1.84 %			4.15 %	1.84 %	
2300	1.89 %			4.60 %	2.00 %	
2400	2.07 %			5.19 %	2.29 %	
2500	3.20 %			6.15 %	3.13 %	

6. CONCLUSIONS

Measurements by the two link laboratories (NPL and PTB) confirmed the stability of the NPL_{2003} and PTB spectral irradiance scales since the time of the CCPR-K1.a Key Comparison and validated the quality of the link provided by these two NMIs to the KCRV of the CCPR-K1.a comparison.

The spectral irradiances measured by NPL (2010 scale), METAS, VNIIOFI and VSL in this comparison agreed with the KCRV determined during the CCPR-K1.a Key Comparison within the combined expanded uncertainties (k = 2) at all wavelengths.

In the case of INM-RO, systematic differences were observed between the laboratory spectral irradiance scale and the CCPR K1.a KCRV, which were larger than the combined expanded uncertainties (k=2) at all wavelengths. This indicates that uncertainties have been underestimated by INM-RO.

In the case of SP, systematic differences were observed between the laboratory spectral irradiance scale and the CCPR K1.a KCRV, which were larger than the combined expanded uncertainties (k=2) at 300 nm – 360 nm, 500 nm – 650 nm, 800 nm, and 950 nm – 1600 nm. Subsequent to the issuing of the Draft A report of the comparison, SP identified an error their measurements, due to incorrect distance-setting for the comparison lamps, leading to values that were approximately 2.3 % higher than would have been be obtained using the correct distance. Allowing for this error would mean that the spectral irradiances measured by SP agreed with the KCRV determined during the CCPR-K1.a Key Comparison within the combined expanded uncertainties (k = 2) at all wavelengths.

APPENDIX A – MEASUREMENT DETAILS FOR EACH PARTICIPANT

A.1. MEASUREMENTS AT NPL (PILOT / FIRST LINK LABORATORY)

The facility and measurement technique described below is similar to that described in the CCPR K1-a report [1] for NPL. The facility has, however, been updated and upgraded since the CCPR-K1.a comparison; in particular, certain key components have been replaced including the monochromator, integrating sphere and UV detector. There has also been some change to the measurement procedure.
As a result of these improvements, a new scale has been realised at NPL, referred to as the NPL_{2010} spectral irradiance scale. It has been accredited by the United Kingdom Accreditation Service (UKAS). It is linked to scale used in the CCPR-K1.a comparison, the NPL_{2003} irradiance scale, by a series of lamps which were measured in 2003, or shortly afterwards, and again in 2010/2011, as described in Section 4.2.

The NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility was used not only to establish the NPL spectral irradiance scale, but also for all NPL's measurements of lamps, as pilot, for this comparison. All measurements were made directly against the NPL primary ultra-high temperature blackbody; no intermediate transfer standards were used.

A.1.1 PRIMARY SCALE REALISATION

The NPL_{2003} spectral irradiance scale was used for the CCPR-K1.a Key Comparison and is therefore the scale that must be used by NPL to provide the link between the EURAMET.PR-K1.a and CCPR-K1.a comparisons. Details of the facility and technique used to realise the NPL_{2003} spectral irradiance scale can be found in the CCPR K1-a Key Comparison final report, so are not detailed here.

Due to the improvements made to the NPL measurement facility and procedures between the two comparisons, it is not possible to realise the NPL_{2003} scale directly. However the magnitude of the systematic change in the NPL spectral irradiance scale that resulted from these upgrades has been determined using a series of reference lamps (3 Polaron type and 7 FEL type) which were measured using both facilities. The differences between the NPL_{2003} and NPL_{2010} spectral irradiance scales are plotted in Figure 26 and tabulated in Table 11, together with the associated standard uncertainties (see also Section 4.2).

Figure 26. Difference between NPL_{2010} and NPL_{2003} spectral irradiance scales. Error bars show uncertainty associated with this difference (k=1).

Table 11. Difference between NPL_{2010} and NPL_{2003} spectral irradiance scales

Wavelength / nm	Change in scale	Uncertainty
250	0.13 %	0.43 %
260	0.53 %	0.43 %
270	1.07 %	0.35 %
280	0.21 %	0.43 %
290	0.61 %	0.35 %
300	0.26 %	0.29 %
310	0.06 %	0.30 %
320	-0.33 %	0.30 %
330	-0.58 %	0.31 %
340	-0.59 %	0.30 %
350	-0.64 %	0.30 %
360	-0.70 %	0.15 %
370	-0.77 %	0.16 %
380	-0.87 %	0.16 %
390	-0.81 %	0.16 %
400	-0.67 %	0.16 %
450	-0.31 %	0.12 %
500	-0.06 %	0.11 %
550	0.03 %	0.11 %
555	0.05 %	0.11 %
600	-0.07 %	0.10 %
650	-0.19 %	0.09 %
700	-0.28 %	0.09 %
750	-0.45 %	0.09 %
800	-0.58 %	0.09 %
850	-0.57 %	0.09 %
900	-0.65 %	0.09 %
950	-0.48 %	0.09 %

Wavelength / nm	Change in scale	Uncertainty
1000	-0.56 %	0.09 %
1100	-0.64 %	0.12 %
1200	-0.72 %	0.13 %
1300	-0.79 %	0.15 %
1400	-0.31 %	0.26 %
1500	-0.69 %	0.16 %
1600	-0.66 %	0.17 %
1700	-0.67 %	0.18 %
1800	-0.63 %	0.18 %
1900	-0.40 %	0.18 %
2000	-0.60 %	0.20 %
2100	-0.56 %	0.24 %
2200	-0.65 %	0.23 %
2300	-0.78 %	0.27 %
2400	-0.44 %	0.32 %
2500	-1.27 %	0.61 %

The traceability chain for the NPL_{2003} and NPL_{2010} spectral irradiance scales is the same and is illustrated in Figure 27. In each case the scale was derived by comparison with a high temperature blackbody source, with traceability to SI being obtained through determination of the temperature of the blackbody via filter radiometry. The filter radiometers were calibrated by comparison with two trap detectors against a tuneable laser-illuminated integrating sphere source. Measurements were made at approximately 0.1 nm intervals across the full transmittance range of the filter used on the radiometer. The trap detectors, in turn, were calibrated against the cryogenic radiometer using a stabilised laser system as the source. The calibrated aperture on the trap detector was used to convert spectral power responsivity to spectral irradiance responsivity. A more detailed description of this process can be found in the literature [3].

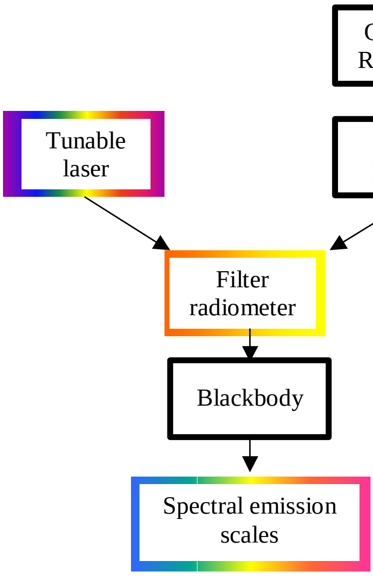

Figure 27. Traceability chain for the primary spectral irradiance scale at NPL

A.1.2 DESCRIPTION OF THE MEASUREMENT FACILITY

The layout of the NPL SRIPS facility is shown in Figures 28 and 29. The primary source (used both for the realisation of the NPL spectral irradiance scales and as a stable reference source for the comparison) was a BB3500 blackbody source purchased from VNIIOFI, typically operated at a temperature around 3050 K. The thermodynamic temperature of the blackbody was determined using a group of filter radiometers built at NPL and calibrated traceably to the primary cryogenic radiometer at NPL. A Bentham DTM300 double grating monochromator was used to select the wavelengths and measurements were made using a range of gratings and photodetectors to cover the full spectral range of the comparison. The monochromator and detectors were mounted on a large translation stage that could be moved in front of each source in turn. The entire facility was computer controlled.

A.1.4.1 Blackbody source

The primary source was a BB3500 blackbody purchased by NPL from VNIIOFI in early 1999. This source is similar in design to the BB3200pg used at a number of other laboratories, which has been extensively investigated [4]. It consists of a cavity made from pyrolytic graphite rings that are directly heated by an electrical current of around 650 A. Measurements at NPL [5] showed the uniformity of the cavity to be < ± 0.05 % and, under active optical stabilisation from the front, a short-term stability of < ± 0.005 % and long-term stability of ± 0.2 % (in radiance) at 800 nm were achieved.

Investigations have shown [6] that this blackbody suffers from the same ultraviolet absorption around 380 nm as has been observed with the BB3200pg [7]. For this reason, the blackbody temperature was kept relatively low, around 3050 K, and corrections were made for absorption for wavelengths from 250 nm to 430 nm.

The radiance of the blackbody was determined from Planck's law, based on a measure of its thermodynamic temperature via filter radiometers, and the geometry was defined by a water-cooled, brass, diamond-turned, aperture in front of the blackbody and the aperture on the integrating sphere at the front of the monochromator.

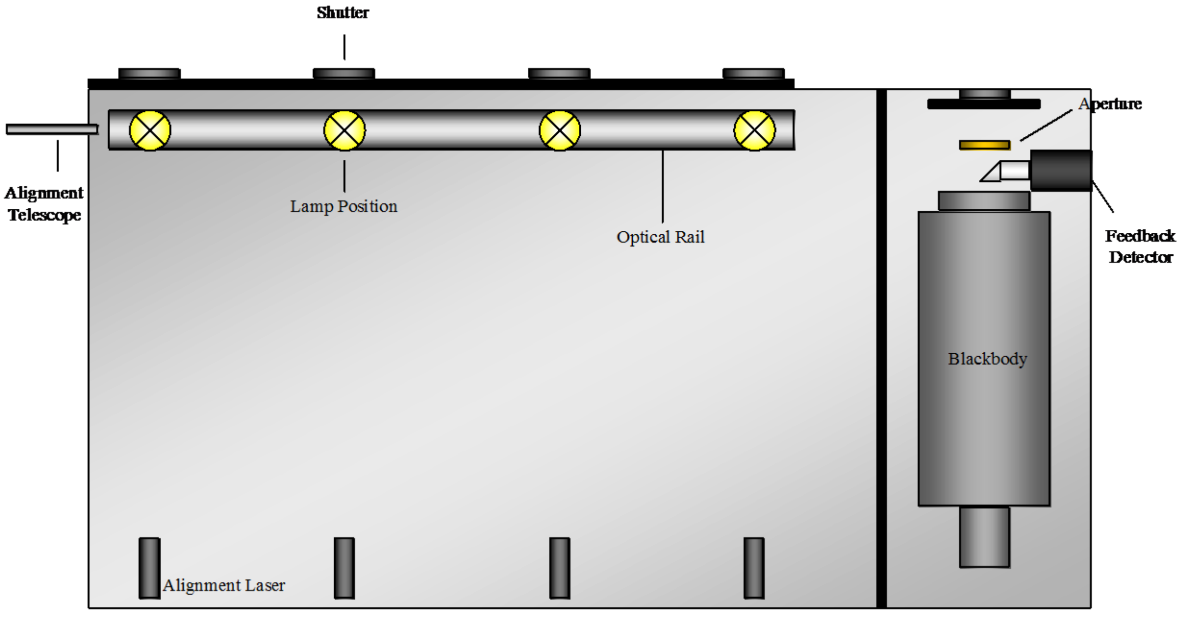

Figure 28. NPL SRIPS source bench

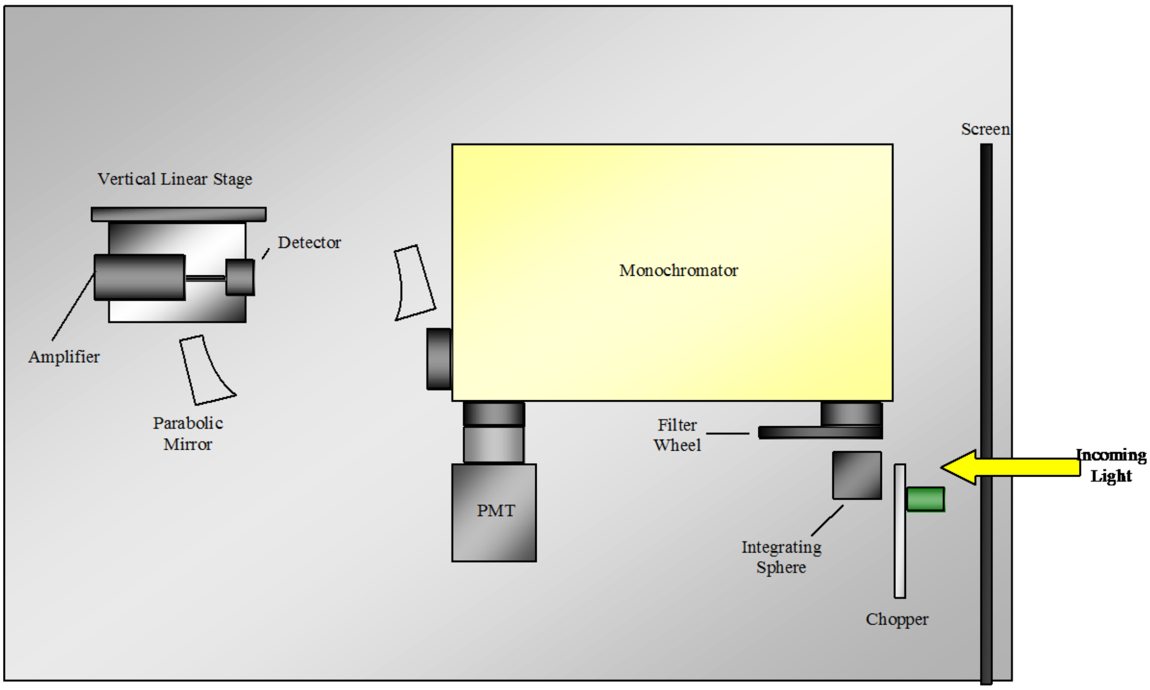

Figure 29. NPL SRIPS detector bench

A.1.4.2 Monochromator

The monochromator used was a Bentham DTM300 monochromator, arranged in a subtractive-mode double Czerny-Turner configuration. The monochromator was used with three grating pairs, and four different bandwidths, as listed in Table 12. Light entered the monochromator through a Spectralon integrating sphere, with an 8 mm diameter precision aperture, at the entrance port of the monochromator. Order sorting filters were placed between this sphere and the monochromator. The order sorting filter blocking, monochromator wavelength accuracy and stray light have all been thoroughly investigated [8] and are included in the uncertainty budget. These uncertainties vary with wavelength.

Table 12. SRIPS monochromator gratings

Grating	Lines per mm	Blaze wavelength	Wavelength range	Measurement bandwidth
UV	2400	250 nm	250 nm – 400 nm	2.5 nm
Visible	1200	500 nm	401 nm – 900 nm	5.0 nm
IR	600	1000 nm	850 nm – 1600 nm 1500 nm – 2500 nm	10 nm 20 nm

A.1.4.3 Detectors

A range of photodetectors, optimised for each spectral region, were used:

- 250 nm to 400 nm - photomultiplier tube (PMT) detector, operating in photon counting mode
- 400 nm to 1000 nm - Si photodiode
- 950 nm to 1600 nm - InGaAs detector
- 1600 nm to 2500 nm - InSb photoconductor with an integral cold filter, to minimise sensitivity to longer wavelengths, used in a phase sensitive detection mode.

Both the PMT and InSb detectors were temperature stabilised to minimise drift. The PMT was temperature stabilised to 19 ° C by means of a fan attached to the detector housing. The InSb detector was cooled by a liquid nitrogen filled housing.

The signal from the Si, InGaAs and InSb detectors was amplified using transimpedance current to voltage converters manufactured by Vinculum Ltd. The InSb detector was further amplified using a phase sensitive detection system, with the phase locked to the frequency of an optical chopper placed in front of the integrating sphere. The PMT was connected to an Electron Tubes Ltd. amplifier discriminator and counter timer.

A.1.4.4 Filter radiometers

The blackbody temperature was measured with an 800 nm filter radiometer used in conjunction with a geometric system to allow it to measure spectral radiance, in a similar manner to that described previously [1]. The filter radiometer comprised a diamond-turned brass aperture, a wedged interference filter with a 10 nm bandwidth and a silicon photodiode, and was housed in a water-cooled jacket. A Vinculum transimpedance amplifier was connected to the silicon photodiode and held in the same water jacket.

A 300 mm focal length lens was used at a distance of 600 mm to image light from the blackbody aperture so as to overfill the filter radiometer aperture. This aperture, and a thin-film aperture on the lens, defined the geometry of the measurement. The filter radiometer was used in the same f/55 geometry in which it had been calibrated. The lens transmittance was calculated using the Fresnel equations, which had previously [9] been shown to agree within 0.05 % of the measured value at this wavelength. A correction was also applied for differences in “size-of-source” based on measurements using similar techniques to those described previously [1].

Additional filter radiometers operating in “irradiance mode” (without a lens) were used to monitor any drift in the primary filter radiometer.

A.1.4.5 Laboratory

Measurements were made in a laboratory maintained at 22 °C ± 2 ºC. The humidity of the laboratory was not controlled.

A.1.3 MEASUREMENT PROCEDURE

Measurements were made at the wavelengths given in Table 13. Due to the length of time needed to measure a lamp over the full wavelength range, from 250 nm to 2500 nm, the measurement was split into two parts, the first from 250 nm to 1600 nm and the second from 1500 nm to 2500 nm. These measurements were typically conducted on adjacent days, with the lamps and blackbody turned off in between but with no re-alignment of the lamps. All lamps were measured in all spectral regions on at least two occasions and were realigned between each set of measurements in a new position on the SRIPS facility. Results were averaged over all measurements; where the wavelength ranges covered by the different grating and detector combinations overlapped, these results were also averaged.

Table 13. Measurement wavelengths

Detector	Grating	Start wavelength	Stop wavelength	Step size and extra wavelengths
PMT	UV	250 nm	400 nm	10 nm
Si	Visible	450 nm	900 nm	50 nm + 555 nm
Si	IR	850 nm	1000 nm	50 nm
InGaAs	IR	950 nm	1600 nm	100 nm + 950 nm
InSb	IR	1500 nm	2500 nm	100 nm

For the UV grating, Visible grating and IR grating regions, measurements were made in the following sequence:

1) Measurement of the temperature of the blackbody using filter radiometer.
2) Measurement of the blackbody using SRIPS over the required wavelength range, using the appropriate detector and grating combinations.
3) Measurement of the temperature of the blackbody with the filter radiometer. If the blackbody temperature had changed significantly, steps 1-3 were repeated and the previous results discarded.
4) Measurement of the lamps using SRIPS over the same wavelength range, sequentially with each lamp being turned on after the previous was turned off.
5) Measurement of the temperature of the blackbody with a filter radiometer.
6) Measurement of the blackbody using SRIPS over the same wavelength range.
7) Measurement of the temperature of the blackbody with the filter radiometer.
8) Measurement of the temperature of the blackbody with the filter radiometer. If the blackbody temperature had changed significantly, steps 6-7 were repeated and the previous results discarded.

A.1.4 UNCERTAINTY BUDGET

When the lamp irradiance is measured by using SRIPS, the measurement equation at any one wavelength is given by:

$$E_{\mathrm{lamp}}(\lambda_i) = \frac{V_{\mathrm{lamp}}(\lambda_i)}{V_{\mathrm{BB}}(\lambda_i,T)} \frac{\pi g}{A} L_{\mathrm{BB}}(\lambda_i,T) \frac{R_{\mathrm{SRIPS}}(\lambda_i)}{R_{\mathrm{SRIPS}}(\lambda_i)} \qquad (12)$$

where:

λ_i	Wavelength of measurement	$\frac{\pi g}{A}$	Geometric factor
$E_{\mathrm{lamp}}(\lambda_i)$	Lamp irradiance	$L_{\mathrm{BB}}(\lambda_i,T)$	Blackbody radiance
$V_{\mathrm{lamp}}(\lambda_i)$	Lamp signal	$\frac{R_{\mathrm{SRIPS}}(\lambda_i)}{R_{\mathrm{SRIPS}}(\lambda_i)}$	System responsivity (should cancel)
$V_{\mathrm{BB}}(\lambda_i,T)$	Blackbody signal		

Each element in the measurement equation has associated uncertainties. Table 14 shows the sources of these uncertainties, grouped into six categories related to different parts of Equation 12. These are discussed in more detail in Sections 6.4.1 to 6.4.6.

Figure 30 shows the typical standard uncertainty for a single measurement of a FEL lamp on the SRIPS facility, divided into those associated with random effect and those associated with systematic effects.

Table 14. Sources of uncertainty

Term in Equation 12	Sources of uncertainty (experimental influences)
λ_i	Monochromator wavelength accuracy Monochromator wavelength repeatability Appropriateness of assumption that monochromator bandpass is 'negligible' or uncertainty associated with correction.
$\frac{\pi g}{A}$	Measurement of aperture diameters Measurement of aperture separation
$L_{\mathrm{BB}}(\lambda_i, T)$	Knowledge of blackbody temperature Knowledge of blackbody emissivity Knowledge of blackbody absorption Blackbody uniformity Blackbody stability between temperature measurement and use
$E_{\mathrm{lamp}}(\lambda_i)$	Lamp alignment accuracy Lamp positioning accuracy Lamp current absolute setting
$V_{\mathrm{BB}}(\lambda_i, T)$ and $\frac{R_{\mathrm{SRIPS}}(\lambda_i)}{R_{\mathrm{SRIPS}}(\lambda_i)}$	Blackbody stability Signal noise in light reading Signal noise in dark reading Dark reading offset (additive) Linearity of system Stability of system for time of measurements Humidity changes in the laboratory
$V_{\mathrm{lamp}}(\lambda_i)$ and $\frac{R_{\mathrm{SRIPS}}(\lambda_i)}{R_{\mathrm{SRIPS}}(\lambda_i)}$	Lamp stability (multiplicative) Signal noise in light reading (multiplicative) Signal noise in dark reading (multiplicative) Dark reading offset (additive) Linearity of system Stability of system for time of measurements Humidity changes in the laboratory

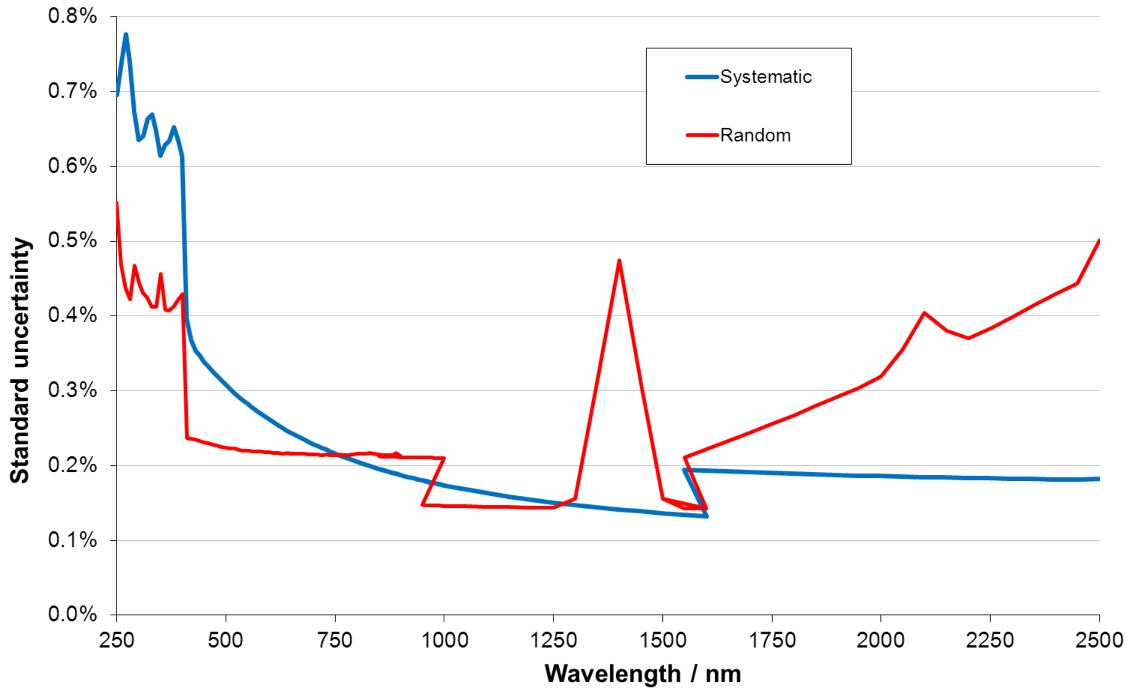

Figure 30. Typical random and systematic uncertainties (*k*=1) for a single measurement on a FEL lamp using SRIPS.

A.1.4.1 Uncertainties due to wavelength and bandwidth

The measurement wavelength is set by the monochromator, which uses three different gratings to cover the full spectral range of interest (250 nm to 2500 nm). The wavelength error has three components:

(1) An absolute error, caused, for example, by slight misalignments of the gratings or by an offset in the angular drive. This can be corrected by scanning a monochromatic source, such as a laser or the emission line from a low pressure mercury lamp, and subtracting the difference from the expected wavelength, but there will be a residual uncertainty associated with this correction.

(2) A wavelength dependent error that changes from one end of the grating to the other, but is constant with time. The wavelength-offset correction determined as described above applies at a single wavelength, and may not be the correct error term for another wavelength.

(3) A random effect that occurs when the measurement is taken at the same nominal wavelength, due to the fact that the monochromator may go to a slightly different wavelength each time.

The effect on the measured spectral irradiance of a wavelength error depends on the first derivative with respect to wavelength of the ratio of the lamp measurement to the blackbody measurement. If both sources are changing in the same way (similar first derivatives), then a wavelength error will affect each source equally and the net result will be reduced. If however, the sources are changing differently (particularly if one is increasing with wavelength while the other decreases) then a small wavelength error will have a larger effect on the calculated irradiance. For the calibration of a tungsten lamp against a blackbody at a similar operating temperature, this overall effect is small.

A related effect is bandwidth error. The measurements are made not at a single wavelength but over a narrow wavelength range. The effect of this depends on the second derivative of the signal ratios. This means that where the signal is changing linearly within the bandwidth and where the two signals have similar second derivatives, the effect is very small. This is the case for calibrating a tungsten lamp against a blackbody.

A.1.4.2 Uncertainties due to geometric factor

The geometric factor describes the energy transfer between two coaxial, parallel, circular apertures. It is therefore defined by the blackbody aperture, the integrating sphere aperture and the distance between them. The associated uncertainty in the measured spectral irradiance values is constant for all wavelengths.

The two apertures have been calibrated at NPL with known uncertainty. The distance between the apertures was measured using a calibrated measuring stick. The full distance uncertainty includes three uncertainty components – the uncertainty associated with the measurement of the recess distance between the front of the sphere and the sphere aperture (using a depth micrometer), the uncertainty associated with the calibration of the length of the measuring stick, and the repeatability of measurements using the measuring stick. The first two come from the associated calibration certificates, the latter from experimental experience, with different people setting and measuring the distance.

A.1.4.3 Uncertainties due to blackbody temperature

Uncertainties associated with the blackbody temperature are described in detail in the CCPR-K1.a report. However where appropriate they have been recalculated for the new SRIPS facility and the revised uncertainty is shown in Table 15. The associated uncertainty in the measured spectral irradiance values varies with wavelength, since the change in the Planck distribution resulting from a given change in blackbody temperature also varies with wavelength.

Table 15. Uncertainties associated with measurement of blackbody temperature

Uncertainty contribution	Value	Uncertainty in temperature / K
FR signal	1.41421E-05 V	0.004
Geometric factor	0.049 %	0.249
Amplifier gain	0.010 %	0.050
FR temperature correction	0.062 %	0.312
Absolute lens transmittance	0.040 %	0.202
Size of source effect	0.060 %	0.302
BB uniformity	0.010 %	0.050
BB emissivity	0.020 %	0.101
BB stability	0.050 %	0.252
FR absolute responsivity	0.062 %	0.312
FR relative responsivity		0.081
Combined standard uncertainty		**0.689**

A.1.4.4 Uncertainties due to lamp

There are two main sources of uncertainty associated with the lamp being measured: current and alignment. The uncertainty associated with the current is determined by two components: the stability of the current supplied to the lamp and the accuracy of the current setting. The SRIPS system uses a computer controlled power supply, PID loop and calibrated standard resistors to control and stabilise the lamp current. The uncertainty in the lamp current was determined from the PID control sensitivity and the resistor calibration certificates. The associated uncertainty in the measured spectral irradiance values varies with wavelength.

The uncertainties associated with alignment of the lamp are due to the setting of the lamp distance at 0.5 m and the alignment of the lamp to the optical axis. The associated uncertainty in the measured spectral irradiance values is independent of wavelength. The distance uncertainty includes uncertainties associated with the length of the measuring stick, the measurement of the sphere aperture depth, the telescope alignment and the optical rail alignment. The uncertainty associated with alignment of the lamp relative to the optical axis was determined by evaluating the difference between the repeatability of the lamp without realignment and the repeatability when the lamp was re-aligned between each measurement. The difference of these repeatabilities gave the uncertainty due to alignment only.

A.1.4.5 Uncertainties due to system responsivity and measurement of blackbody irradiance

The uncertainty associated with measurement of the blackbody spectral irradiance comes in part from the stability of the blackbody temperature, which has already been mentioned (Section 6.4.3), and random effects. These random effects (that also affect the system stability) can change on different timescales:

- At very short timescales (up to a couple of seconds) the measured signal changes due to random noise from electrical and optical shot noise, etc. This is seen by looking at the standard deviation of multiple measurements made on a very short timescale.
- At medium timescales (5 – 20 minutes) the signal changes due to the blackbody and system stability. This can be seen in the repeatability of multiple repeat measurements of the blackbody.
- Over longer timescales (3 – 6 hours) the system can drift due to changes such as room humidity, or changes in the monochromator throughput. The blackbody is measured at the beginning and end of each measurement run in order to monitor this drift.

In addition to these random effects, there can also be a systematic effect where the system responsivity is different for the two sources. This can be due to linearity or stray light within the monochromator, for example. For the measurement of a tungsten lamp against a blackbody, where both sources have very similar spectral profiles, such effects are generally insignificant. However analysis of the results from the comparison suggest that around the water absorption lines (~1400 nm in particular) the SRIPS system does behave differently for the lamp and blackbody, possibly due to differences in humidity as a result of different heating effects for the two sources.

All these effects have been evaluated and allowed for in the uncertainty budget. The associated uncertainty in the measured spectral irradiance values varies with wavelength.

A.1.4.6 Uncertainties due to measurement of lamp irradiance

The random system effects described above (A.1.4.5) as being associated with measurement of the blackbody spectral irradiance are also important for measurement the lamp irradiance and are therefore included twice in the uncertainty budget. The only term that differs significantly between the two types of source (lamp and blackbody) is the very-short-timescale effect (the SEOM of the measurements). This is because the sources have very different irradiance levels in the UV, meaning that the signal-to-noise is very different in this region. This uncertainty is therefore calculated separately for each measurement.

A.1.4.7 Uncertainty budget summary

Typical uncertainties for measurement of the spectral irradiance of a FEL lamp using SRIPS are given in Table 16 below. The uncertainties associated with correlated effects were the same for all lamps measured at NPL during the course of the comparison. The uncertainties associated with uncorrelated effects were determined separately for each lamp, since these were dependent on the performance of each individual lamp (see Section 6.4.6).

Table 16. Uncertainties associated with measurement of lamp spectral irradiance at NPL

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
250	0.41 %	0.70 %	0.82 %	1.64 %
260	0.32 %	0.74 %	0.81 %	1.62 %
270	0.31 %	0.78 %	0.84 %	1.68 %
280	0.30 %	0.74 %	0.80 %	1.61 %
290	0.36 %	0.67 %	0.77 %	1.54 %
300	0.35 %	0.64 %	0.73 %	1.47 %
310	0.35 %	0.64 %	0.74 %	1.47 %
320	0.37 %	0.66 %	0.76 %	1.53 %
330	0.37 %	0.67 %	0.77 %	1.54 %
340	0.38 %	0.65 %	0.75 %	1.51 %
350	0.45 %	0.61 %	0.76 %	1.53 %
360	0.39 %	0.63 %	0.75 %	1.49 %
370	0.40 %	0.63 %	0.75 %	1.51 %
380	0.42 %	0.65 %	0.78 %	1.56 %
390	0.42 %	0.63 %	0.76 %	1.53 %
400	0.42 %	0.61 %	0.75 %	1.50 %
450	0.31 %	0.34 %	0.46 %	0.92 %
500	0.30 %	0.31 %	0.43 %	0.86 %
550	0.31 %	0.28 %	0.42 %	0.84 %
555	0.31 %	0.28 %	0.42 %	0.84 %
600	0.32 %	0.26 %	0.41 %	0.83 %
650	0.33 %	0.24 %	0.41 %	0.82 %
700	0.34 %	0.23 %	0.41 %	0.81 %
750	0.34 %	0.22 %	0.40 %	0.81 %
800	0.35 %	0.21 %	0.40 %	0.80 %
850	0.13 %	0.20 %	0.24 %	0.47 %
900	0.14 %	0.19 %	0.23 %	0.47 %
950	0.12 %	0.18 %	0.22 %	0.43 %
1000	0.12 %	0.17 %	0.21 %	0.43 %
1100	0.16 %	0.16 %	0.23 %	0.45 %
1200	0.16 %	0.15 %	0.22 %	0.45 %
1300	0.18 %	0.15 %	0.23 %	0.46 %
1400	0.52 %	0.14 %	0.54 %	1.07 %
1500	0.15 %	0.14 %	0.20 %	0.41 %
1600	0.14 %	0.13 %	0.19 %	0.39 %
1700	0.36 %	0.19 %	0.40 %	0.81 %
1800	0.36 %	0.19 %	0.41 %	0.82 %
1900	0.37 %	0.19 %	0.42 %	0.84 %
2000	0.42 %	0.19 %	0.46 %	0.92 %
2100	0.48 %	0.18 %	0.51 %	1.02 %
2200	0.44 %	0.18 %	0.48 %	0.95 %
2300	0.45 %	0.18 %	0.49 %	0.97 %
2400	0.48 %	0.18 %	0.51 %	1.02 %
2500	0.86 %	0.18 %	0.88 %	1.76 %

A.2. MEASUREMENTS AT PTB, GERMANY (SECOND LINK LABORATORY)

The PTB measurements have been described in detail for the CCPR-K1.a intercomparison in [1]. Since then the primary scale realisation has not been modified. Nevertheless the measurement facility for the lamp calibration was completely rebuilt in 2006 in a new building. Extensive measurements of a group of standard lamps (including the CCPR-K1.a lamps) and several scale realisations with the

PTB blackbody were used to validate the new facility. Since the 2000 scale realization for the CCPR-K1.a intercomparison the spectral irradiance scale of the PTB has not been changed or modified.

A.2.1 PRIMARY SCALE REALISATION

The spectral irradiance scale at the PTB in Braunschweig is realized, maintained and disseminated [10] using a high temperature blackbody radiator of type BB3200pg [11]. The various radiometric parameters of this black body have been characterized in detail and it has been found very suitable for use as a primary standard of spectral irradiance [4, 12, 13]. The main parameter of a black body, the temperature, has to be determined very accurately. At the PTB in Braunschweig, broadband-filter detectors are well established for the detector-based determination of the so-called radiometric temperature [12]. Improvements of this procedure and comparisons with other methods have been carried out [13, 14].

The spectral irradiance at the reference plane of the spectroradiometer was calculated according to Planck's law using the geometric parameters and the measured radiometric temperatures of the blackbody.

A.2.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.2.2.1 Facility for spectral irradiance realisation

The PTB spectroradiometer for spectral irradiance calibrations (see Figure 31) consists of an integrating sphere as entrance optics, an Acton-Research Spectra-Pro^{TM}-500 double monochromator system with triple grating turrets and three detectors to cover the spectral range from 250 nm to 2500 nm [15]. The entrance port of the integrating sphere is formed by a precise aperture which defines the reference plane for spectral irradiance measurements. The detectors at the exit ports of the monochromators are a photomultiplier tube for the spectral range from 250 nm to 670 nm, a Si-Photodiode (680 nm to 1100 nm) and an extended InGaAs-detector (1200 nm to 2500 nm). A built-in monitor lamp is used to monitor the stability of the spectroradiometer system during extended measurement campaigns. The system is placed on a translation stage to allow the quasi-simultaneous measurement of a group of lamps with respect to the blackbody radiation.

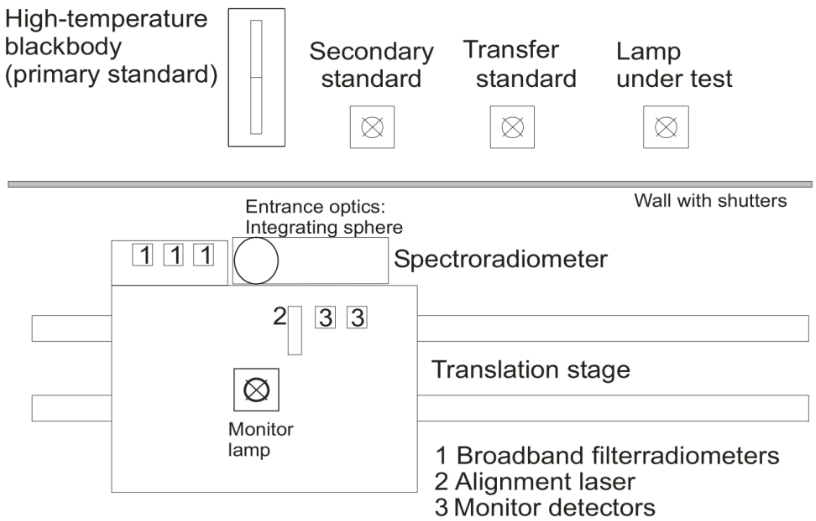

Figure 31. Set-up of the spectroradiometer facility at PTB.

A.2.2.2 Laboratory

The measurement facility is located in the Albert-Einstein building at the PTB Braunschweig. The building has been finished in 2003 and contains air-conditioned labs with a constant relative humidity of 50 % ± 5 % at 22 °C ± 0.5 °C.

A.2.3 MEASUREMENT PROCEDURE

The measurement procedure is documented in the PTB quality-management system in document QM-AA-4.11-02 (spectral irradiance calibrations).

The blackbody, working standards, or lamps under test, were measured in nearly identical optical configurations of the system in different successive measurement cycles covering each the entire wavelength range for the comparison (250 nm – 2500 nm). The stability of the system was assured using the monitor lamp during each measurement cycle such that the photo-signal caused by the blackbody source, the standard lamp, or the test lamp was directly compared to the photo-signal caused by the monitor lamp at each wavelength position by opening two different entrance ports of the integrating sphere. The stability of the monitor lamp is known to be better than $1 \cdot 10^{-3}\ h^{-1}$ in the UV spectral region.

During each measurement campaign at the PTB where the spectral irradiance scale is realised, the standard lamps have been measured repeatedly in alternation with blackbody measurements and measurements of the PTB working standards. The disseminated spectral irradiance scale was averaged over multiple blackbody calibrations using the photo-signal ratio to the monitor lamp. The results were compared to earlier scale realisations using selected standard lamps. This internal comparison has been used to validate the new measurement facility in comparison with the spectral irradiance scale realisation in 2002 used for the CCPR-K1.a comparison (Figure 32).

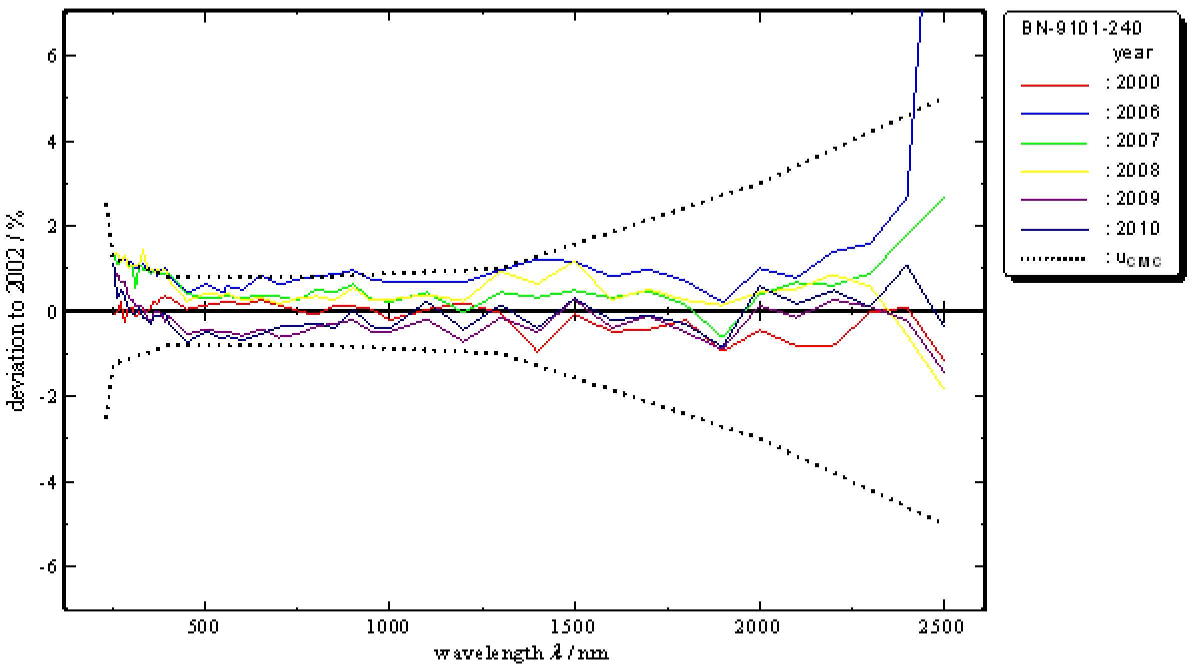

Figure 32. Exemplary validation of independent spectral irradiance realisations compared to the 2002 measurements (CCPR-K1.a): Repeated calibration of lamp BN-9101-240.

A.2.4 UNCERTAINTY BUDGET

A detailed uncertainty analysis is given in [1].

Table 17. Uncertainties associated with measurement of lamp spectral irradiance at PTB

Wavelength / nm	Uncertainty associated with correlated (systemtic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
250	0.30 %	0.52 %	0.60 %	1.20 %
260	0.29 %	0.50 %	0.58 %	1.16 %
270	0.29 %	0.50 %	0.58 %	1.16 %
280	0.29 %	0.50 %	0.58 %	1.16 %
290	0.29 %	0.50 %	0.58 %	1.16 %
300	0.29 %	0.49 %	0.57 %	1.14 %
310	0.24 %	0.41 %	0.48 %	0.95 %
320	0.24 %	0.41 %	0.48 %	0.95 %
330	0.24 %	0.41 %	0.48 %	0.95 %
340	0.24 %	0.41 %	0.48 %	0.95 %
350	0.24 %	0.41 %	0.48 %	0.95 %
360	0.21 %	0.35 %	0.41 %	0.82 %
370	0.21 %	0.34 %	0.40 %	0.80 %
380	0.21 %	0.35 %	0.41 %	0.82 %
390	0.21 %	0.34 %	0.40 %	0.80 %
400	0.21 %	0.34 %	0.40 %	0.80 %
450	0.17 %	0.30 %	0.35 %	0.69 %
500	0.17 %	0.29 %	0.34 %	0.68 %
550	0.17 %	0.29 %	0.34 %	0.68 %
555	0.17 %	0.29 %	0.34 %	0.68 %
600	0.17 %	0.29 %	0.34 %	0.68 %
650	0.11 %	0.34 %	0.36 %	0.71 %
700	0.11 %	0.34 %	0.36 %	0.71 %
750	0.11 %	0.34 %	0.36 %	0.71 %
800	0.11 %	0.34 %	0.36 %	0.71 %
850	0.08 %	0.27 %	0.28 %	0.56 %
900	0.08 %	0.27 %	0.28 %	0.56 %
950	0.08 %	0.27 %	0.28 %	0.56 %
1000	0.08 %	0.27 %	0.28 %	0.56 %
1100	0.08 %	0.42 %	0.43 %	0.86 %
1200	0.08 %	0.42 %	0.43 %	0.86 %
1300	0.08 %	0.42 %	0.43 %	0.86 %
1400	0.07 %	0.99 %	0.99 %	1.99 %
1500	0.07 %	0.99 %	0.99 %	1.99 %
1600	0.07 %	0.99 %	0.99 %	1.99 %
1700	0.07 %	1.00 %	1.00 %	2.00 %
1800	0.07 %	1.00 %	1.00 %	2.00 %
1900	0.07 %	1.02 %	1.02 %	2.04 %
2000	0.07 %	1.03 %	1.03 %	2.06 %
2100	0.06 %	1.24 %	1.24 %	2.48 %
2200	0.06 %	1.22 %	1.22 %	2.44 %
2300	0.06 %	1.23 %	1.23 %	2.46 %
2400	0.06 %	1.20 %	1.20 %	2.40 %
2500	0.19 %	2.20 %	2.21 %	4.42 %

A.2.5 COMPARISON LAMPS

The following lamps were used for the intercomparison:

BN-9101-227, BN-9101-240 (lamps used during the CCPR K1.a intercomparison)

PTB-SL-196, PTB-SL-197 (PTB working standards).

All four lamps are 1000 W FEL-type quartz-halogen lamps. The lamps were measured at a distance of 500 mm with respect to the front plate of their mount using alignment jigs supplied with the lamps. The lamps were all operated at 8.1 A constant DC current. The polarity was marked at the lamp's mount. The lamps showed no significant voltage changes during their operations. Measurements were made in the sequence PTB-NPL-PTB-NPL. The lamps were hand-carried between the NMIs.

BN-9101-227		lamp voltage	burning time
PTB	Jan 2009	104.544 V	7:06 h
NPL	Jun 2010	104.561 V	5:04 h
PTB	Jul 2010	104.614 V	2:21 h
NPL	Jan 2011	104.536 V	4:28 h

BN-9101-240		lamp voltage	burning time
PTB	Feb 2009	111,061 V	7:08 h
NPL	Jun 2010	111,110 V	5:00 h
PTB	Jul 2010	111,138 V	2:21 h
NPL	Jan 2011	111.099 V	4:22 h

PTB-SL-196		lamp voltage	burning time
PTB	Jan 2009	101.761 V	7:04 h
NPL	Jun 2010	101.744 V	5:15 h
PTB	Aug 2010	101.755 V	2:21 h

PTB-SL-197		lamp voltage	burning time
PTB	Jan 2009	102.041 V	7:05 h
NPL	Jun 2010	102.155 V	5:12 h
PTB	Aug 2010	102.080 V	2:20 h
NPL	Jan 2011	102.047 V	4:22 h

A.3. MEASUREMENTS AT INM-RO, ROMANIA

A.3.1 PRIMARY SCALE REALISATION

The INM spectral irradiance reference standards are traceable to the Metrology Research Institute of the Helsinki University of Technology (Calibration certificate T-R 527 / 2008).

A.3.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.3.2.1 Facility for spectral irradiance measurements

The INM measurement set up is shown in Figure 33. The flux generated by the lamp under test was integrated by a sphere with a diameter of 80 mm, coated with a thick layer of $BaSO_4$. The sphere had an input aperture of 30 mm. The sphere wall was imaged on the input slit of the monochromator with an achromatic lens. A black painted trap was used to block the flux emitted backwards or reflected by the surrounding walls. For the lamp alignment procedure, the trap was removed from the optical path. An f8 Ebert monochromator was used at fixed wavelengths. The monochromator bandwidth was set at 3.0 nm +/- 0.2 nm and its wavelength scale was calibrated against low pressure, spectral Hg and He lamps with an estimated combined uncertainty: *u* = 0.5 nm. The flux collected at the exit slit of the monochromator was converted to an electrical signal by a photometric system consisting of a photomultiplier, a transimpedance amplifier and a digital multimeter set on the 100 mV dc range. According to previous characterisations, the photometric system provides for an estimated combined measurement uncertainty: *u* = 0.10 %.

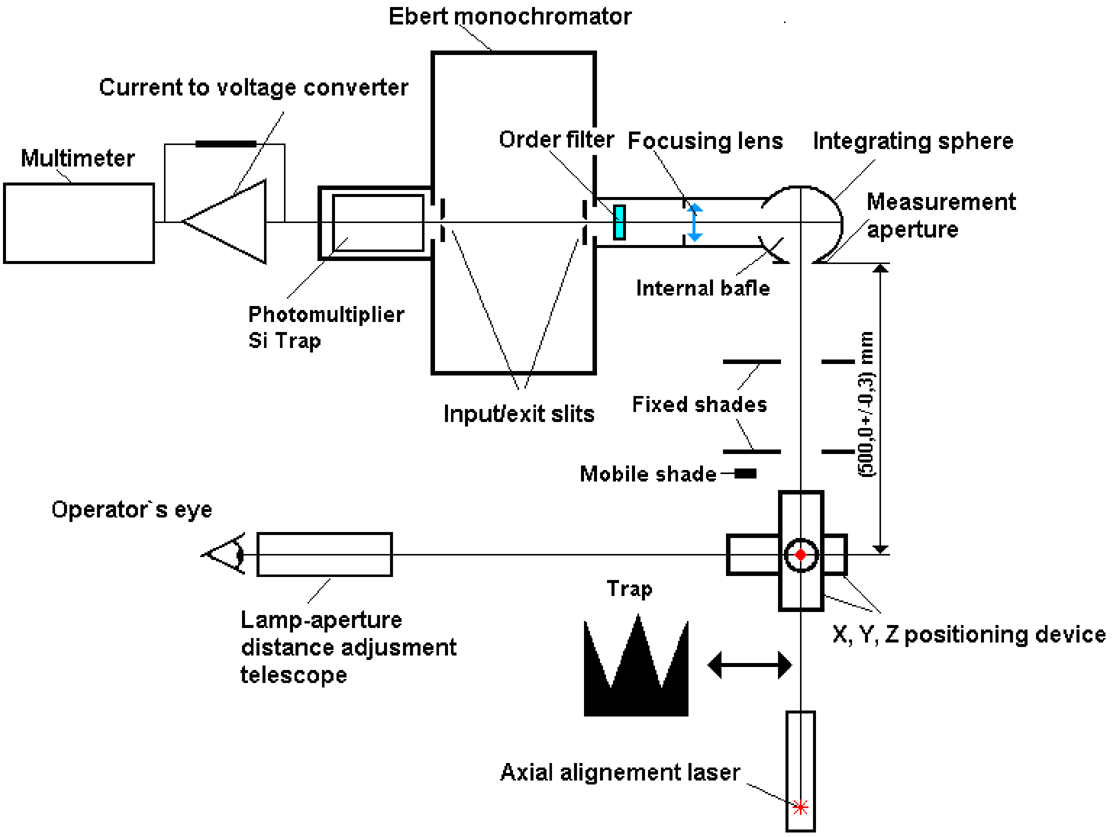

Figure 33. INM Spectral irradiance measurement setup

The lamps were supplied with highly stabilised dc current, according to the scheme given in Figure 34. The standard resistor and the DVMs were calibrated by the dc calibration laboratory of INM, according to its corresponding CMCs and accreditation scope (see www.kcdb.org/appendixC and www.dkd.eu).

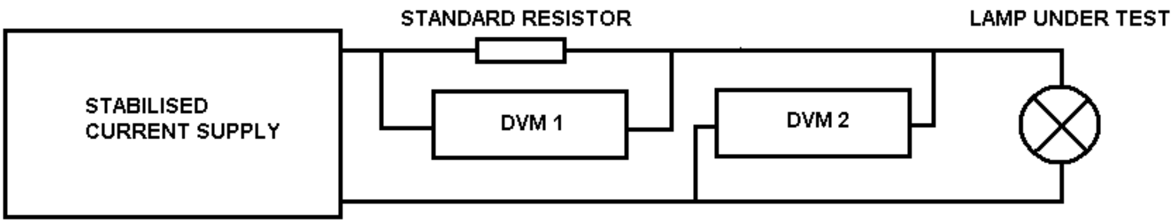

Figure 34. Lamp supply and control at INM

A laser diode was used for individual lamp alignment to the integrating sphere axis. A system providing four degrees of freedom was used. The alignment device provided with each lamp was used in order to align the lamp filament to the integrating sphere entrance aperture. The EURAMET.PR-K1.a protocol recommendations were closely followed. Briefly:

- First, the irradiance axis was adjusted with a small pointer laser as to be horizontal and to intercept the centre of the integrating sphere (Figure 33). (The pointer remained fixed throughout the measurements of the comparison.)
- Next, the viewing axis was adjusted as to be normal to and to intercept the irradiance measurement axis at a distance of 500 mm from the input aperture centre. A small viewing telescope was used for this purpose.
- Finally, each of the measured lamps (including the reference standard) were mounted on the X, Y, Z positioning device and the small adjustment devices provided with the lamps were used in order to perform final adjustment of their filaments to the irradiance axis.

All in all, considering the physical dimensions of the filaments and their spatial stability when supplied, this system was assumed to ensure a lamp filament (axis) – sphere aperture distance of 500.0 mm, with a combined estimated uncertainty: u =0.5 mm (0.1 %).

A.3.2.2 Laboratory

The measurements were performed on an optical table, mounted in an isolated room. The environmental parameters (temperature and humidity) were controlled throughout the measurements.
T = (24+/-1) °C
Rh = (30+/-5) %

A.3.3 MEASUREMENT PROCEDURE

The INM laboratory used a substitution technique. For each lamp, the measurement sequence was as follows:

Comparison lamp - Standard lamp - Comparison lamp

As reported in the lamp burning sheets, for each of the circulated lamps, this sequence was repeated three times. For every comparison lamp the following procedure was followed:

(i) Measurements for all wavelengths were performed.
(ii) The lamp was then replaced with the reference standard lamp and the measurements on the standard lamp were performed at all wavelengths.
(iii) The reference standard was replaced again with the comparison lamp and the measurements were performed at all wavelengths.

Note 1: In order to allow for the dark signal correction, for a given lamp (standard or unknown), the irradiance measurements at a given wavelength were performed in a time symmetrical sequence: lamp signal – dark signal – lamp signal.

Note 2: The dark signal was recorded with a small baffle inserted in the optical path so as that only the directly emitted flux was blocked from reaching the sphere aperture while most of the stray light reflected by the surrounding walls was taken into consideration (Figure 33).

Note 3: For every lamp, the measurements were performed after the warm up time.

For a given wavelength, the mean measurement reading was computed using Equation 13:

$$\overline{Y_x(\lambda)} = \frac{\overline{Y_{x1}(\lambda)} + \overline{Y_{x2}(\lambda)} - 2\overline{Y_d(\lambda)}}{2} \qquad (13)$$

where:

$\overline{Y_{x1}(\lambda)}$ is the mean first reading;

$\overline{Y_{x2}(\lambda)}$ is the mean second reading;

$\overline{Y_{d}(\lambda)}$ is the mean dark signal reading;

Averaging was performed by setting the DVM on the slow integrating mode and averaging 5 consecutive readings resulting in ~10 s averaging for each reading.

A.3.4 UNCERTAINTY BUDGET

A.3.4.1 Origin of uncertainty budget

The uncertainty components mainly originate in the calibration of the standard lamp used and in the calibration technique. The spectral irradiance of the lamp under test, $E_x(\lambda)$, was estimated according to Equation 14:

$$E_x(\lambda) = E_E(\lambda) * C_0^E * \frac{\overline{Y_x(\lambda)} * C_1^x * C_2^x * C_3^x * C_4^x * C_5^x * C_6^x * C_7^x * C_8^x}{\overline{Y_E(\lambda)} * C_1^E * C_2^E * C_3^E * C_4^E * C_5^E * C_6^E * C_7^E * C_8^E} * C_9^x \qquad (14)$$

where:

$E_E(\lambda)$ is the spectral irradiance of the standard lamp, at wavelength, λ, as specified in its calibration certificate. Its associated uncertainty is given in the standard lamp calibration certificate and is considered as a B type component.

$\overline{Y_x(\lambda)}$ is the mean reading for the comparison lamp, at wavelength λ.

$\overline{Y_E(\lambda)}$ is the mean reading for the standard lamp at the wavelength λ.

C_0^E is the correction factor for lamp drift in the reference lamp (see below), with an associated standard uncertainty.

C_1^x, $C_1^E = 1.0000$ are correction factors for the current in each lamp filament.

$C_2^x = C_2^E = 1.0000$ are correction factors for the wavelength setting when the standard lamp/lamp under test are measured; *u* ~ 0.50 % (type B, normal distribution).

$C_3^x = C_3^E = 1.0000$ are correction factors for the measurement distance in the case of the standard lamp/lamp under test; *u* ~ 0.20 % (type B, normal distribution).

$C_4^x = C_4^E = 1.0000$ are correction factors for standard lamp/lamp under test alignment; *u* ~ 0.10 % (type B, normal distribution)

$C_5^x = C_5^E = 1.0000$ are correction factors for ambient temperature during standard lamp/lamp under test measurements; *u* ~ 0.20 % (type B, normal distribution)

$C_6^x = C_6^E = 1.0000$ are correction factors for stray light when the standard lamp/unknown lamp are under test measurements; *u* = 0.10 % (type B, normal distribution).

$C_7^x = C_7^E = 1.0000$ are correction factors for the photometric linearity when the standard lamp/unknown lamp are measured; *u* = 0.10 % (type B, normal distribution).

$C_8^x = C_8^E$ are correction factors for the photometric system drift during standard lamp/unknown lamp measurements; *u* = 0.10 % (type B, normal distribution).

C_9^x is the repeatability correction factor; *u* = 0.20 % at 400 nm and 0.15 % for other wavelengths (type A, normal distribution).

The value of the drift correction factor, C_0^E, was determined as follows. The reference lamps were calibrated by the Metrology Research Institute of the Helsinki University of Technology in May 2008 and were not burned until their use in this comparison. Hence, for the first calibration at INM, the correction was $C_0^E = 1.0000$. For subsequent operations the drift of the reference lamps values was computed with the formula:

$$C_0^E = (100 + t * \frac{\partial E}{\partial t})/100\,. \tag{15}$$

It was assumed that

$$\frac{\partial E}{\partial t} = -0{,}05\%/h\,. \tag{16}$$

Hence, for the second calibration at INM, a drift correction factor was applied with a residual estimated uncertainty of 0.17 % (type B, rectangular distribution) i.e. standard uncertainty u = 0.10 %. The estimated relative uncertainty of C_1^x, C_1^e was determined as follows:

Since $$E = E_R \cdot \left(\frac{I}{I_R} \right)^m \tag{17}$$

where:

I_R is the specified current flown in the lamp filament;
E_R is the generated irradiance for the specified current;
E is the irradiance generated for a current I, close to the specified current I_R.

Then: $$\frac{\partial E}{\partial I} = m \cdot \frac{E}{I} \tag{18}$$

or: $$\frac{\partial E}{E} = m \cdot \frac{\partial I}{I} \tag{19}$$

The m exponent may be experimentally estimated as a function of wavelength:

$$m(\lambda) = \frac{\Delta Y(\lambda) \cdot I(\lambda)}{\Delta I(\lambda) \cdot Y(\lambda)} \tag{20}$$

where ΔY is the change in reading corresponding to the incremental increase in current ΔI. The experimentally estimated values of $m(\lambda)$ as a wavelength function range from ~6.5 at 400 nm to ~3.5 at 1000 nm. The irradiance relative uncertainty u_E generated by the relative uncertainty of the current in the lamp filament u_I , is:

$$u_E = m(\lambda) \cdot u_I \tag{21}$$

Thus, for a relative absolute uncertainty of the filament current of 0.0125 %, the relative irradiance uncertainty will range from ~0.08 % (at 400 nm) to 0.04 % (at 1000 nm).

A.3.4.2 Uncertainty budget summary

According to Equation 14, for each measurement wavelength, the irradiance uncertainties of the reference standard $E_E(\lambda)$ (as given in the calibration certificate from HUT and ranging from 0.8 % at 400 nm to 0.6 % at all other wavelengths) are correlated (systematic) components to all measurements. All other components listed in Section 9.4.1 are uncorrelated (random) components. Their combined contribution is ~ 0.9 % for all comparison wavelengths.

Table 18. Uncertainties associated with measurement of lamp spectral irradiance at INM-RO / %

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
400	0.8	0.9	1.2	2.4
450	0.6	0.9	1.1	2.2
500	0.6	0.9	1.1	2.2
550	0.6	0.9	1.1	2.2
555	0.6	0.9	1.1	2.2
600	0.6	0.9	1.1	2.2
650	0.6	0.9	1.1	2.2
700	0.6	0.9	1.1	2.2
750	0.6	0.9	1.1	2.2
800	0.6	0.9	1.1	2.2
850	0.6	0.9	1.1	2.2
900	0.6	0.9	1.1	2.2

A.3.5 COMPARISON LAMPS

Three FEL lamps of BN 9101 type, produced by Gigahertz were used in the comparison. The serial numbers were: BN 9101- 472, BN 9101- 473 and BN 9101- 473, respectively.

Alignment and operation were performed according to the comparison protocol and Section 9.2.1 of this report.

The lamps were supplied with stabilised dc current as shown in Figure 34. The shunt resistor value is traceable to the national standard of Romania and was calibrated by the INM dc calibrations laboratory, according to its published CMC (please see www.kcdb/appendix C). A multimeter calibrated by the same laboratory was used. This way, the current was controlled at 8.100 A to ± 0.002 A.

All lamps performed very well as specified in the burning record sheets.

Nothing unexpected happened during the INM calibration.

A.4. MEASUREMENTS AT METAS

A.4.1 PRIMARY SCALE REALISATION

Since 1994 the spectral irradiance scale of METAS has been traceable to the NPL irradiance scale through regular calibration (typically every 3 to 4 years) of a set of 3 lamps. The scale is maintained on a set of FEL 1000W lamps. The last transfer to the NPL scale was realized in October 2007. In addition, METAS uses a 15 channel filter radiometer to monitor the stability of the spectral irradiance scale between 400 nm and 900 nm. The filter radiometer is traceable via the spectral responsivity scale to the METAS cryogenic radiometer.

The traceability of the primary quantities (i.e. spectral irradiance) and secondary quantities (i.e. current, voltage, wavelength) is illustrated in Figure 35:

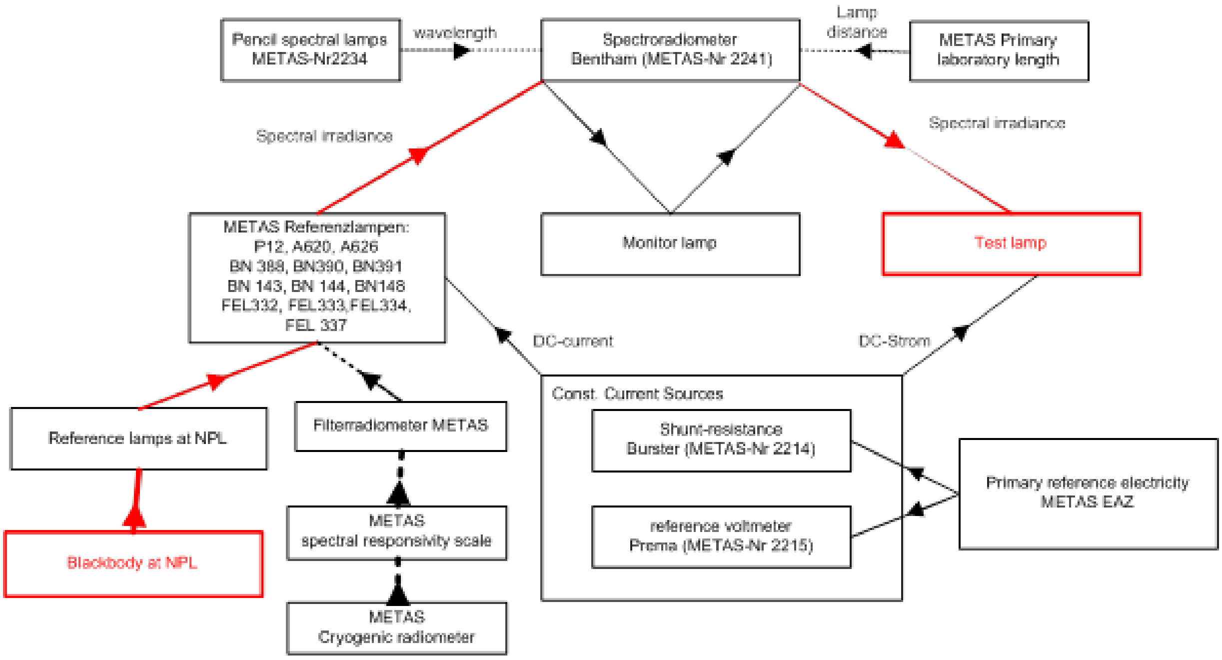

Figure 35. Traceability at METAS.

A.4.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.4.2.1 Facility for spectral irradiance realisation

The setup of the spectroradiometer is schematically shown in Figure 36. The measuring system consists of four main components of the input optics, wavelength selection, detection and evaluation and control electronics. The radiation of the reference lamp and the test lamp passes through an entrance aperture defined in a predefined reference distance from the lamp into an integrating sphere with internal diffuser screen. The radiation of a monitor lamp is coupled into the sphere at 90° to the measurement-beam path. Two computer controlled shutters allow the selection of measuring radiation. The reason for this arrangement is due to the mechanical properties of the grating drive of the monochromator. As a result of unavoidable small fluctuations in the grating positioning, the spectral transmittance of the monochromator changes randomly slightly between a test series to the next, leading to variations in measurement results. Using a monitor lamp, this error is reduced if the monitor lamp is sufficiently stable. Furthermore, the influence of temporal fluctuations in the photomultiplier gain is reduced, as is the measurement of test and monitor lamp at a wavelength within a short time. As the first step of the transfer is made only every 30h of monitor burning time, the ageing of the reference lamps is minimised.

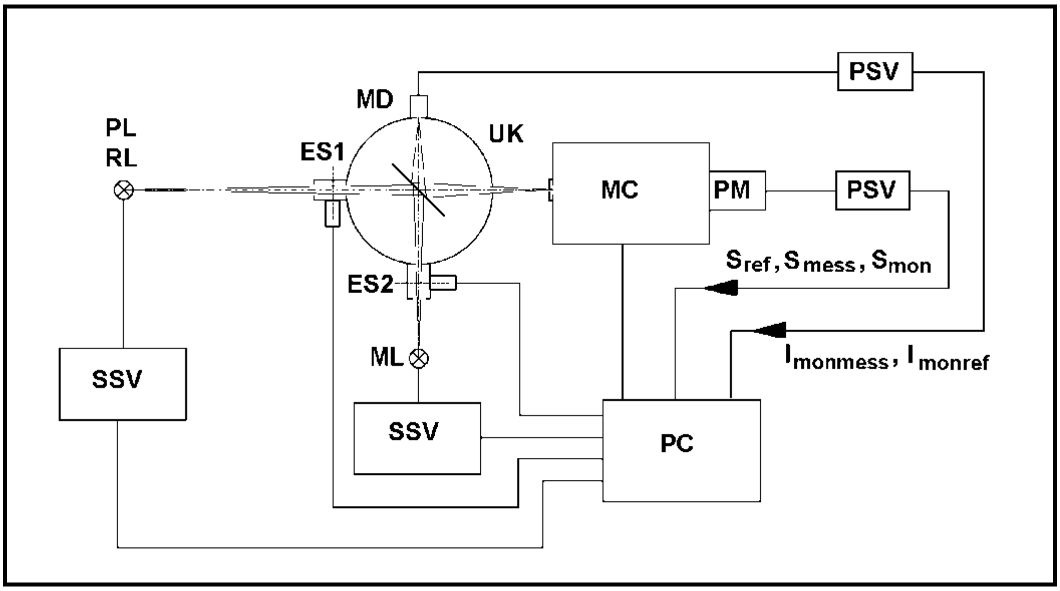

Figure 36. Set up of the spectroradiometer: PL: test lamp, RL: reference lamp, ML: monitor lamp, UK: integrating sphere: ES1 ES2: electronical shutter, ssv: stabilized power supply, MC: double monochromator, PM: photomultiplier / silicon diode, MD: monitor detector (integral signal), PSV: picoammeter, PC: computer control.

A.4.2.2 Laboratory

The laboratory is composed of two rooms: The lamp room and the device room (see Figure 37). Both rooms are equipped with temperature monitors. The room temperature is maintained in the range (22 ± 1) °C, the relative humidity between 30 % and 45 %.

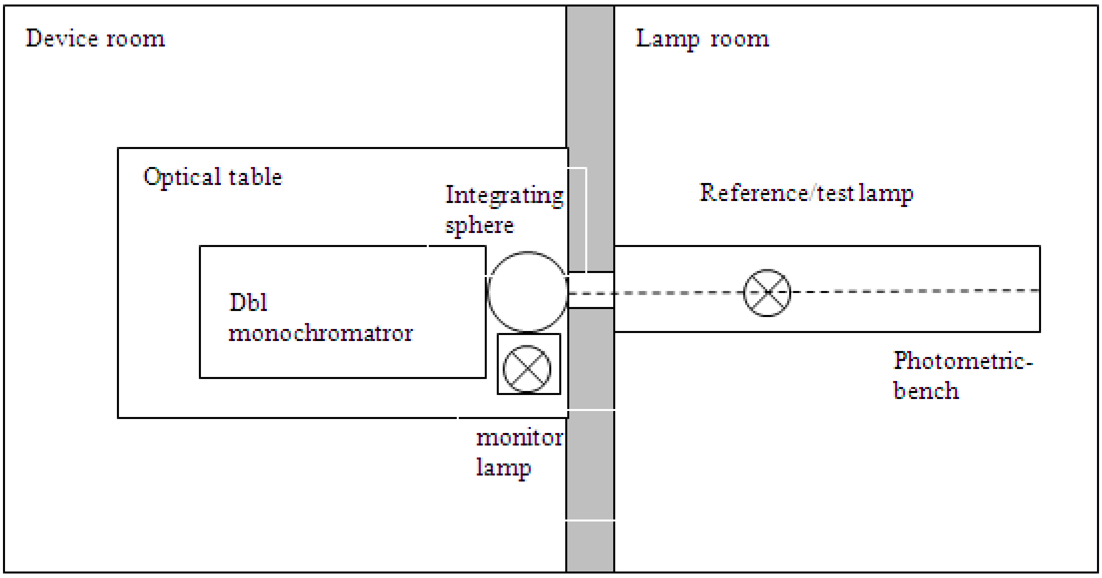

Figure 37. Laboratory arrangement

A.4.3 MEASUREMENT PROCEDURE

The input optics of the monochromator is composed of an integrating sphere with two entrance port: One for the reference and test lamps and a second with a fixed installed monitor lamp. The calibration is done in two steps: First the monitor lamp is compared at each wavelength to a reference lamp. In the second step the reference lamp is replaced by the test lamp. To make the transfer to the monitor lamp, usually a set of three reference lamp is used. This transfer is made typically every 30 h burning time of the monitor lamp. Each reference or test lamp is measured at least three times. At each wavelength the number of measurement is repeated until the standard deviation of the mean is smaller than 0.1 % but at maximum 30 times.

The alignment of the lamp is made by different laser and telescopes according to the internal calibration procedure 116.21K01 which is in full agreement with the technical protocol of this comparison (see Figure 38).

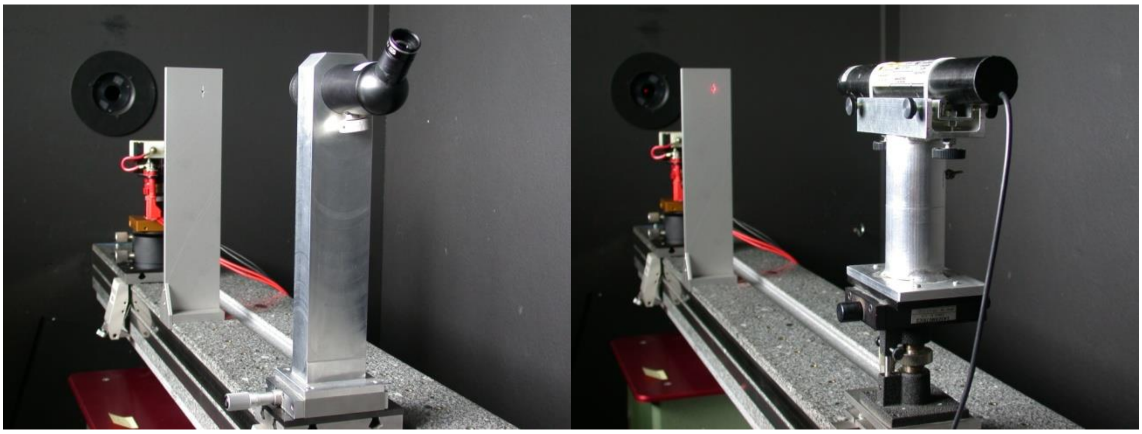

Figure 38. Lamp alignment system.

An absolute encoded magnetic ruler with a reading uncertainty of 0.1 mm is used for the distance measurement (see Figure 39).

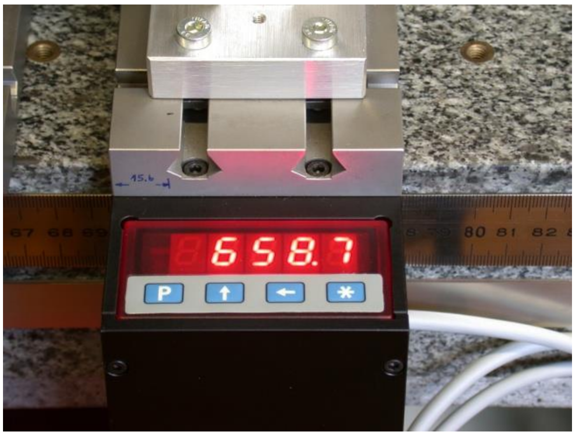

Figure 39. Absolute encoded magnetic ruler

A.4.4 UNCERTAINTY BUDGET

A.4.4.1 Origin of uncertainty budget

All contributions were determined by prior knowledge, except the stability of the lamps and the drift of the measurement scale. As indicated above, the last calibration of the reference lamps to the NPL scale was carried out in October 2007. The scale was then directly transferred to a set of 6 working lamps. For regular measurement the scale is maintained on the monitor lamp (see description of the system), calibrated through the working lamps. For this comparison, however, the transfer lamps were reused. The overall burning time of the transfer lamps since their calibration at NPL was about 8h and a “worst case” drift of 1 % (found by filter radiometer measurements) has been taken into account in the uncertainty budget.

The wavelength dependent contribution is mainly composed of the uncertainty of the reference lamps, correlated to all measurements. It also includes a contribution for the uncertainty in lamp current, which is based on the following assumption: an uncertainty (k=1) in the current of 0.002 % will produce a change of distribution temperature of about 0.05 K, which leads to an change of spectral irradiance of 0.03 % at 250 nm to 0.006 % at 1100 nm. For the budget a wavelength independent average was taken (0.01 %), knowing that this contribution makes a negligible contribution to the overall uncertainty, which is dominated by the uncertainty associated with the reference lamps.

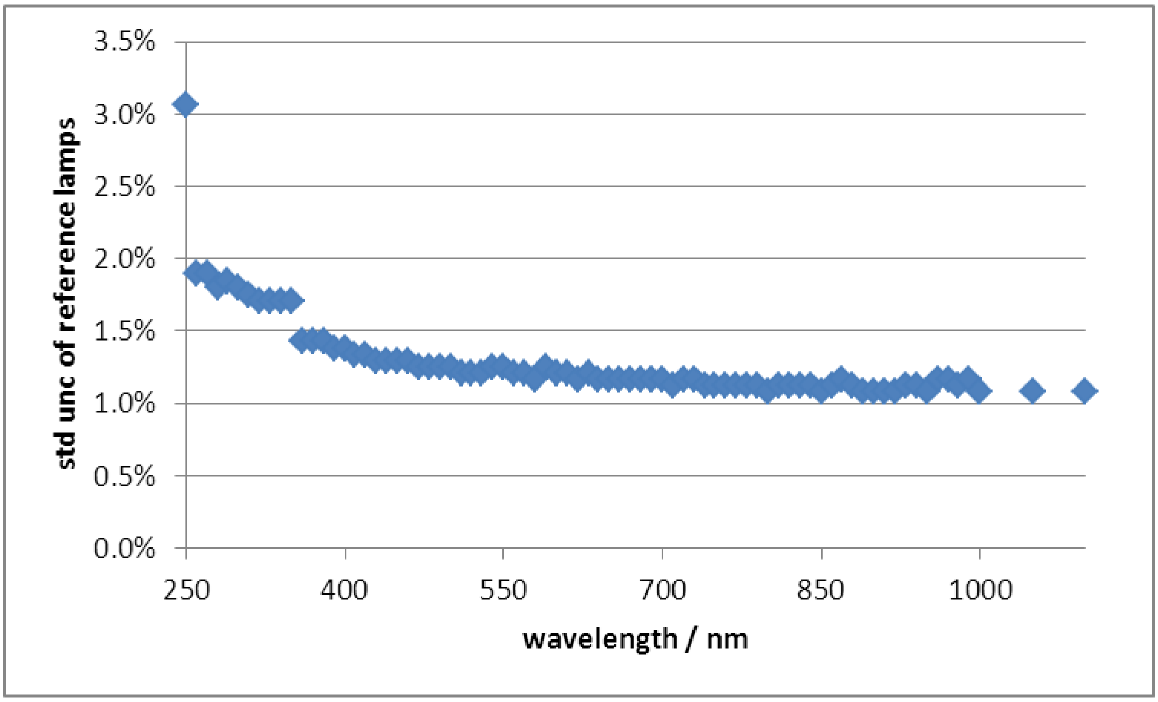

Figure 40. Standard uncertainty of reference lamps.

The combined uncertainty is by far dominated by the uncertainty of the reference lamps. The other contributions are therefore simplified to wavelength independent contributions. Table 19 shows the wavelength independent uncertainty contributions of the calibration of a spectral irradiance lamp.

Table 19. Wavelength independent uncertainty contributions.

Wavelength independent quantities						
	Quantity	**Value**		**Typ**	**sensitivity**	**u cont.**
Ref lamps	Overall distance*	1.00E-3	rel	B	1/sqrt(3)	5.77E-4
	Lamp positioning*	2.00E-3	rel	B	1/sqrt(3)	1.15E-3
	Lamp current*	1.00E-4	rel	B	1	1.00E-4
	Drift*	1.00E-2	rel	B	1/sqrt(3)	5.77E-3
	Stability	1.00E-4	rel	A		5.77E-5
monitor	Lamp current	1.00E-4	rel	B	1	5.77E-5
	Stability	1.00E-3	rel	A	1	1.00E-3
	Drift	2.00E-3	rel	B	1/sqrt(3)	1.15E-3
Test lamp	Stability	2.00E-3	rel	A	1	2.00E-3
	Wavelength	5.77E-4	rel	B	1	5.77E-4

	Positioning	2.00E-3	rel	B	1/sqrt(3)	1.15E-3
	Distance	1.00E-3	rel	B	1/sqrt(3)	5.77E-4
	Lamp current	1.00E-4	rel	B	1	1.00E-4
					Total (k=1)	**6.58E-3**

*) correlated quantity to all lamps

A.4.4.2 Uncertainty budget summary

Table 20. Uncertainties associated with measurement of lamp spectral irradiance at METAS

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
250	3.06 %	0.46 %	3.09 %	6.19 %
260	1.89 %	0.39 %	1.94 %	3.87 %
270	1.89 %	0.33 %	1.92 %	3.85 %
280	1.80 %	0.39 %	1.84 %	3.69 %
290	1.85 %	0.32 %	1.87 %	3.75 %
300	1.80 %	0.31 %	1.83 %	3.65 %
310	1.75 %	0.30 %	1.78 %	3.56 %
320	1.71 %	0.29 %	1.73 %	3.46 %
330	1.71 %	0.32 %	1.73 %	3.47 %
340	1.71 %	0.30 %	1.73 %	3.46 %
350	1.71 %	0.30 %	1.73 %	3.46 %
360	1.43 %	0.32 %	1.46 %	2.93 %
370	1.43 %	0.30 %	1.46 %	2.92 %
380	1.43 %	0.31 %	1.46 %	2.92 %
390	1.38 %	0.30 %	1.42 %	2.83 %
400	1.38 %	0.32 %	1.42 %	2.84 %
450	1.29 %	0.29 %	1.33 %	2.65 %
500	1.25 %	0.29 %	1.28 %	2.56 %
550	1.25 %	0.29 %	1.28 %	2.56 %
555	1.23 %	0.29 %	1.26 %	2.52 %
600	1.21 %	0.29 %	1.24 %	2.48 %
650	1.16 %	0.29 %	1.20 %	2.40 %
700	1.16 %	0.29 %	1.20 %	2.40 %
750	1.12 %	0.29 %	1.16 %	2.31 %
800	1.08 %	0.29 %	1.12 %	2.23 %
850	1.08 %	0.29 %	1.12 %	2.23 %
900	1.08 %	0.29 %	1.12 %	2.23 %
950	1.08 %	0.29 %	1.12 %	2.23 %
1000	1.08 %	0.29 %	1.12 %	2.23 %
1100	1.08 %	0.30 %	1.12 %	2.23 %

A.4.5 COMPARISON LAMPS

The following lamps were used during the comparison (all FEL Type I):
Lamp 1: BN-9101-388
Lamp 2: BN-9101-389
Lamp 3: BN-9101-390

A constant current of 8.1 A was used and the lamps were positioned 500 mm to front plate.

The stabilities of all lamps were as expected. As an example Figure 41 shows the lamp voltage of BN-9101-388 during the second round.

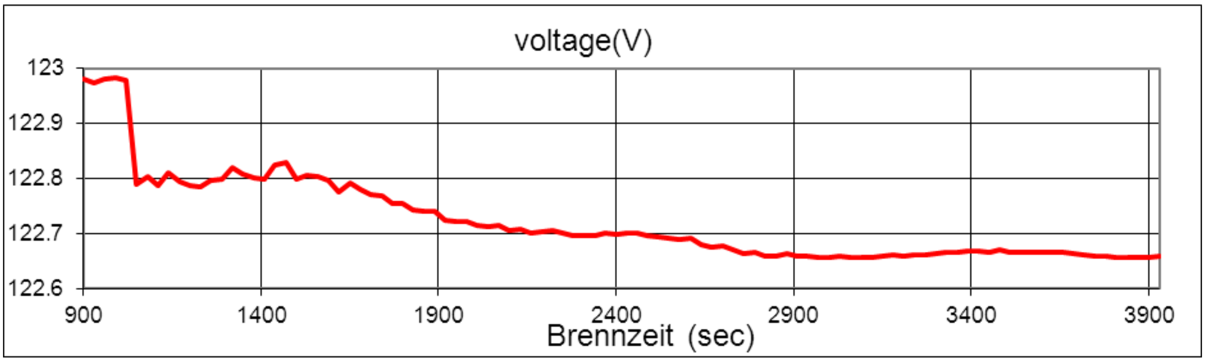

Figure 41. Typical lamp voltage stability.

A.5. MEASUREMENTS AT SP

A.5.1 PRIMARY SCALE REALISATION

SP's spectral irradiance scale is maintained using two different groups of lamps. Two FEL-lamps calibrated at HUT (Finland) are used in the wavelength range 400 nm to 900 nm. In the range outside this (250 nm to 400 nm and 900 nm to 2500 nm) a group of currently 3 lamps originally calibrated at NIST during 1995-1999 is used. All these lamps are burnt less than 1 h/year, as they are only used for calibration of working standards and occasionally for making stability checks. Also, the original calibration values from NIST have been slightly corrected for the change in the NIST scale that took place around the year 2000 (based on article published 1 October 2002, Applied Optics Vol. 41, No. 28).

A.5.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.5.2.1 Facility for spectral irradiance realisation

Spectral irradiance calibrations at SP are done by direct comparisons to working standards, by using a double prism monochromator (Zeiss MM12) with different detectors and prisms for different wavelength ranges. The wavelength and bandwidth is computer controlled using step motors. The lamp radiation is collected either by an integrating sphere or by a white diffuser. For this comparison, two working standards were first calibrated against the whole group of primary standards and then used throughout the comparison.

The lamps are run by a HP 6675A 0-120V/18A DC power supply, and the current is measured using a precision resistor in series with the lamp. At currents around 8 A, the current can be set to about ±2 mA. One stray light shield is used between the lamp and the input optics.

250 nm – 800 nm: A quartz prism is used with the monochromator (total coverage 200 nm – 1000 nm) and a 4 inch integrating sphere is used for the input. A PMT is used as the detector. The Typical bandwidth is 5 nm - 10 nm. The distance is set to 50.0 cm from each lamp's reference plane to the sphere opening using a calibrated ruler.

800 nm – 2500 nm: A glass prism is used (covering 360 nm – 2500 nm) in the monochromator and a barium sulphate reflectance plaque is used for the input. The radiation is chopped at about 15 Hz and detected with a cooled PbS-detector. The typical bandwidth is 50 nm - 80 nm. The distance is set to 50.0 cm from each lamp's reference plane to the diffuser plane using a calibrated ruler.

A.5.2.2 Laboratory

Normally temperature is controlled to 23 °C ±1 °C. However, due to cooling problems the temperature currently is (and has been for the last year) 25 °C.

A.5.3 MEASUREMENT PROCEDURE

For each of the previously described wavelength ranges, measurements were performed according to the scheme: Working standards – Measurement objects – Workings standard. Each measurement contained all relevant wavelengths in the whole range, starting from the lowest wavelength. Depending on the signal level, 5 to 10 repeated detector readings were taken for each wavelength.
For this comparison, the above measurement scheme was repeated twice. Each full series was linearly corrected for drift based on the working standard measurements before and after the measurement objects (comparison lamps).

The lamps were aligned using the alignment jig, with distance being measured from the plane containing the crosshair, as shown in Figure 42. Following the comparison, SP realised that this choice of reference plane for the distance measurement did not comply with the comparison protocol, which specified that distance should be measured from the front plate of the lamp mount. This meant that measurements were made at a distance that was 6 mm less than that specified, and resulted in irradiance values that were about 2.3 % higher than would be obtained using the correct distance. This problem was identified after the Draft A report had been issued and therefore the results given in this report (including the DoE values for SP) were not corrected for this error.

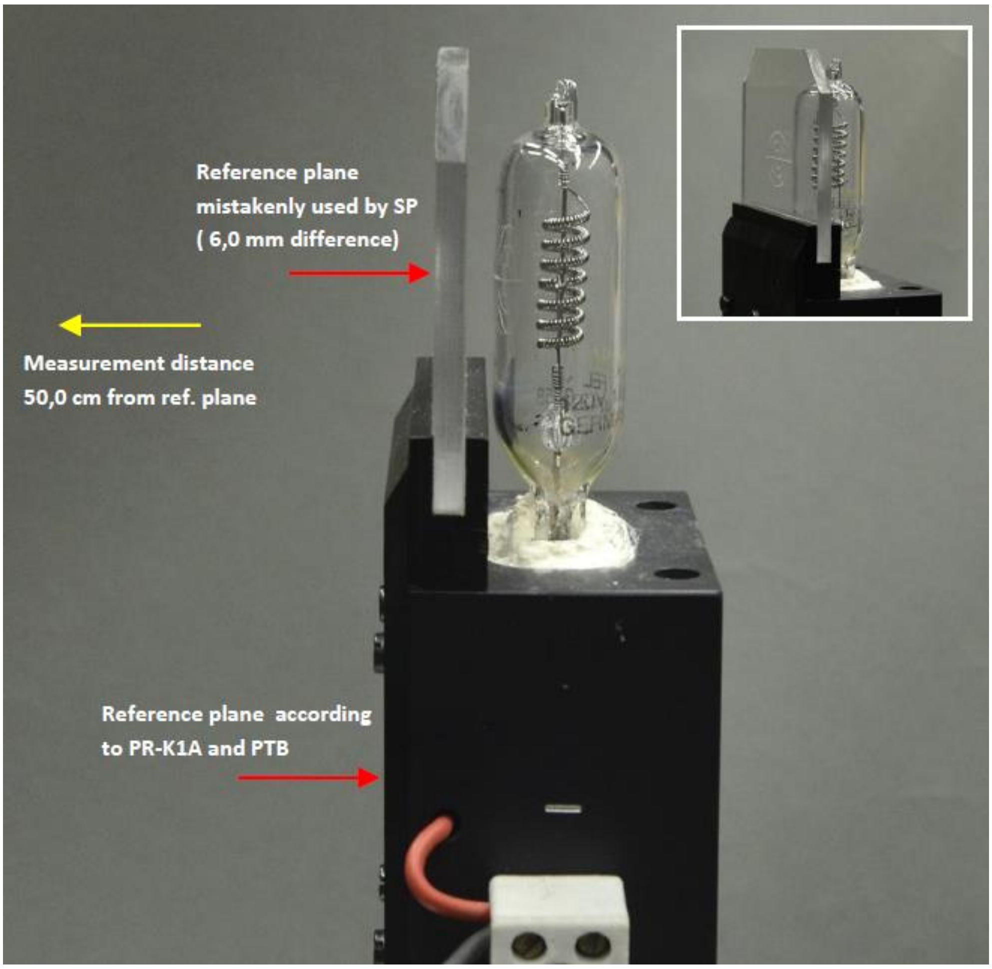

Figure 42. Reference plane used for distance measurement used at SP.

A.5.4 UNCERTAINTY BUDGET

A.5.4.1 Origin of uncertainty budget

Tests have been done to determine short-term repeatability and drift nonlinearity. Also, the influence of a change in current has been determined for all wavelengths of interest. In most cases bandwidth and wavelength effects and stray light effects will be quite small as used lamps are quite similar. There are, however, some small differences between the modified FEL-lamps (NIST) and the type I FEL-lamps used (including fixtures) as well as small variations in currents and output powers, which is believed to give some non-negligible uncertainty components.

For the reference lamps used to maintain the irradiance scale, possible drift has been estimated based on the approximate run time (from NIST). This is supported by the total measured variation between lamps in each group and when comparing the NIST and HUT lamps in the overlapping range. In general, all measured differences are quite small compared to the stated uncertainties so the overall stability is believed to be very good.

The original discreet calibration values from NIST have in the IR region been interpolated over certain ranges using a 3rd degree polynomial and the Planck function. The deviations between the discreet values and the fitted curve have been taken as a measure of the possible maximum error in the new fitted values. Also, for 2500 nm, which is outside the NIST range, an extrapolation has been made with a quite large estimated uncertainty.

Note that the uncertainty budget has been somewhat simplified by not taking into account any small individual variations for the different lamps used. Also, many of the generally small uncertainty components (repeatability, alignment, stray light etc.) may not be totally independent of each other, which may result in a slight over-estimation of the final measurement uncertainty. However, as the largest part of this uncertainty is from the scale realisation itself, these small effects have not been further analysed.

All uncertainties below are expressed as a percentage of the measured irradiance. The uncertainty contributions can be summarised as follows (see also Table 32):

- ***Long-term drift (reference lamps)***: Type B. This component is estimated based on NIST data and a total burn time of 20 h for all reference lamps.
- ***Calibration uncertainty (reference lamps)***: Type B. Taken from calibration certificates.
- ***Interpolation and extrapolation (NIST reference lamps)***: Type B. In the range 900 nm to 2400 nm this component is taken as the typical max deviation of the fitted curve to the calibration values. At 2500 nm an extra safety factor of ± 2 % is estimated.
- ***Repeatability (all lamps)***: Type B. This uncertainty component has been determined as the typical standard deviation for the used lamps but is not individually determined for each lamp. None of the lamps used show any indication of instability, which is why this method should be sufficiently accurate.
- ***Non-linearity drift (all lamps)***: Type B. The combined drift of the standard lamps and the measurement facility during a normal measurement sequence is usually within 1 % - 1.5 %. This is linearly corrected for based on the time of measurement. This component estimates the remaining uncertainty associated with non-linearity of the drift.
- ***Alignment (all lamps)***: Type B. Based on small changes in alignment corresponding to the possible maximum error. This component is in the order of the general short-term repeatability and is estimated to be a maximum of ± 0.2 %.
- ***Lamp distance (all lamps)***: Type B. This is estimated to be within ±0.8 mm.
- ***Lamp current (all lamps)***: Type B. The estimated maximum error in current is ±3 mA. This corresponds to changes in irradiance within about ±0.5 % at 250 nm and ±0.15 % at 2500 nm

- ***Bandwidth and wavelength effect (all lamps)***: Type B. Estimated by varying the bandwidth for measurements around 1000 nm, where this effect should have the largest contribution due to slightly different lamp characteristics.
- ***Stray light (all lamps)***: Type B. The different lamp design and lamp fixtures give raise to a small uncertainty. With a diffuser at the input, the set-up is slightly more sensitive to stray light.

Table 21. Individual standard uncertainty components for each wavelength (*k*=1) / %

Wave-length / nm	Long-term drift	Calibra-tion	Interpol-ation	Repeat-ability	Drift	Align-ment	Distance	Current	Band-width	Stray light
250	0.75	0.91	0.00	0.80	0.29	0.12	0.18	0.55	0.30	0.12
260	0.64	0.87	0.00	0.70	0.17	0.12	0.18	0.53	0.30	0.12
270	0.55	0.84	0.00	0.60	0.17	0.12	0.18	0.52	0.20	0.12
280	0.49	0.80	0.00	0.50	0.17	0.12	0.18	0.49	0.20	0.12
290	0.48	0.76	0.00	0.40	0.17	0.12	0.18	0.46	0.10	0.12
300	0.47	0.73	0.00	0.30	0.17	0.12	0.18	0.44	0.10	0.12
310	0.46	0.69	0.00	0.20	0.17	0.12	0.18	0.42	0.10	0.12
320	0.45	0.65	0.00	0.20	0.17	0.12	0.18	0.40	0.10	0.12
330	0.44	0.62	0.00	0.20	0.17	0.12	0.18	0.39	0.10	0.12
340	0.43	0.58	0.00	0.20	0.17	0.12	0.18	0.38	0.10	0.12
350	0.42	0.55	0.00	0.20	0.17	0.12	0.18	0.37	0.10	0.12
360	0.41	0.55	0.00	0.20	0.17	0.12	0.18	0.35	0.10	0.12
370	0.41	0.54	0.00	0.20	0.17	0.12	0.18	0.34	0.10	0.12
380	0.40	0.53	0.00	0.20	0.17	0.12	0.18	0.33	0.10	0.12
390	0.39	0.53	0.00	0.20	0.17	0.12	0.18	0.32	0.10	0.12
400	0.39	0.52	0.00	0.20	0.17	0.12	0.18	0.31	0.10	0.12
450	0.36	0.50	0.00	0.20	0.17	0.12	0.18	0.27	0.10	0.12
500	0.34	0.50	0.00	0.20	0.17	0.12	0.18	0.24	0.10	0.12
550	0.32	0.50	0.00	0.20	0.17	0.12	0.18	0.21	0.10	0.12
555	0.31	0.50	0.00	0.20	0.17	0.12	0.18	0.21	0.10	0.12
600	0.30	0.50	0.00	0.20	0.17	0.12	0.18	0.19	0.10	0.12
650	0.28	0.50	0.00	0.20	0.17	0.12	0.18	0.18	0.10	0.12
700	0.27	0.50	0.00	0.20	0.17	0.12	0.18	0.17	0.10	0.12
750	0.26	0.50	0.00	0.20	0.17	0.12	0.18	0.16	0.10	0.12
800	0.25	0.50	0.00	0.30	0.17	0.12	0.18	0.15	0.10	0.12
850	0.24	0.50	0.00	0.40	0.29	0.12	0.18	0.15	0.20	0.23
900	0.23	0.50	0.00	0.40	0.29	0.12	0.18	0.15	0.30	0.23
950	0.22	0.54	0.17	0.40	0.29	0.12	0.18	0.15	0.30	0.23
1000	0.21	0.54	0.23	0.40	0.29	0.12	0.18	0.15	0.30	0.23
1100	0.20	0.54	0.23	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1200	0.19	0.55	0.23	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1300	0.18	0.57	0.23	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1400	0.17	0.61	0.23	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1500	0.17	0.66	0.23	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1600	0.16	0.71	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1700	0.15	0.82	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1800	0.15	0.94	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
1900	0.14	1.05	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
2000	0.14	1.17	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
2100	0.13	1.43	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
2200	0.13	1.69	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
2300	0.13	1.96	0.29	0.40	0.29	0.12	0.18	0.15	0.20	0.23
2400	0.12	2.22	0.29	0.50	0.29	0.12	0.18	0.15	0.20	0.23
2500	0.12	2.45	0.29	0.80	0.29	0.12	0.18	0.15	0.20	0.23

A.5.4.2 Uncertainty budget summary

Table 22. Uncertainties associated with measurement of lamp spectral irradiance at SP / %

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (*k* = 1)	Expanded uncertainty (*k* = 2)
250	1.54	0.99	1.83	3.66
260	1.39	0.87	1.64	3.28
270	1.26	0.76	1.47	2.94
280	1.16	0.68	1.34	2.68
290	1.07	0.58	1.21	2.43
300	1.00	0.51	1.12	2.24
310	0.94	0.45	1.04	2.08
320	0.91	0.44	1.01	2.02
330	0.88	0.44	0.98	1.96
340	0.84	0.44	0.95	1.90
350	0.81	0.43	0.92	1.84
360	0.80	0.43	0.91	1.82
370	0.79	0.42	0.90	1.80
380	0.79	0.42	0.89	1.78
390	0.78	0.42	0.88	1.77
400	0.77	0.42	0.88	1.75
450	0.74	0.41	0.84	1.68
500	0.72	0.40	0.83	1.65
550	0.71	0.39	0.81	1.63
555	0.71	0.39	0.81	1.62
600	0.70	0.39	0.80	1.61
650	0.69	0.39	0.80	1.59
700	0.69	0.39	0.79	1.58
750	0.68	0.39	0.78	1.57
800	0.71	0.45	0.84	1.68
850	0.84	0.63	1.04	2.09
900	0.86	0.66	1.09	2.18
950	0.90	0.66	1.12	2.24
1000	0.91	0.66	1.13	2.26
1100	0.88	0.63	1.08	2.16
1200	0.89	0.63	1.08	2.17
1300	0.89	0.63	1.09	2.18
1400	0.92	0.63	1.11	2.23
1500	0.95	0.63	1.14	2.28
1600	1.00	0.63	1.18	2.36
1700	1.08	0.63	1.25	2.50
1800	1.17	0.63	1.33	2.66
1900	1.26	0.63	1.41	2.82
2000	1.36	0.63	1.50	3.00
2100	1.59	0.63	1.71	3.42
2200	1.83	0.63	1.94	3.87
2300	2.08	0.63	2.17	4.34
2400	2.35	0.69	2.45	4.89
2500	2.64	0.93	2.80	5.60

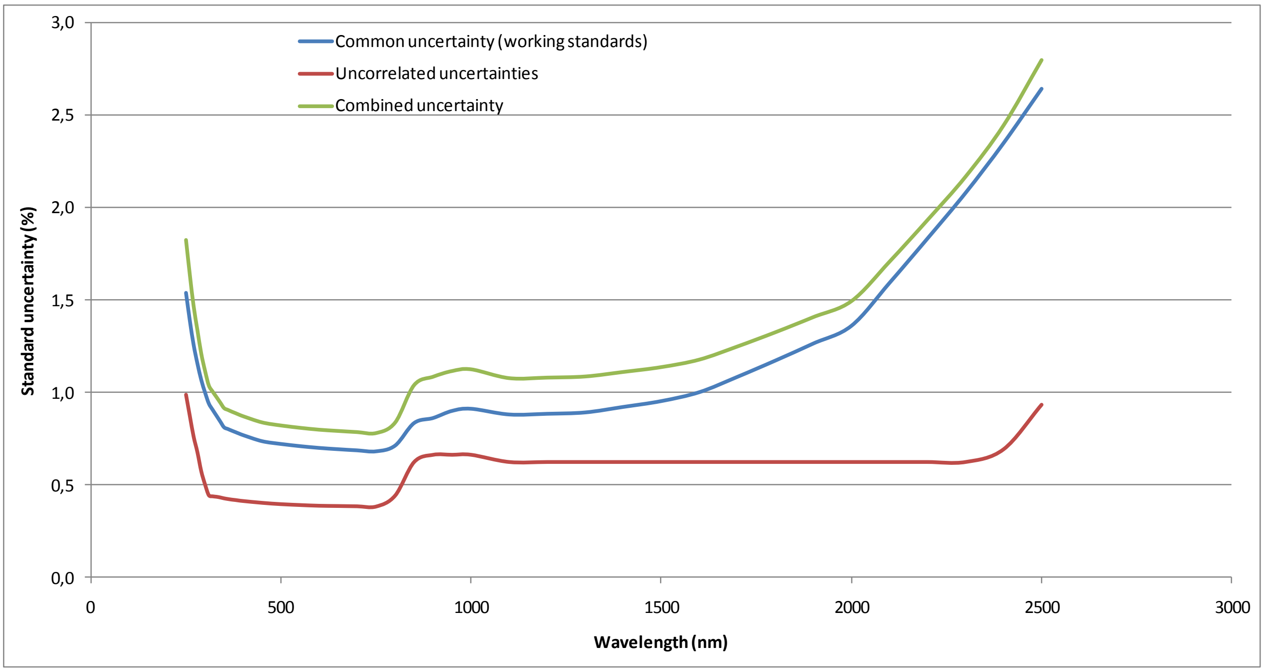

Figure 43. Uncertainties for measurements at SP.

A.5.5 COMPARISON LAMPS

Three FEL type I lamps were used for the comparison, measured at 50.0 cm in front of the removable cross-hair.

Lamp ID	Current (A)	Voltage round 1 (V)	Voltage round 2 (V)
PTB-SL-135	8.100	102.70	102.76
SP 96-5	8.100	117.30	117.35
SP 96-7	8.100	119.80	119.76

Based on the stable voltages and the measured irradiances in round 1 and 2 respectively, no significant changes for any of the lamps used by SP during the comparison can be detected.

A.6. MEASUREMENTS AT VNIIOFI

A.6.1 PRIMARY SCALE REALISATION

The spectral irradiance scale was realised using a high-temperature blackbody of the BB3500M type. The effective emissivity of the BB3500M was estimated to be approximately 0.9995, with standard uncertainty of 0.1 % in the spectral range from 250 nm to 350 nm and 0.05 % in the range from 360 nm to 2500 nm.

The temperature of the B3500M was approximately 3020 K. A radiation thermometer of the TSP type was used to measure the BB3500M temperature. The thermometer was calibrated against high-temperature fixed points (HTFP) Co-C, Re-C and WC-C. Temperatures of the HTFPs were measured against a copper point blackbody. The calibration of the TSP thermometer was checked against the WC-C fixed-point blackbody just before calibration of a standard lamp used for the comparison. The standard uncertainty the temperature measurement was 0.7 K.

In front of the BB3500M blackbody there was a precision aperture with diameter of approximately 8 mm. The temperature of the aperture holder was stabilised at 20 ºC using a liquid thermostat.

A FEL lamp was used as the standard lamp to calibrate the comparison lamps. The standard lamp was calibrated against the BB3500M blackbody just after the second round measurements.

A.6.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.6.2.1 Facility for spectral irradiance realisation

The facility used is shown schematically in Figure 44. The facility consists of the following elements:

1. The BB3500M blackbody
2. Precision aperture
3. LEL lamps
4. Alignment lasers (for the lamp alignment)
5. TSP radiation thermometer
6. Integrating sphere
7. Monochromator
8. Set of detectors
9. Focusing mirror
10. Flat mirrors
11. Alignment laser (for the blackbody alignment)
12. Set of light shields
13. Shutters

The blackbody, lamps and alignment lasers (4) were installed on an optical table and covered with a light tight box with holes in front of the sources equipped with the shutters (13). A spectral comparator consisted of the integrating sphere (6), monochromator (7), focusing optics (9, 10) and set of detectors (8) was assembled on a translation stage. The radiation thermometer (5) and the alignment laser (11) were installed on the same translation stage. The optical plate of the translation stage was covered with a light tight box with holes in front of the sphere and thermometer.

The integrating sphere was made of PTFE and had an internal diameter of 40 mm, a circular entrance aperture with diameter of 11 mm and an exit slit with the dimensions of 4 mm × 15 mm.

The monochromator used for the standard lamp calibration and for the second round measurements was an additive-mode double grating monochromator of the DTMc300 type (manufactured by Bentham Instruments Limited) with a focal length of 300 mm. Gratings with 1200 g/mm were used in the spectral range from 250 nm to 1100 nm and gratings with 600 g/mm were used in the spectral range from 1100 nm to 2500 nm.

The wavelength accuracy and wavelength repeatability of the monochromator are 0.2 nm and 0.05 nm respectively. The dispersion is 1.35 nm/mm for 1200 g/mm. The slit width used was 3 mm for both entrance and exit. In the range from 1700 nm to 2500 nm the monochromator was used in single mode. Therefore, the bandwidth was:

- 4 nm for the range from 250 nm to 1100 nm
- 8 nm for the range from 1100 nm to 1700 nm
- 16 nm for the range from 1700 nm to 2500 nm

Note that the monochromator and the translation stage were replaced between the first and the second rounds of measurements. For the first round an old double grating monochromator of the HRD1 type (JOBIN YVON) was used that had been intensively used for more than 20 years. Because of the lower efficiency (due to degraded mirrors reflections) the signal level with this monochromator was lower, especially in the UV range; therefore, the first round measurements were noisier. However due to an error in the lamp current and distance used in the first round of measurements, only results from the second round are considered.

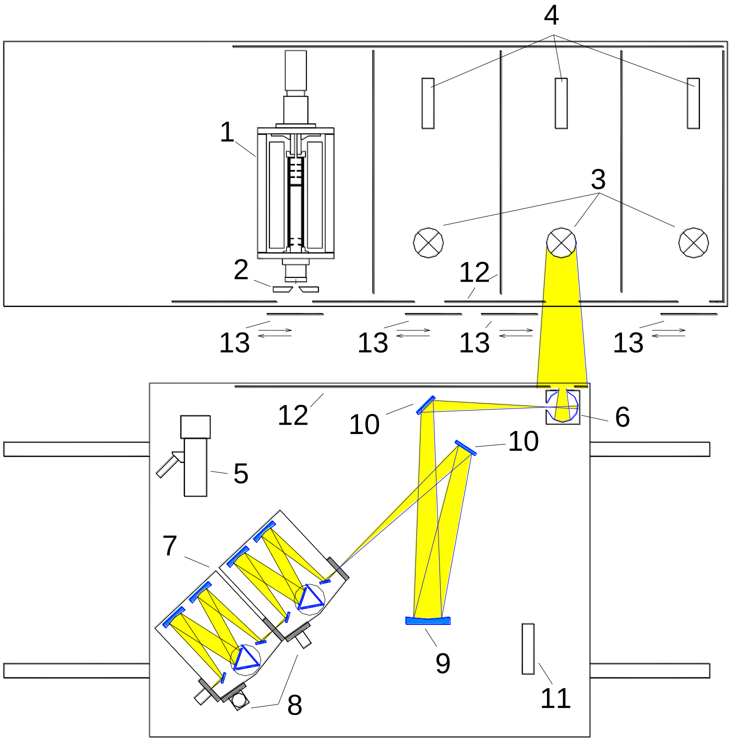

Figure. 44 Spectral Irradiance facility of VNIIOFI

The detectors used were:

- PMT for the range from 250 nm to 550 nm
- Si photodiode for the range from 550 nm to 1000 nm
- InGaAr photodiode for the range from 1000 nm to 1700 nm
- PbS photoresistor for the range from 1700 nm to 2500 nm

Distance between the lamp and the sphere (as well as between the blackbody aperture and the sphere) was measured using an extension rod type micrometer (manufacturer is Mitutoyo). The micrometer was accurate to 10µm. However, the distance uncertainty was much higher than this, due to instability of the lamp, aperture and sphere stands.

Specially designed high-stability DC power supplies were used. The lamp current was measured using a standard resistor and a precision voltmeter. The combined standard uncertainty of the current measurement and current stability was estimated as 1 mA.

A.6.2.2 Laboratory

The laboratory temperature was maintained at a level of 22 ºC within ± 2 ºC.

A.6.3 MEASUREMENT PROCEDURE

The measurements (both the standard lamp against the blackbody and the comparison lamps against the standard lamp) were done wavelength-by-wavelength, i.e. the sources were compared at each wavelength. The measurement procedure was as follows:

- Wavelength set
- Stage moved to Source 1 position
- Shutter of the Source 1 opened
- Detector signal read 25 to 50 times (depend on wavelength) and average value and its standard deviation saved

- Shutter closed, dark signal read 25 to 50 times and average value and its standard deviation saved
- Stage moved to the Source 2 position
- Shutter of the Source 2 opened
- Detector signal read 25 to 50 times and average value and its standard deviation saved.
- Shutter closed, dark signal read 25 to 50 times and average value and its standard deviation saved
- Ratio Source 1 / Source 2 calculated and saved

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 standard deviations of the measured signals were used later for estimation of Type A uncertainties. The associated uncertainty component is identified below as "Repeatability".
The spectral range was divided into several blocks of wavelength:

- 250 nm to 300 nm
- 310 nm to 400 nm
- 450 nm to 650 nm
- 600 nm to 1000 nm
- 950 nm to 1700 nm
- 1600 nm to 2500 nm

After the first and the second blocks the PMT voltage was changed. After the third block the PMT was changed to the Si photodiode. After the fourth block the Si photodiode was changed to the InGaAs photodiode. After the fifth block the InGaAs detector was changed to the PbS detector.

Before each block the lamp current was checked. When the blackbody was used, its temperature was measured before and after each black and its stability was evaluated.

Four independent measurements were done for each comparison lamp as well as for the standard lamp. Each independent measurement was done with independent realignment of the lamps. The standard deviation of the mean calculated from these independent measurements was used for estimation of the uncertainty component identified below as "Reproducibility".

The First Round measurements were performed using an incorrect value for the lamp current: 8.0 A instead 8.1 A. Therefore, the results of the First Round measurements were not reported and were not included in the comparison. In addition, the analysis of the internal consistency of the lamps (presented at the Pre-Draft A stage) revealed a significant inconsistency between one lamp and the other two and as a result it was decided to request withdrawal of one lamp; more details are given in the Appendix. The comparison results for VNIIOFI are therefore based on measurements of just two lamps, each measured once at NPL and once at VNIIOFI.

A.6.4 UNCERTAINTY BUDGET

A.6.4.1 Origin of uncertainty budget

The following sources of uncertainty were considered:

- ***Air refractive index (n)***: It was assumed that the uncertainty associated with *n* was 0.00003. The blackbody spectral irradiance uncertainty associated with *n* was calculated using the Planck law.
- ***Blackbody emissivity uncertainty***: This was estimated as 0.001 for the spectral range from 250 nm to 350 nm and 0.0005 for the spectral range from 360 nm to 2500 nm. The estimation was based on modelling using the STEEP3 software. The spectral irradiance relative uncertainty is spectrally independent and equals to 0.1 % and 0.05 % respectively.

- ***Blackbody temperature measurement uncertainty***: This was estimated as 0.7 K. The blackbody spectral irradiance uncertainty associated with *T* was calculated using the Planck law.
- ***Blackbody non-uniformity***: This was estimated on the basis of preliminary blackbody mapping. It corresponds to a temperature non-uniformity standard uncertainty of approximately 0.3 K. The associated blackbody spectral irradiance uncertainty was calculated using the Planck law.
- ***Blackbody instability***: This was measured directly during the standard lamp calibration. The typical temperature instability standard uncertainty was approximately 0.12 K. The blackbody associated spectral irradiance uncertainty was calculated using the Planck law.
- ***Blackbody aperture area***: This was measured with standard uncertainty of approximately 0.08 μm that corresponds to a spectral irradiance relative uncertainty of 0.02 %.
- ***Lamp (or blackbody aperture) to sphere distance measurement uncertainty***: This was estimated as 0.07 mm. The main reason for this uncertainty was mechanical instability of the stands.
- ***Lamp current measurement and stability***: This was estimated as 1 mA. The associated spectral irradiance uncertainties were evaluated comparing the measurements the FEL lamps at 8.1 A and 8.0 A current.
- ***Uncertainty associated with wavelength***: There are two sources of uncertainty associated with wavelength: accuracy of wavelength setting (2 nm) and bandwidth. These components were estimated independently and then combined. The value of the spectral irradiance uncertainty component at a specific wavelength depends on the rate of change of the ratio between the compared sources at this wavelength. Because the spectra of the compared sources are quite similar (two lamps of the same type and regime, or a lamp and the blackbody with nearly the same distribution temperature) the ratios were small, and, therefore, the spectral irradiance uncertainties were small as well.
- ***Type A uncertainty associated with noise of the signal***: This uncertainty component is identified as “Repeatability”. See also the section 13.3. The uncertainty was calculated as

  $$u_{\mathrm{repeat}} = \max\left\{\sqrt{\frac{\sigma_{L1}^2+\sigma_{L2}^2+\sigma_{d1}^2+\sigma_{d2}^2}{n\cdot m}};\sqrt{\frac{\sigma_{ratio}^2}{m}}\right\}$$

  where σ_{L1} is the standard deviation of the lamp position 1 readings, σ_{L2} is the standard deviation of the lamp position 2 (or blackbody) readings, σ_{d1} is the standard deviation of the dark readings in lamp position 1, σ_{d2} - is the standard deviation of the dark readings in lamp position 2 (or blackbody), *n* is the number of readings, *m* is the number of measurement cycles at the specific wavelength, σ_{ratio} is the standard deviation of the Lamp1/Lamp2 ratios (number of ratios equals to number of cycles). This uncertainty was similar for all comparison lamps. Therefore, the average values for all lamps were used.
- ***Type A uncertainty associated with lamp reproducibility***: The uncertainty u_{reproduc} is associated with reproducibility of lamp spectral irradiance values measured in independent measurements. This uncertainty component was calculated as:

  $$u_{\mathrm{reproduc}} = \sqrt{\frac{1}{k\cdot(k-1)}\cdot\sum_{i=1}^{k}(E_i(\lambda)-\overline{E})^2}$$

  where *k* is the number of the independent measurements. Four independent measurements were peformed for both the standard lamp and the comparison lamps. The “Reproducibility” uncertainty was similar for all comparison lamps. Therefore, the same values were used for all lamps, averaged and spectrally smoothed.
- ***Type A combined uncertainty***: The Type A combined uncertainty was calculated as:

  $$u_a = \sqrt{\frac{u_{repeat}^2}{k}+u_{reproduc}^2}$$

Table 23. Uncertainties associated with the blackbody (scale uncertainty budget), *k*=1 / %

λ / nm	Air refractive index *n* (Δn = 0.00003)	Emissivity	Temperature measurement (ΔT = 0.7 K)	Blackbody uniformity (0.3 K)	Blackbody stability (0.12 K)	Aperture area	Blackbody-to-sphere distance	Combined (*k*=1)
250	0.05	0.1	0.44	0.19	0.08	0.02	0.03	**0.50**
260	0.05	0.1	0.43	0.18	0.07	0.02	0.03	**0.48**
270	0.05	0.1	0.41	0.18	0.07	0.02	0.03	**0.47**
280	0.05	0.1	0.39	0.17	0.07	0.02	0.03	**0.45**
290	0.04	0.1	0.38	0.17	0.07	0.02	0.03	**0.44**
300	0.04	0.1	0.37	0.16	0.06	0.02	0.03	**0.42**
310	0.04	0.1	0.36	0.15	0.06	0.02	0.03	**0.41**
320	0.04	0.1	0.35	0.15	0.06	0.02	0.03	**0.40**
330	0.04	0.1	0.34	0.15	0.06	0.02	0.03	**0.39**
340	0.04	0.1	0.33	0.14	0.06	0.02	0.03	**0.38**
350	0.04	0.1	0.32	0.14	0.05	0.02	0.03	**0.37**
360	0.03	0.05	0.31	0.13	0.05	0.02	0.03	**0.35**
370	0.03	0.05	0.30	0.13	0.05	0.02	0.03	**0.34**
380	0.03	0.05	0.29	0.13	0.05	0.02	0.03	**0.33**
390	0.03	0.05	0.28	0.12	0.05	0.02	0.03	**0.32**
400	0.03	0.05	0.28	0.12	0.05	0.02	0.03	**0.31**
450	0.03	0.05	0.25	0.11	0.04	0.02	0.03	**0.28**
500	0.02	0.05	0.22	0.10	0.04	0.02	0.03	**0.25**
550	0.02	0.05	0.20	0.09	0.03	0.02	0.03	**0.23**
555	0.02	0.05	0.20	0.09	0.03	0.02	0.03	**0.23**
600	0.02	0.05	0.18	0.08	0.03	0.02	0.03	**0.21**
650	0.02	0.05	0.17	0.07	0.03	0.02	0.03	**0.20**
700	0.02	0.05	0.16	0.07	0.03	0.02	0.03	**0.19**
750	0.01	0.05	0.15	0.06	0.03	0.02	0.03	**0.17**
800	0.01	0.05	0.14	0.06	0.02	0.02	0.03	**0.17**
850	0.01	0.05	0.13	0.06	0.02	0.02	0.03	**0.16**
900	0.01	0.05	0.12	0.05	0.02	0.02	0.03	**0.15**
950	0.01	0.05	0.12	0.05	0.02	0.02	0.03	**0.14**
1000	0.01	0.05	0.11	0.05	0.02	0.02	0.03	**0.14**
1100	0.01	0.05	0.10	0.04	0.02	0.02	0.03	**0.13**
1200	0.01	0.05	0.09	0.04	0.02	0.02	0.03	**0.12**
1300	0.01	0.05	0.09	0.04	0.01	0.02	0.03	**0.11**
1400	0.01	0.05	0.08	0.04	0.01	0.02	0.03	**0.11**
1500	0	0.05	0.08	0.03	0.01	0.02	0.03	**0.10**
1600	0	0.05	0.07	0.03	0.01	0.02	0.03	**0.10**
1700	0	0.05	0.07	0.03	0.01	0.02	0.03	**0.10**
1800	0	0.05	0.07	0.03	0.01	0.02	0.03	**0.10**
1900	0	0.05	0.06	0.03	0.01	0.02	0.03	**0.09**
2000	0	0.05	0.06	0.03	0.01	0.02	0.03	**0.09**
2100	0	0.05	0.06	0.03	0.01	0.02	0.03	**0.09**
2200	0	0.05	0.06	0.02	0.01	0.02	0.03	**0.09**
2300	0	0.05	0.05	0.02	0.01	0.02	0.03	**0.09**
2400	0	0.05	0.05	0.02	0.01	0.02	0.03	**0.09**
2500	0	0.05	0.05	0.02	0.01	0.02	0.03	**0.08**

Table 24. Uncertainties associated with the standard lamp, *k*=1 / %

λ / nm	Scale	Distance	Lamp current (1 mA)	Wave-length	Repeat-ability	Reprodu-cibility	Type A combined	Combined (*k*=1)
250	0.50	0.03	0.14	0.11	1.13	0.52	0.77	0.94
260	0.48	0.03	0.14	0.11	0.80	0.37	0.54	0.75
270	0.47	0.03	0.13	0.09	0.57	0.30	0.41	0.64
280	0.45	0.03	0.13	0.08	0.43	0.28	0.35	0.59
290	0.44	0.03	0.12	0.08	0.30	0.25	0.29	0.54
300	0.42	0.03	0.12	0.06	0.27	0.23	0.27	0.52
310	0.41	0.03	0.11	0.05	0.25	0.20	0.24	0.49
320	0.40	0.03	0.11	0.05	0.24	0.20	0.23	0.48
330	0.39	0.03	0.11	0.05	0.23	0.19	0.22	0.46
340	0.38	0.03	0.10	0.05	0.20	0.18	0.21	0.44
350	0.37	0.03	0.10	0.05	0.16	0.17	0.19	0.43
360	0.35	0.03	0.10	0.05	0.14	0.16	0.17	0.40
370	0.34	0.03	0.09	0.05	0.12	0.15	0.16	0.39
380	0.33	0.03	0.09	0.05	0.11	0.14	0.15	0.38
390	0.32	0.03	0.08	0.05	0.10	0.14	0.15	0.37
400	0.31	0.03	0.08	0.05	0.10	0.14	0.15	0.36
450	0.28	0.03	0.07	0.05	0.07	0.14	0.14	0.33
500	0.25	0.03	0.06	0.05	0.05	0.14	0.14	0.30
550	0.23	0.03	0.05	0.05	0.04	0.13	0.13	0.28
555	0.23	0.03	0.05	0.05	0.03	0.13	0.13	0.28
600	0.21	0.03	0.05	0.05	0.03	0.13	0.13	0.26
650	0.20	0.03	0.04	0.05	0.03	0.12	0.12	0.24
700	0.19	0.03	0.04	0.05	0.03	0.12	0.12	0.23
750	0.17	0.03	0.04	0.05	0.03	0.10	0.10	0.21
800	0.17	0.03	0.03	0.05	0.03	0.10	0.10	0.20
850	0.16	0.03	0.03	0.05	0.03	0.10	0.10	0.20
900	0.15	0.03	0.03	0.05	0.03	0.10	0.10	0.19
950	0.14	0.03	0.03	0.05	0.07	0.10	0.11	0.19
1000	0.14	0.03	0.02	0.06	0.07	0.10	0.11	0.19
1100	0.13	0.03	0.02	0.06	0.07	0.10	0.11	0.18
1200	0.12	0.03	0.02	0.06	0.07	0.10	0.11	0.18
1300	0.11	0.03	0.02	0.06	0.07	0.10	0.11	0.17
1400	0.11	0.03	0.01	0.06	0.07	0.10	0.11	0.17
1500	0.10	0.03	0.01	0.06	0.07	0.10	0.11	0.16
1600	0.10	0.03	0.01	0.06	0.07	0.10	0.11	0.16
1700	0.10	0.03	0.01	0.07	0.15	0.12	0.14	0.19
1800	0.10	0.03	0.01	0.07	0.20	0.14	0.17	0.21
1900	0.09	0.03	0.01	0.07	0.20	0.17	0.20	0.23
2000	0.09	0.03	0.01	0.07	0.20	0.19	0.21	0.25
2100	0.09	0.03	0.01	0.07	0.27	0.22	0.26	0.28
2200	0.09	0.03	0.01	0.07	0.27	0.25	0.28	0.31
2300	0.09	0.03	0.01	0.07	0.33	0.30	0.34	0.36
2400	0.09	0.03	0.01	0.07	0.40	0.38	0.43	0.44
2500	0.08	0.03	0.01	0.07	0.50	0.47	0.53	0.54

Table 25 Uncertainties for the comparison lamps, *k*=1 / %

λ / nm	**Std. lamp**	**Distance std. lamp**	**Distance comp. lamp**	**Current std. lamp (1 mA)**	**Current comp. lamp (1 mA)**	**Wave-length**	**Type A** *Repeat-ability*	**Type A** *Reprod-ucibility*	**Type A** **Type A com-bined**	**Com-bined (*k*=1)**
	Corre-lated	Uncorre-lated	Uncorre-lated	Corre-lated	Corre-lated	Corre-lated	Uncorrelated			
250	0.94	0.03	0.03	0.14	0.14	0.08	*0.40*	*0.31*	0.37	**1.03**
260	0.75	0.03	0.03	0.14	0.14	0.08	*0.30*	*0.26*	0.30	**0.84**
270	0.64	0.03	0.03	0.13	0.13	0.08	*0.25*	*0.24*	0.27	**0.73**
280	0.59	0.03	0.03	0.13	0.13	0.08	*0.22*	*0.23*	0.25	**0.68**
290	0.54	0.03	0.03	0.12	0.12	0.08	*0.20*	*0.22*	0.24	**0.63**
300	0.52	0.03	0.03	0.12	0.12	0.08	*0.19*	*0.22*	0.24	**0.60**
310	0.49	0.03	0.03	0.11	0.11	0.07	*0.18*	*0.21*	0.23	**0.57**
320	0.48	0.03	0.03	0.11	0.11	0.07	*0.17*	*0.21*	0.23	**0.56**
330	0.46	0.03	0.03	0.11	0.11	0.07	*0.16*	*0.20*	0.22	**0.54**
340	0.44	0.03	0.03	0.10	0.10	0.07	*0.15*	*0.20*	0.21	**0.52**
350	0.43	0.03	0.03	0.10	0.10	0.07	*0.15*	*0.19*	0.20	**0.50**
360	0.40	0.03	0.03	0.10	0.10	0.07	*0.15*	*0.19*	0.20	**0.48**
370	0.39	0.03	0.03	0.09	0.09	0.07	*0.14*	*0.18*	0.19	**0.46**
380	0.38	0.03	0.03	0.09	0.09	0.05	*0.14*	*0.18*	0.19	**0.45**
390	0.37	0.03	0.03	0.08	0.08	0.05	*0.14*	*0.17*	0.18	**0.43**
400	0.36	0.03	0.03	0.08	0.08	0.05	*0.13*	*0.17*	0.18	**0.42**
450	0.33	0.03	0.03	0.07	0.07	0.05	*0.13*	*0.16*	0.17	**0.39**
500	0.30	0.03	0.03	0.06	0.06	0.05	*0.13*	*0.16*	0.17	**0.36**
550	0.28	0.03	0.03	0.05	0.05	0.05	*0.12*	*0.16*	0.17	**0.34**
555	0.28	0.03	0.03	0.05	0.05	0.05	*0.12*	*0.16*	0.17	**0.34**
600	0.26	0.03	0.03	0.05	0.05	0.05	*0.12*	*0.16*	0.17	**0.33**
650	0.24	0.03	0.03	0.04	0.04	0.05	*0.12*	*0.16*	0.17	**0.31**
700	0.23	0.03	0.03	0.04	0.04	0.04	*0.10*	*0.16*	0.17	**0.30**
750	0.21	0.03	0.03	0.04	0.04	0.04	*0.09*	*0.16*	0.17	**0.28**
800	0.20	0.03	0.03	0.03	0.03	0.04	*0.09*	*0.16*	0.17	**0.27**
850	0.20	0.03	0.03	0.03	0.03	0.04	*0.08*	*0.16*	0.16	**0.27**
900	0.19	0.03	0.03	0.03	0.03	0.04	*0.08*	*0.16*	0.16	**0.26**
950	0.19	0.03	0.03	0.03	0.03	0.04	*0.08*	*0.16*	0.16	**0.26**
1000	0.19	0.03	0.03	0.02	0.02	0.04	*0.08*	*0.16*	0.16	**0.26**
1100	0.18	0.03	0.03	0.02	0.02	0.04	*0.08*	*0.16*	0.16	**0.25**
1200	0.18	0.03	0.03	0.02	0.02	0.04	*0.08*	*0.16*	0.16	**0.25**
1300	0.17	0.03	0.03	0.02	0.02	0.04	*0.08*	*0.16*	0.16	**0.25**
1400	0.17	0.03	0.03	0.01	0.01	0.04	*0.09*	*0.16*	0.17	**0.24**
1500	0.16	0.03	0.03	0.01	0.01	0.04	*0.09*	*0.16*	0.17	**0.24**
1600	0.16	0.03	0.03	0.01	0.01	0.04	*0.10*	*0.17*	0.18	**0.25**
1700	0.19	0.03	0.03	0.01	0.01	0.04	*0.16*	*0.18*	0.20	**0.28**
1800	0.21	0.03	0.03	0.01	0.01	0.04	*0.20*	*0.20*	0.22	**0.31**
1900	0.23	0.03	0.03	0.01	0.01	0.04	*0.30*	*0.23*	0.27	**0.36**
2000	0.25	0.03	0.03	0.01	0.01	0.04	*0.40*	*0.27*	0.34	**0.42**
2100	0.28	0.03	0.03	0.01	0.01	0.04	*0.46*	*0.31*	0.39	**0.48**
2200	0.31	0.03	0.03	0.01	0.01	0.04	*0.52*	*0.36*	0.44	**0.54**
2300	0.36	0.03	0.03	0.01	0.01	0.04	*0.63*	*0.43*	0.53	**0.65**
2400	0.44	0.03	0.03	0.01	0.01	0.04	*0.72*	*0.50*	0.62	**0.76**
2500	0.54	0.03	0.03	0.01	0.01	0.04	*0.86*	*0.58*	0.72	**0.91**

A.6.4.2 Uncertainty budget summary

Table 26. Uncertainties associated with measurement of lamp spectral irradiance at VNIIOFI / %

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
250	0.96	0.37	1.03	2.06
260	0.78	0.30	0.84	1.67
270	0.67	0.27	0.73	1.46
280	0.63	0.26	0.68	1.36
290	0.58	0.25	0.63	1.25
300	0.55	0.24	0.60	1.20
310	0.52	0.23	0.57	1.13
320	0.51	0.23	0.56	1.11
330	0.49	0.22	0.54	1.08
340	0.47	0.22	0.52	1.04
350	0.46	0.21	0.50	1.00
360	0.43	0.21	0.48	0.96
370	0.41	0.20	0.46	0.92
380	0.40	0.20	0.45	0.89
390	0.39	0.19	0.43	0.86
400	0.38	0.19	0.42	0.85
450	0.35	0.18	0.39	0.78
500	0.32	0.18	0.36	0.73
550	0.29	0.18	0.34	0.68
555	0.29	0.18	0.34	0.68
600	0.28	0.18	0.33	0.65
650	0.25	0.18	0.31	0.62
700	0.24	0.17	0.30	0.60
750	0.22	0.17	0.28	0.57
800	0.21	0.17	0.27	0.55
850	0.21	0.17	0.27	0.54
900	0.20	0.17	0.26	0.53
950	0.20	0.17	0.26	0.52
1000	0.19	0.17	0.26	0.52
1100	0.19	0.17	0.25	0.51
1200	0.18	0.17	0.25	0.50
1300	0.18	0.17	0.25	0.49
1400	0.17	0.17	0.24	0.49
1500	0.17	0.17	0.24	0.48
1600	0.17	0.18	0.25	0.49
1700	0.19	0.20	0.28	0.56
1800	0.22	0.23	0.31	0.63
1900	0.24	0.28	0.36	0.73
2000	0.25	0.34	0.42	0.84
2100	0.29	0.39	0.48	0.97
2200	0.31	0.45	0.54	1.09
2300	0.36	0.53	0.65	1.29
2400	0.45	0.62	0.76	1.52
2500	0.55	0.72	0.91	1.81

A.6.5 COMPARISON LAMPS

The following lamps were used during the comparison (all FEL Type I):
Lamp 1: SL-217
Lamp 2: SL-218
Lamp 3: SL-219

A constant current of 8.1 A was used and the lamps were positioned 500 mm to front plate.

The voltage stabilities of all lamps were as expected.

A.7. MEASUREMENTS AT VSL

A.7.1 PRIMARY SCALE REALISATION

The spectral irradiance scale of VSL is traceable to NIST. The most recent calibration dates from October 2004, certificate number: 312601-340. The irradiance scale is transferred to working standard lamps using the spectral irradiance facility (SIRF), the irradiance response of which is determined using the calibrated lamps from NIST. The uncertainty associated with the NIST standard lamps is given in Table 27.

Table 27. Uncertainties associated with NIST spectral irradiance standard lamps

Wavelength / nm	Expanded uncertainty / %	Wavelength / nm	Expanded uncertainty / %
250	1.57	450	0.86
260	1.57	500	0.86
270	1.57	555	0.72
280	1.57	600	0.72
290	1.57	654.6	0.63
300	1.57	700	0.63
310	1.57	800	0.63
320	1.57	900	0.50
330	1.57	1050	0.50
340	1.57	1150	0.50
350	1.1	1200	0.50
360	1.1	1300	0.50
370	1.1	1540	0.50
380	1.1	1600	0.37
390	1.1	1700	0.37
400	1.1	2000	0.35

A.7.2 DESCRIPTION OF THE MEASUREMENT FACILITY

A.7.2.1 Facility for spectral irradiance realisation

Lamps are measured in the VSL SIRF using the equipment and procedures described in [16]. This facility consists of a McPherson double monochromator in subtractive mode with an integrating sphere mounted to the entrance port and a detector stage located at the exit port – see Figure 45. The monochromator specifications are listed in Table 28 and the detector specifications are given in Table 29.

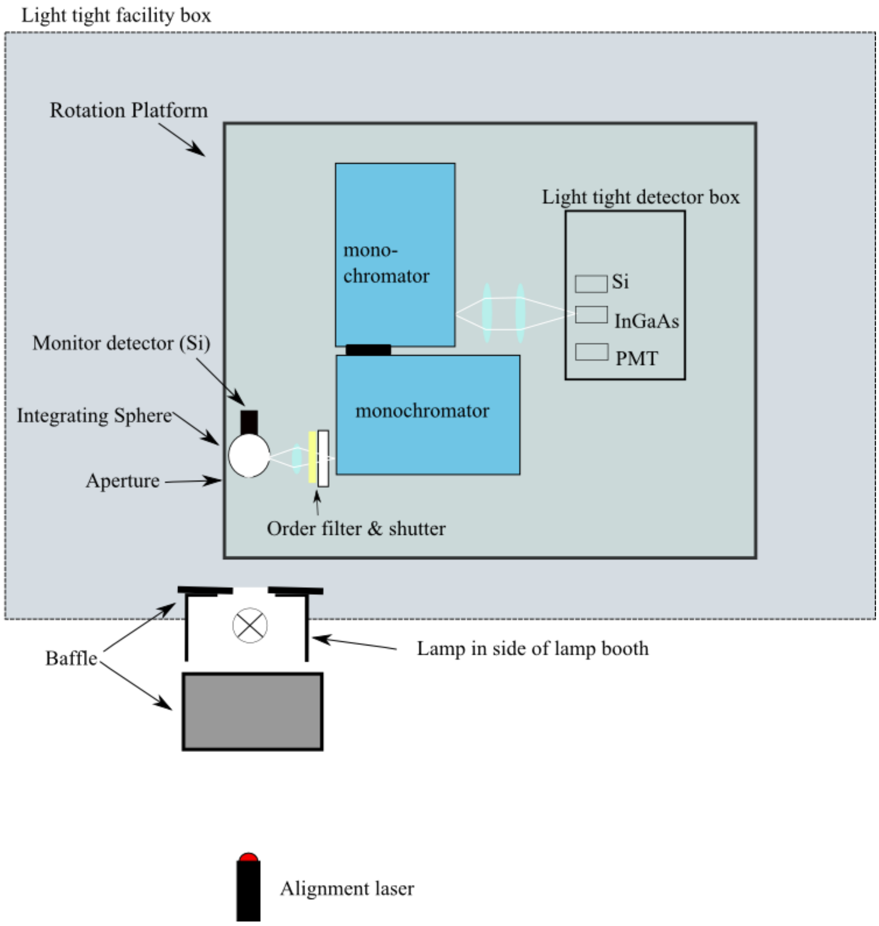

Figure 45. Spectral irradiance facility (SIRF) at VSL.

Table 28. Monochromator specification

Monochromator arrangement	Double
Manufacturer	McPherson
Type	Grating
Slit width	2.5 nm
Focal length	0.45 m
f - number	8

Table 29. Detector specifications

Detector type	PMT (Round 1)	PMT (Round 2)	Si	InGaAs
Manufacturer	Hamamatsu	Hamamatsu	Hamamatsu	Hamamatsu
Model	H9305-04	R6358	S1337-1010-BQ	G6122-3
Spectral range	250-400 nm	250-400 nm	400-1000 nm	1000-2500 nm
Operating temperature	23 °C	23 °C	23 °C	-15 °C

A.7.2.2 Laboratory

The room temperature and humidity were monitored and controlled. The room temperature was (23.0 ± 0.5) °C and the relative humidity (45 ± 10) %.

A.7.3 MEASUREMENT PROCEDURE

The measurements were conducted according to the instructions given in the document "PROTOCOL-EURAMET.PR-K1A".

The lamps were placed in a black metal u-shaped enclosure. The enclosure was open at the rear and a black metal plate was placed behind the lamp at an angle of 45° to reflect the light upwards. A baffle was placed between the lamp and the input aperture of the SIRF, about 200 mm from the lamp and with an aperture diameter of 75 mm. The reference plane of the lamps was placed at a distance of 500.0 mm from the input aperture of the SIRF using an inside micrometer. The area of the input aperture was 31.84 mm^2.

Measurements of the spectral irradiance were performed in three wavelength ranges: 250 nm - 400 nm, 400 nm -1000 nm and 1000 nm - 2000 nm. For each range the measurements were carried out according to the following procedure:

- Wavelength calibration of the SIRF.
- Determination of spectral irradiance response of SIRF using two reference lamps calibrated by NIST.
- Measurement of the irradiance of the transfer lamps: BN-9101-266, BN-9101-310, BN-9101-312.
- Measurement of the irradiance of the check lamps: BN-9101-356, BN-9101-382, BN-9101-383.

All lamps were aligned and measured at least 2 times per spectral range.

A.7.4 UNCERTAINTY BUDGET

A.7.4.1 Origin of uncertainty budget

A description of the uncertainty components is given below. Tables 30 to 34 give an overview of all uncertainties as function of wavelength. Uncertainty types and correlations are also listed in these tables; 'N' indicates uncorrelated, 'R' indicates correlated within the round and 'C' indicates entirely correlated.

- ***Calibration uncertainty of reference lamp***: This is the uncertainty associated with irradiance scale from the reference lamps calibrated by NIST.
- ***Distance of transfer lamp***: This is the uncertainty associated with the alignment of a transfer lamp. The distance between the lamp and the SIRF aperture is measured with a calibrated inside micrometer. The uncertainty in the distance of 500 mm is estimated to be 0.1 mm.
- ***Distance of reference lamp***: This is the uncertainty associated with the alignment of a reference lamp. The distance between the lamp and the SIRF aperture is measured with a calibrated inside micrometer. The uncertainty in the distance of 500 mm is estimated to be 0.1 mm.
- ***Current through transfer lamp***: This is the uncertainty associated with the current through the transfer lamp as measured with a zero flux and a digital multimeter.
- ***Current through reference lamp***: This is the uncertainty associated with the current through the reference lamp as measured with a zero flux and a digital multimeter.
- ***Long-term stability of reference lamp***: This is the uncertainty associated with the long-term stability of the reference lamps. It is an estimate of the drift of the lamp irradiance for a burning period of 25 hours.
- ***Spline of reference spectral irradiance***: This is the uncertainty associated with the determination of a reference irradiance of the NIST lamps using a cubic spline function. The cubic spline function is used to interpolate the spectral irradiance scale for wavelengths at which no direct measurements results were available on the reference lamps. The spectral irradiance response of the SIRF was determined based on the interpolated reference spectral irradiance.

- ***Wavelength of SIRF (reference lamp)***: This is the uncertainty associated with the wavelength setting of the SIRF monochromator in the measurements of the reference lamps. The wavelength of the SIRF monochromator is calibrated against Hg, He and Cs spectral lines. The uncertainty associated with the wavelength is determined from a least squared fit of repeated spectral line measurements.
- ***Wavelength of SIRF (transfer lamp)***: This is the uncertainty associated with the wavelength setting of the SIRF monochromator in the measurements of the transfer lamps. The wavelength of the SIRF monochromator is calibrated against Hg, He and Cs spectral lines. The uncertainty associated with the wavelength is determined from a least squared fit of repeated measurements.
- ***Repeatability of reference lamp measurement***: The uncertainty associated with the repeatability is determined from successive lamp measurements without re-alignment of the reference lamps.
- ***Repeatability of transfer lamp***: The uncertainty associated with the repeatability is determined from successive lamp measurements without re-alignment of the transfer lamps.

Table 30. VSL Spectral irradiance scale uncertainty 250 nm - 310 nm (*k*=1) / %

Type	Corre-lation	Source of uncertainty	Wavelength /nm						
			250	**260**	**270**	**280**	**290**	**300**	**310**
B	R	Wavelength reference lamp	0.67	0.52	0.48	0.42	0.38	0.35	0.32
A	N	Stability of reference lamp	0.65	0.38	0.62	0.37	0.35	0.27	0.28
B	N	Distance of reference lamp	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	C	Calibration uncertainty of reference	0.79	0.79	0.79	0.79	0.79	0.79	0.79
B	R	Long-term stability of working standard	0.65	0.63	0.61	0.59	0.57	0.55	0.53
B	R	Spline of reference spectral irradiance	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	R	Wavelength lamp under calibration	0.47	0.36	0.33	0.29	0.27	0.25	0.23
A	N	Stability of lamp under calbration	0.65	0.38	0.62	0.37	0.35	0.27	0.28
B	N	Distance of lamp under calibration	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	N	Lamp current reference	0.04	0.03	0.03	0.03	0.03	0.03	0.03
B	N	Lamp current of lamp under calibration	0.04	0.03	0.03	0.03	0.03	0.03	0.03
		Total type A	0.92	0.54	0.88	0.52	0.50	0.39	0.39
		Total type B	1.31	1.19	1.15	1.11	1.08	1.05	1.03
		Total (A+B)	**1.60**	**1.31**	**1.45**	**1.22**	**1.19**	**1.12**	**1.10**
		Correlated within the round	1.04	0.90	0.84	0.78	0.73	0.70	0.66
		Uncorrelated	0.93	0.54	0.88	0.53	0.50	0.39	0.40
		Entirely correlated	0.79	0.79	0.79	0.79	0.79	0.79	0.79

Table 31. VSL Spectral irradiance scale uncertainty 320 nm - 390 nm (*k*=1) / %

Type	Corre-lation	Source of uncertainty	Wavelength /nm							
			320	**330**	**340**	**350**	**360**	**370**	**380**	**390**
B	R	Wavelength reference lamp	0.30	0.28	0.25	0.23	0.22	0.20	0.19	0.17
A	N	Stability of reference lamp	0.25	0.24	0.22	0.19	0.18	0.25	0.62	0.18
B	N	Distance of reference lamp	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	C	Calibration uncertainty of reference	0.79	0.79	0.79	0.55	0.55	0.55	0.55	0.55
B	R	Long-term stability of working standard	0.51	0.49	0.48	0.47	0.46	0.46	0.45	0.45
B	R	Spline of reference spectral irradiance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	R	Wavelength lamp under calibration	0.21	0.19	0.18	0.16	0.15	0.14	0.13	0.12
A	N	Stability of lamp under calbration	0.25	0.24	0.22	0.19	0.18	0.25	0.62	0.18
B	N	Distance of lamp under calibration	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	N	Lamp current reference	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
B	N	Lamp current of lamp under calibration	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
		Total type A	0.36	0.33	0.31	0.26	0.25	0.36	0.87	0.26
		Total type B	1.01	0.99	0.97	0.78	0.77	0.76	0.75	0.75
		Total (A+B)	**1.07**	**1.04**	**1.02**	**0.82**	**0.81**	**0.84**	**1.15**	**0.79**
		Correlated within the round	0.63	0.60	0.57	0.55	0.53	0.52	0.51	0.50
		Uncorrelated	0.36	0.34	0.32	0.27	0.26	0.36	0.87	0.27
		Entirely correlated	0.79	0.79	0.79	0.55	0.55	0.55	0.55	0.55

Table 32. VSL Spectral irradiance scale uncertainty 400 nm - 650 nm (*k*=1) / %

Type	Corre-lation	Source of uncertainty	Wavelength /nm						
			400	**450**	**500**	**550**	**555**	**600**	**650**
B	R	Wavelength reference lamp	0.16	0.12	0.08	0.06	0.06	0.04	0.03
A	N	Stability of reference lamp	0.26	0.20	0.17	0.16	0.16	0.17	0.17
B	N	Distance of reference lamp	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	C	Calibration uncertainty of reference	0.55	0.43	0.43	0.36	0.36	0.36	0.32
B	R	Long-term stability of working standard	0.45	0.47	0.49	0.47	0.46	0.38	0.26
B	R	Spline of reference spectral irradiance	0.00	0.00	0.00	0.33	0.00	0.00	0.27
B	R	Wavelength lamp under calibration	0.16	0.12	0.08	0.06	0.06	0.04	0.03
A	N	Stability of lamp under calbration	0.26	0.20	0.17	0.16	0.16	0.17	0.17
B	N	Distance of lamp under calibration	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	N	Lamp current reference	0.02	0.02	0.02	0.01	0.01	0.01	0.01
B	N	Lamp current of lamp under calibration	0.02	0.02	0.02	0.01	0.01	0.01	0.01
		Total type A	0.25	0.18	0.08	0.09	0.09	0.07	0.09
		Total type B	0.75	0.66	0.67	0.69	0.60	0.53	0.50
		Total (A+B)	**0.79**	**0.68**	**0.67**	**0.70**	**0.60**	**0.53**	**0.51**
		Correlated within the round	0.51	0.50	0.51	0.58	0.47	0.38	0.38
		Uncorrelated	0.26	0.19	0.10	0.11	0.11	0.09	0.11
		Entirely correlated	0.55	0.43	0.43	0.36	0.36	0.36	0.32

Table 33. VSL Spectral irradiance scale uncertainty 700 nm - 1000 nm (*k*=1) / %

Type	Corre-lation	Source of uncertainty	Wavelength /nm						
			700	**750**	**800**	**850**	**900**	**950**	**1000**
B	R	Wavelength reference lamp	0.02	0.01	0.004	0.0001	0.003	0.005	0.004
A	N	Stability of reference lamp	0.19	0.23	0.24	0.27	0.28	0.29	0.29
B	N	Distance of reference lamp	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	C	Calibration uncertainty of reference	0.31	0.32	0.31	0.28	0.25	0.24	0.24
B	R	Long-term stability of working standard	0.18	0.15	0.14	0.16	0.18	0.20	0.21
B	R	Spline of reference spectral irradiance	0.00	0.24	0.00	0.21	0.00	0.00	0.18
B	R	Wavelength lamp under calibration	0.02	0.01	0.01	0.00	0.00	0.00	0.00
A	N	Stability of lamp under calbration	0.19	0.23	0.24	0.27	0.28	0.29	0.29
B	N	Distance of lamp under calibration	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	N	Lamp current reference	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	N	Lamp current of lamp under calibration	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Total type A	0.12	0.13	0.28	0.31	0.26	0.23	0.30
		Total type B	0.37	0.43	0.35	0.39	0.31	0.31	0.37
		Total (A+B)	**0.39**	**0.45**	**0.45**	**0.50**	**0.40**	**0.39**	**0.48**
		Correlated within the round	0.18	0.28	0.14	0.26	0.18	0.20	0.27
		Uncorrelated	0.13	0.14	0.29	0.31	0.26	0.24	0.30
		Entirely correlated	0.31	0.32	0.31	0.28	0.25	0.24	0.24

Table 34. VSL Spectral irradiance scale uncertainty 1100 nm - 2000 nm (*k*=1) / %

Type	Corre-lation	Source of uncertainty	Wavelength /nm									
			1100	**1200**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**
B	R	Wavelength reference lamp	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A	N	Stability of reference lamp	0.82	0.69	1.02	1.22	1.08	0.83	0.98	1.02	1.25	1.48
B	N	Distance of reference lamp	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	C	Calibration uncertainty of reference	0.25	0.25	0.25	0.28	0.28	0.19	0.19	0.19	0.18	0.17
B	R	Long-term stability of working standard	0.21	0.20	0.18	0.15	0.12	0.10	0.09	0.08	0.08	0.08
B	R	Spline of reference spectral irradiance	0.16	0.15	0.13	0.12	0.11	0.10	0.10	0.09	0.09	0.10
B	R	Wavelength lamp under calibration	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A	N	Stability of lamp under calbration	0.82	0.69	1.02	1.22	1.08	0.83	0.98	1.02	1.25	1.48
B	N	Distance of lamp under calibration	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
B	N	Lamp current reference	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

B	N	Lamp current of lamp under calibration	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Total type A	1.16	0.98	1.44	1.73	1.53	1.18	1.39	1.45	1.77	2.09
		Total type B	0.37	0.36	0.34	0.34	0.33	0.24	0.23	0.24	0.23	0.22
		Total (A+B)	**1.22**	**1.04**	**1.48**	**1.76**	**1.57**	**1.20**	**1.41**	**1.47**	**1.78**	**2.10**
		Correlated within the round	0.27	0.25	0.22	0.19	0.16	0.14	0.13	0.13	0.13	0.13
		Uncorrelated	1.16	0.98	1.44	1.73	1.53	1.18	1.39	1.45	1.77	2.09
		Entirely correlated	0.25	0.25	0.25	0.28	0.28	0.19	0.19	0.19	0.18	0.17

A.7.4.2 Uncertainty budget summary

Table 35. Uncertainties associated with measurement of lamp spectral irradiance at VSL

Wavelength / nm	Uncertainty associated with correlated (systematic) effects	Uncertainty associated with uncorrelated (random) effects	Combined standard uncertainty (k = 1)	Expanded uncertainty (k = 2)
250	1.31 %	0.93 %	1.60 %	3.20 %
260	1.19 %	0.54 %	1.31 %	2.62 %
270	1.15 %	0.88 %	1.45 %	2.90 %
280	1.11 %	0.53 %	1.22 %	2.45 %
290	1.07 %	0.50 %	1.19 %	2.37 %
300	1.05 %	0.39 %	1.12 %	2.24 %
310	1.02 %	0.40 %	1.10 %	2.20 %
320	1.01 %	0.36 %	1.07 %	2.14 %
330	0.99 %	0.34 %	1.04 %	2.09 %
340	0.97 %	0.32 %	1.02 %	2.04 %
350	0.78 %	0.27 %	0.82 %	1.65 %
360	0.77 %	0.26 %	0.81 %	1.62 %
370	0.76 %	0.36 %	0.84 %	1.68 %
380	0.75 %	0.87 %	1.15 %	2.30 %
390	0.74 %	0.27 %	0.79 %	1.58 %
400	0.75 %	0.26 %	0.79 %	1.58 %
450	0.66 %	0.19 %	0.68 %	1.37 %
500	0.66 %	0.10 %	0.67 %	1.34 %
550	0.69 %	0.11 %	0.70 %	1.39 %
555	0.59 %	0.11 %	0.60 %	1.21 %
600	0.52 %	0.09 %	0.53 %	1.06 %
650	0.50 %	0.11 %	0.51 %	1.02 %
700	0.37 %	0.13 %	0.39 %	0.78 %
750	0.43 %	0.14 %	0.45 %	0.90 %
800	0.35 %	0.29 %	0.45 %	0.90 %
850	0.39 %	0.31 %	0.50 %	1.00 %
900	0.31 %	0.26 %	0.40 %	0.81 %
950	0.31 %	0.24 %	0.39 %	0.78 %
1000	0.37 %	0.30 %	0.48 %	0.95 %
1100	0.37 %	1.16 %	1.22 %	2.44 %
1200	0.35 %	0.98 %	1.04 %	2.08 %
1300	0.33 %	1.44 %	1.48 %	2.96 %
1400	0.34 %	1.73 %	1.76 %	3.52 %
1500	0.32 %	1.53 %	1.57 %	3.13 %
1600	0.23 %	1.18 %	1.20 %	2.40 %
1700	0.23 %	1.39 %	1.41 %	2.82 %
1800	0.23 %	1.45 %	1.47 %	2.93 %
1900	0.22 %	1.77 %	1.78 %	3.57 %
2000	0.22 %	2.09 %	2.10 %	4.21 %

A.7.5 COMPARISON LAMPS

The following lamps were submitted to NPL by VSL: BN 9101 266, BN 9101 310, BN-9101 312.

All lamps submitted by VSL were of the following type: FEL, Sylvania, 1000 W, T6 120 V

Measurements were made in the sequence: VSL – NPL – VSL.

The lamps were operated at 8.100 A at both laboratories; the lamp voltage measured is shown in Table 36 and the lamp history is shown in Table 37.

Table 36. Transfer lamps submitted by VSL

Lamp	Potential first VSL measurement /V	Potential second VSL measurement /V
BN-9101-266	100.046	99.913
BN-9101-310	107.017	107.103
BN-9101-312	111.751	111.728

Table 37. History of lamps submitted by VSL

Lamp	Date	Transport from	Transport to	Hand carried or freight?	Vehicle (car/ bus/ train/ aeroplane)
BN-9101-266	12-1-2011	VSL	NPL	Hand carried	Car & Train
	5-4-2011	NPL	VSL	Hand carried	Car & Train
BN-9101-310	12-1-2011	VSL	NPL	Hand carried	Car & Train
	5-4-2011	NPL	VSL	Hand carried	Car & Train
BN-9101-312	12-1-2011	VSL	NPL	Hand carried	Car & Train
	5-4-2011	NPL	VSL	Hand carried	Car & Train

A.8. REFERENCES

[1] E.R. Woolliams, N.P. Fox, M.G. Cox, P.M. Harris and N.J. Harrison, Final report on CCPR K1-a: Spectral Irradiance from 250 nm to 2500 nm, Metrologia, 43 (1A Tech. Suppl.), (2006) S98-S104.

[2] Ojanen, M., M. Shpak, P. Kärhä, R. Leecharoen and E. Ikonen (2009). "Uncertainty evaluation for linking a bilateral key comparison with the corresponding CIPM key comparison." Metrologia 46(5): 379-403

[3] Fox N.P., Martin J.E., Nettleton D.H., Absolute spectral radiometric determination of the thermodynamic temperatures of the melting/freezing points of gold, silver and aluminium, *Metrologia*, **28**, 1991, 357-374

[4] Sperfeld P., Metzdorf J., Harrison N.J., Fox N. P., Khlevnoy B.B., Khromchenko V.B., Mekhontsev S. N., Shapoval V.I., Zelener M.F., Sapritsky V.I., Investigation of high-temperature blackbody BB3200. *Metrologia*, 1998, **35**, 419–422

[5] Woolliams E. R., Harrison N. J., Fox N. P., Preliminary results of the investigation of a 3500 K black body *Metrologia*, 2000, **37(5)**, 501-504

[6] Woolliams E. R., Harrison N. J., Khlevnoy B.B., Rogers L.J., Fox N.P., Realisation and dissemination of spectral irradiance at NPL. *UV News*, 2002, **7**, 39-42

[7] Sperfeld P., Galal Yousef S., Metzdorf J., Nawo B., Möller W., The use of self-consistent calibrations to recover absorption bands in the black-body spectrum. *Metrologia*, 2000, **37(5)**, 373-376

[8] Woolliams E.R., PhD Thesis, *Development and evaluation of a high temperature blackbody source for the realisation of NPL's primary spectral irradiance scale*, University of Manchester, 2003

[9] Woolliams E.R., Pollard D.F., Harrison N.J., Theocharous E., Fox N.P., New facility for the high-accuracy measurement of lens transmission. *Metrologia*, 2000, **37(5)**, 603-605

[10] Metzdorf J., Metrologia, 1993, 30, 403-408.

[11] Sapritsky V. I., Khlevnoy B. B., Khromchenko V. B., Lisiansky B. E., Mekhontsev S. N., Melenevsky U. A., Morozova S. P., Prokhorov A. V., Samoilov L. N., Shapoval V. I., Sudarev K. A., Zelener M. F., Appl. Opt., 1997, 36, 5403-5408.

[12] Sperfeld P., Metzdorf J., Galal Yousef S., Stock K. D., Möller W., Metrologia, 1998, 35, 267-271.

[13] Sperfeld P., Entwicklung einer empfängergestützten spektralen Bestrahlungs-stärkeskala, Braunschweig, 1999. http://www.biblio.tu-bs.de/ediss/data/19990628a/19990628a.html

[14] Khlevnoy B.B., Harrison N.J., Rogers L.J., Pollard D.F., Fox N.P., Sperfeld P., Fischer J., Friedrich R., Metzdorf J., Seidel J., Samoylov M.L., Stolyarevskaya R.I., Khromchenko V.B., Ogarev S.A., Sapritsky V.I., Metrologia, 2003, 40, S39–S44

[15] P. Sperfeld, S. Pape and B. Barton, From Primary Standard to Mobile Measurements - Overview of the Spectral Irradiance Calibration Equipment at PTB, MAPAN- Journal of Metrology Society of India, 25 (2010) 11-19.

[16] E W M van der Ham, H C D Bos and C A Schrama: Primary realization of a spectral irradiance employing monochromator-based cryogenic radiometry between 200 nm and 20 µm, Metrologia 40, S177-S180 (2003).

APPENDIX B – CHANGES MADE AT PRE-DRAFT A STAGE

DMDM, Serbia, withdrew from the comparison due to a technical problem with the spectroradiometer.

INM-RO, Romania, submitted a slightly revised uncertainty budget, to take account of the ageing of the reference lamps during the course of the comparison. The additional standard uncertainty for the correction applied for ageing was 0.1 %, resulting in an increase in the combined standard uncertainty for the comparison measurements from 1.0 % to 1.1 % for wavelengths of 450 nm and above (the standard uncertainty at 400 nm, of 1.2 %, was unaffected).

VNIIOFI, Russia, requested the removal of one lamp from the comparison following review of the Pre-Draft A analysis of the internal consistency of all the lamps measured at each participant's laboratory. This analysis revealed a significant inconsistency between one lamp and the other two, as shown in Figure 46. It had been noted by VNIIOFI during the measurements that a white deposit had appeared on the inside of the envelope of one of the lamps (see Figure 47), but it was not known whether this had affected the spectral irradiance and it was decided to submit the data for all 3 lamps at that stage. The analysis of the internal consistency of all the lamps revealed that the lamp had definitely drifted and it was therefore requested that it be removed. Since VNIIOFI had used the incorrect current for the lamps in the first round, and thus submitted results only for the second round, the subsequent withdrawal of one lamp means that the comparison results for VNIIOFI are based on measurements of just two lamps, each measured once at NPL and once at VNIIOFI.

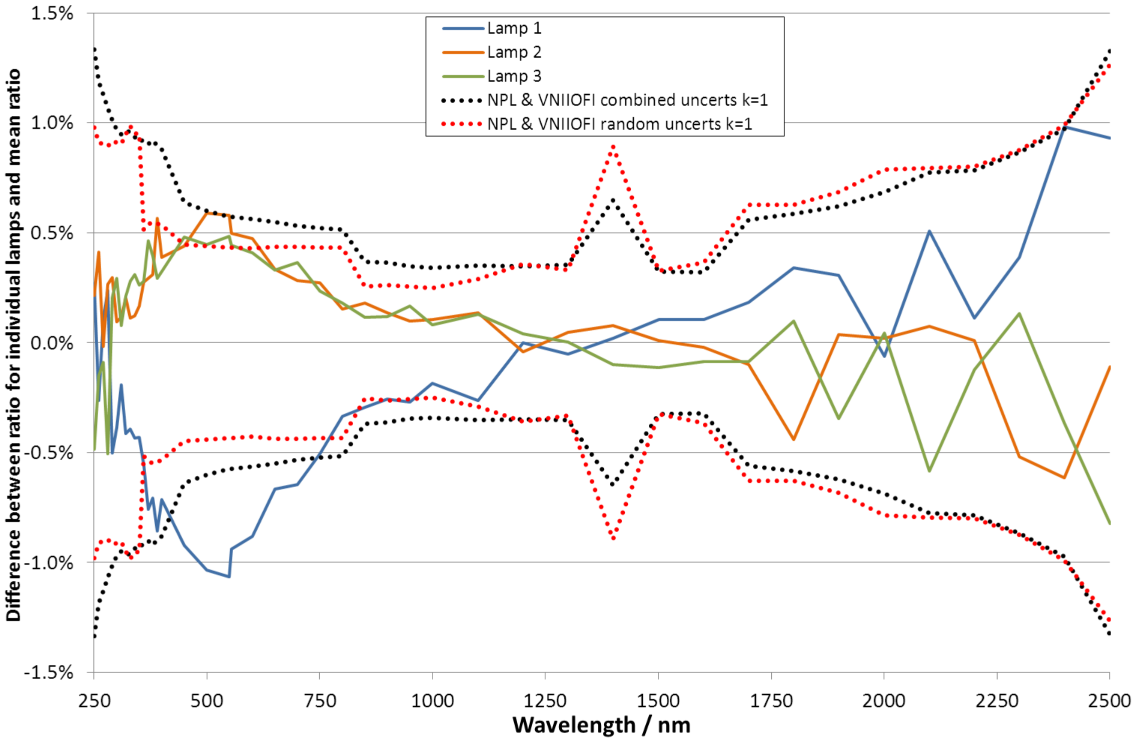

Figure 46. Difference between ratios of values assigned to each lamp by VNIIOFI to values assigned to the same lamp by NPL and mean VNIIOFI-to-NPL ratio for all lamps measured by VNIIOFI (i.e. before removal of one lamp from the comparison).

Figure 47. Photograph of lamps measured by VNIIOFI; note white deposit at base of lamp SL 217.

VSL, The Netherlands, made a small change to the initially-submitted data at 1600 nm for two of the lamps, due to rounding errors. The changes were of the order of 0.1 % and therefore insignificant in terms of the results of the comparison.

APPENDIX C – SUMMARY OF RESULTS

Results for the individual participants are summarised in the Tables and Figures below, which show the unilateral DoE to the CCPR KCRV for the participants and the associated uncertainties. In the case of NPL, the scale considered is that realised in 2010 (see Section 4.1).

Table 38. Unilateral DoE and associated uncertainties for NPL_{2010} scale

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (k=1)
250	-0.76 %	1.43 %
260	-0.74 %	1.28 %
270	-1.02 %	1.25 %
280	-1.76 %	1.25 %
290	-0.90 %	1.23 %
300	-0.75 %	1.19 %
310	-0.80 %	1.16 %
320	-1.03 %	1.16 %
330	-1.16 %	1.14 %
340	-1.02 %	1.13 %
350	-0.78 %	1.15 %
360	-0.96 %	1.06 %
370	-1.05 %	1.06 %
380	-1.08 %	1.09 %
390	-1.20 %	1.06 %
400	-0.93 %	1.06 %
450	-0.50 %	0.70 %
500	-0.39 %	0.65 %
550	-0.18 %	0.65 %
555	-0.24 %	0.65 %
600	-0.27 %	0.63 %
650	-0.32 %	0.63 %
700	-0.40 %	0.62 %
750	-0.33 %	0.61 %
800	-0.51 %	0.60 %
850	-0.27 %	0.46 %
900	-0.32 %	0.42 %
950	-0.15 %	0.42 %
1000	-0.22 %	0.41 %
1100	-0.24 %	0.45 %
1200	-0.36 %	0.48 %
1300	-0.35 %	0.45 %
1400	0.39 %	1.06 %
1500	-0.10 %	0.47 %
1600	0.10 %	0.49 %
1700	0.07 %	0.80 %
1800	0.34 %	0.81 %

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
1900	0.37 %	0.86 %
2000	0.04 %	0.93 %
2100	0.06 %	0.98 %
2200	-0.27 %	0.92 %
2300	0.05 %	0.95 %
2400	0.99 %	1.04 %
2500	0.32 %	1.60 %

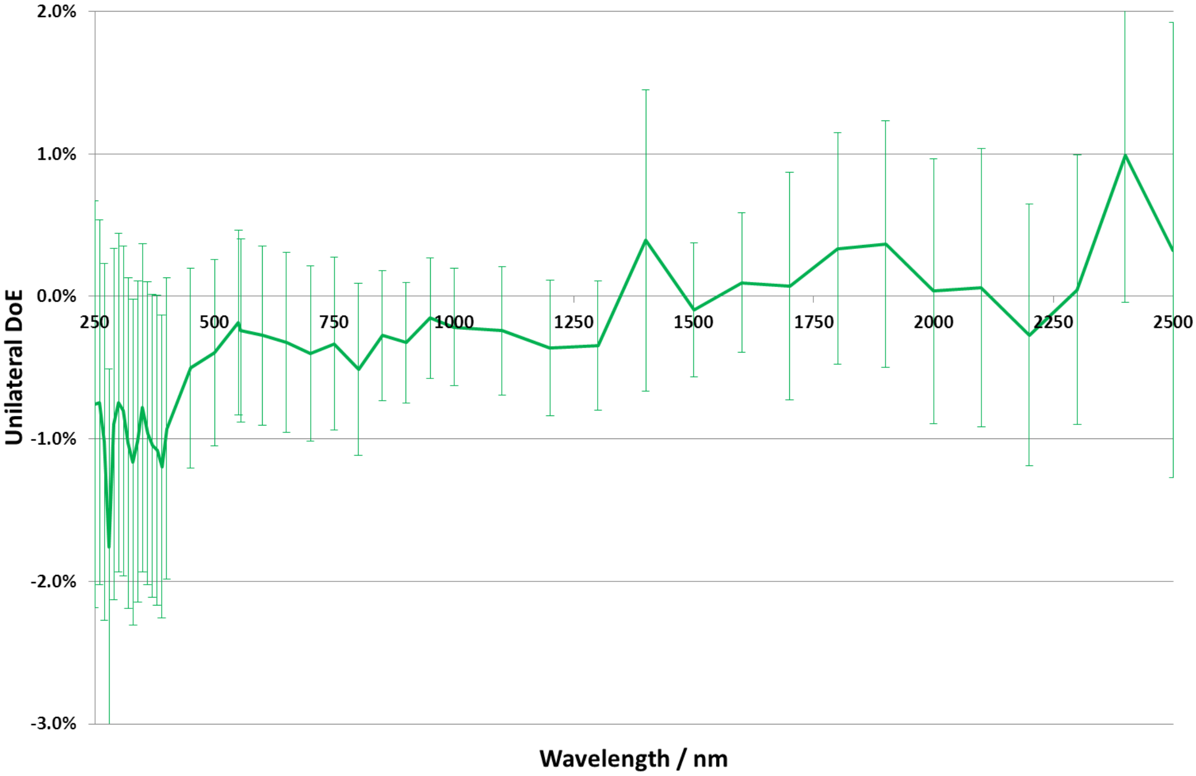

Figure 48. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for NPL_{2010} scale.

Table 39. Unilateral DoE and associated uncertainties for INM-RO

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (k=1)
400	3.21 %	1.35 %
450	5.01 %	1.13 %
500	3.94 %	1.11 %
550	2.98 %	1.11 %
555	2.74 %	1.11 %
600	2.84 %	1.10 %
650	2.93 %	1.10 %
700	3.02 %	1.10 %
750	3.17 %	1.09 %
800	3.24 %	1.09 %
850	3.52 %	1.07 %
900	3.53 %	1.05 %

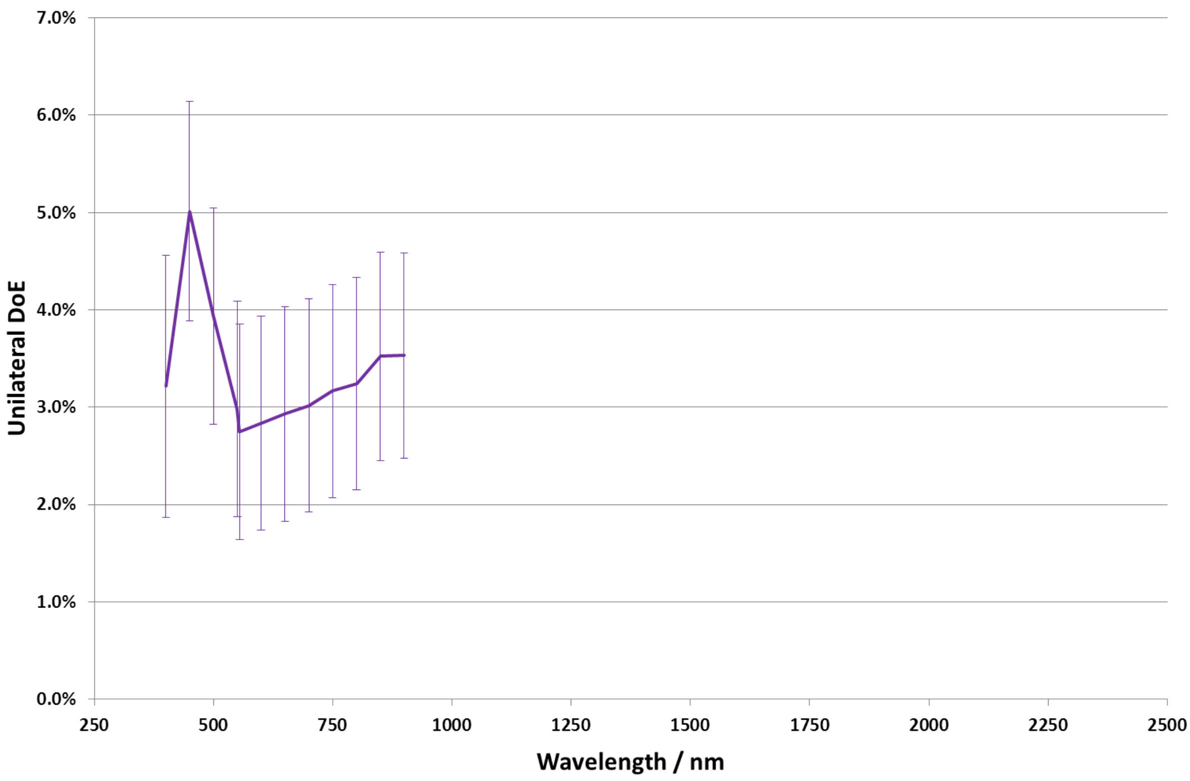

Figure 49. Unilateral DoE to CCPR KCRV and associated uncertainties (k=1) for INM-RO.

Table 40. Unilateral DoE and associated uncertainties for METAS

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
250	-2.28 %	3.26 %
260	-3.75 %	2.12 %
270	-3.83 %	2.09 %
280	-3.84 %	2.03 %
290	-2.94 %	2.06 %
300	-2.58 %	2.00 %
310	-2.21 %	1.94 %
320	-1.66 %	1.89 %
330	-1.95 %	1.89 %
340	-2.01 %	1.88 %
350	-1.18 %	1.88 %
360	-1.29 %	1.59 %
370	-1.13 %	1.59 %
380	-1.15 %	1.59 %
390	-1.34 %	1.54 %
400	-1.21 %	1.55 %
450	-0.88 %	1.42 %
500	-0.83 %	1.37 %
550	-0.74 %	1.37 %
555	-0.71 %	1.35 %
600	-0.64 %	1.32 %
650	-0.62 %	1.28 %
700	-0.53 %	1.28 %
750	-0.35 %	1.24 %
800	-0.38 %	1.20 %
850	-0.09 %	1.18 %
900	-0.01 %	1.16 %
950	-0.02 %	1.17 %
1000	0.00 %	1.17 %
1100	-0.03 %	1.17 %

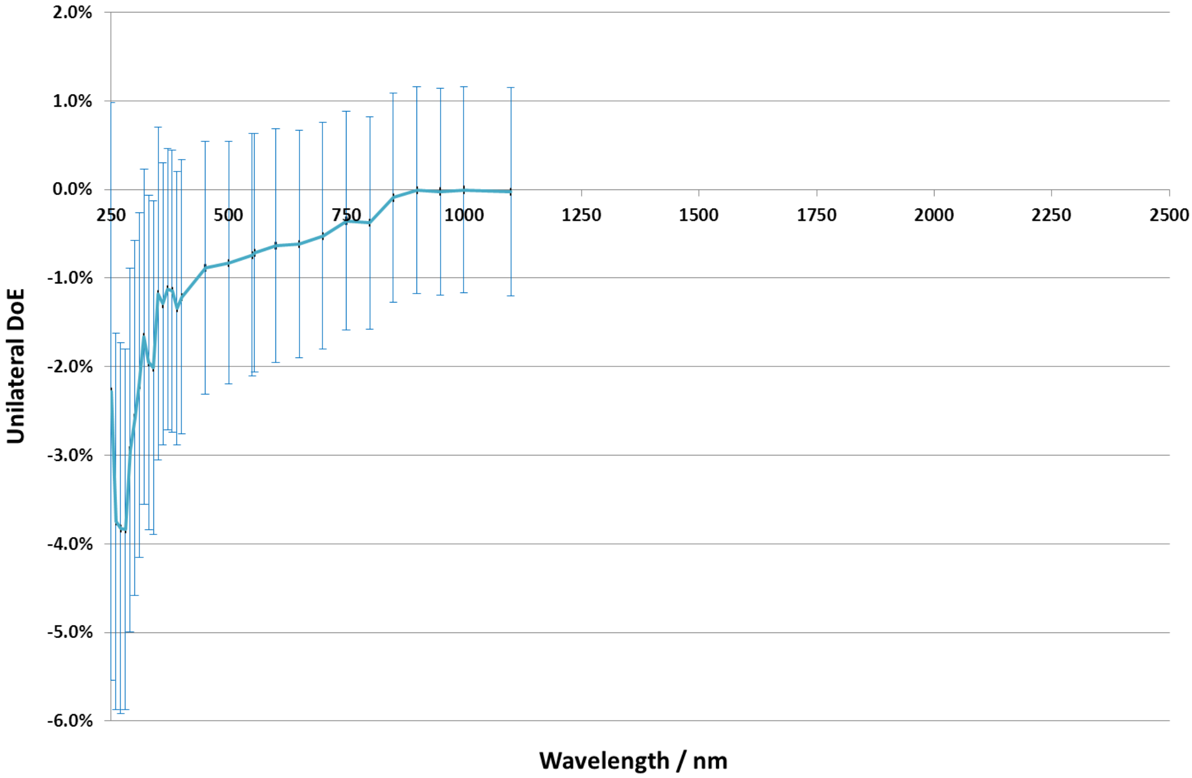

Figure 50. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for METAS.

Table 41. Unilateral DoE and associated uncertainties for SP

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (k=1)
250	2.95 %	2.10 %
260	3.22 %	1.86 %
270	3.00 %	1.68 %
280	3.23 %	1.59 %
290	2.98 %	1.48 %
300	3.16 %	1.39 %
310	2.69 %	1.30 %
320	3.00 %	1.27 %
330	2.77 %	1.23 %
340	2.63 %	1.20 %
350	2.58 %	1.17 %
360	2.30 %	1.11 %
370	2.23 %	1.10 %
380	1.88 %	1.09 %
390	1.73 %	1.07 %
400	1.89 %	1.07 %
450	1.81 %	0.99 %
500	2.23 %	0.96 %
550	2.64 %	0.94 %
555	2.60 %	0.94 %
600	2.51 %	0.92 %
650	2.14 %	0.93 %
700	1.74 %	0.91 %
750	1.75 %	0.90 %
800	1.99 %	0.95 %
850	2.15 %	1.11 %
900	2.17 %	1.14 %
950	2.60 %	1.17 %
1000	2.73 %	1.18 %
1100	2.71 %	1.14 %
1200	3.02 %	1.15 %
1300	2.49 %	1.15 %
1400	2.91 %	1.40 %
1500	2.61 %	1.21 %
1600	2.71 %	1.26 %
1700	2.82 %	1.41 %
1800	2.89 %	1.48 %
1900	2.41 %	1.58 %
2000	2.59 %	1.68 %
2100	2.60 %	1.88 %
2200	2.44 %	2.08 %
2300	2.57 %	2.30 %
2400	3.42 %	2.59 %
2500	2.84 %	3.08 %

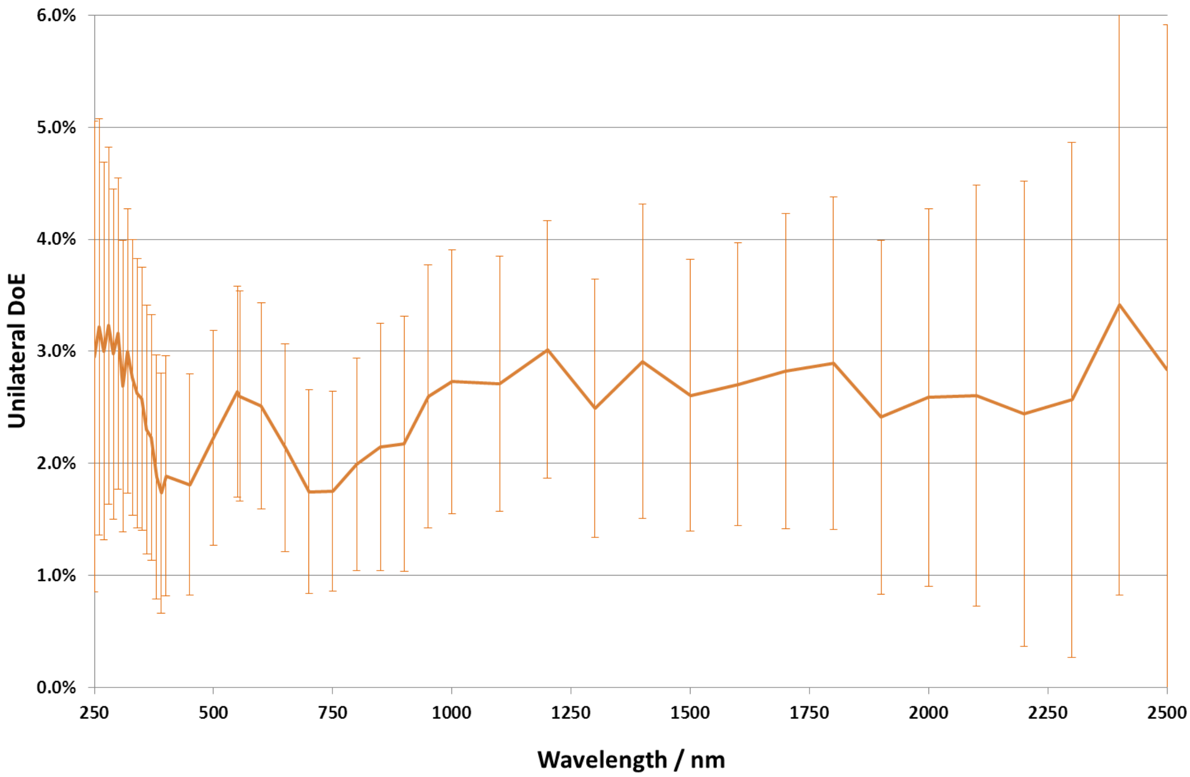

Figure 51. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for SP.

Table 42. Unilateral DoE and associated uncertainties for VNIIOFI

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
250	-1.00 %	1.46 %
260	-0.73 %	1.21 %
270	-0.64 %	1.10 %
280	0.56 %	1.10 %
290	-0.80 %	1.05 %
300	-0.72 %	1.02 %
310	-0.45 %	0.97 %
320	-0.70 %	0.95 %
330	-0.57 %	0.92 %
340	-0.34 %	0.90 %
350	-0.24 %	0.88 %
360	-0.05 %	0.80 %
370	-0.16 %	0.78 %
380	0.07 %	0.77 %
390	0.17 %	0.75 %
400	0.02 %	0.75 %
450	-0.34 %	0.65 %
500	-0.03 %	0.60 %
550	0.24 %	0.59 %
555	0.16 %	0.58 %
600	0.12 %	0.56 %
650	-0.03 %	0.56 %
700	0.02 %	0.54 %
750	-0.02 %	0.52 %
800	-0.17 %	0.52 %
850	-0.06 %	0.46 %
900	-0.08 %	0.43 %
950	0.02 %	0.43 %
1000	0.02 %	0.42 %
1100	0.21 %	0.44 %
1200	0.05 %	0.47 %
1300	0.17 %	0.45 %
1400	0.38 %	0.89 %
1500	0.24 %	0.48 %
1600	0.49 %	0.51 %
1700	0.27 %	0.71 %
1800	0.11 %	0.73 %
1900	0.27 %	0.80 %
2000	-0.59 %	0.87 %
2100	-0.51 %	0.92 %
2200	-0.77 %	0.92 %
2300	0.03 %	1.00 %
2400	0.40 %	1.14 %
2500	0.17 %	1.57 %

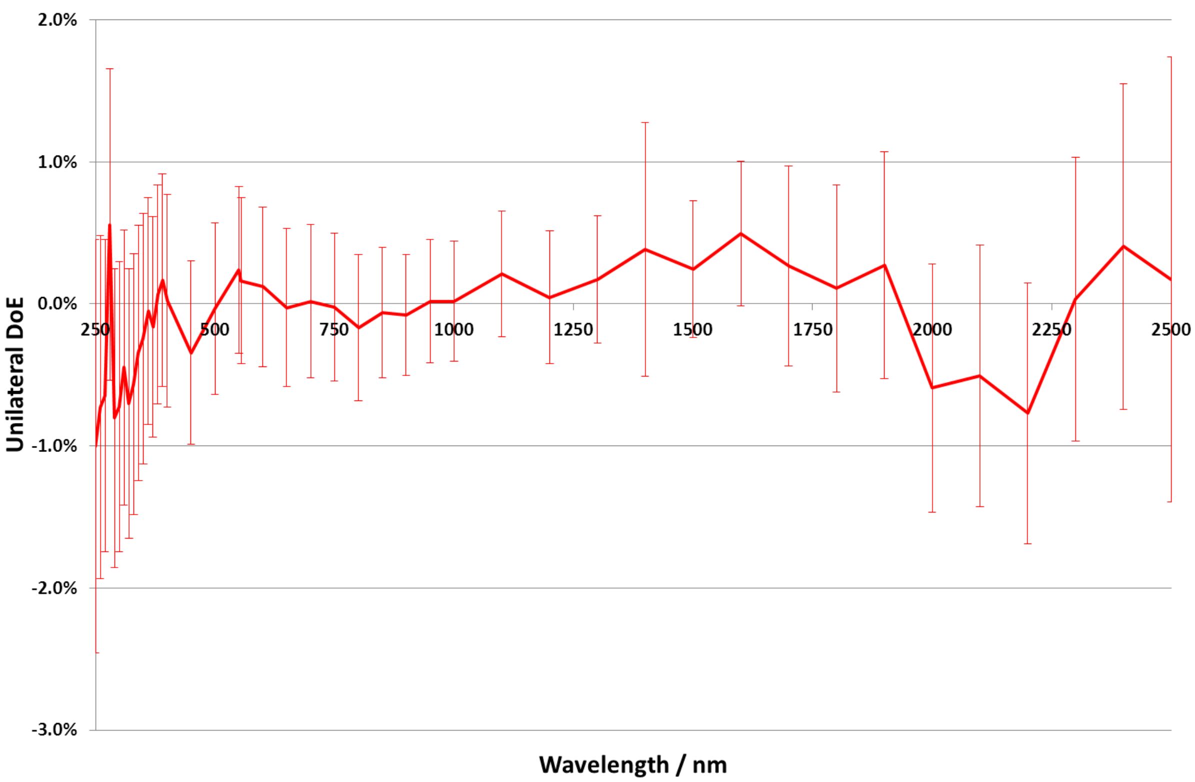

Figure 52. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for VNIIOFI.

Table 43. Unilateral DoE and associated uncertainties for VSL

Wavelength / nm	DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
250	-1.42 %	1.90 %
260	-0.93 %	1.57 %
270	-0.86 %	1.67 %
280	-1.85 %	1.49 %
290	-1.40 %	1.46 %
300	-1.50 %	1.39 %
310	-1.66 %	1.35 %
320	-1.57 %	1.32 %
330	-1.26 %	1.28 %
340	-1.49 %	1.26 %
350	-1.35 %	1.10 %
360	-2.18 %	1.03 %
370	-2.00 %	1.05 %
380	-1.99 %	1.31 %
390	-2.03 %	1.00 %
400	-1.92 %	1.00 %
450	-1.36 %	0.85 %
500	-1.08 %	0.83 %
550	-0.82 %	0.85 %
555	-0.95 %	0.77 %
600	-0.97 %	0.70 %
650	-0.83 %	0.69 %
700	-1.06 %	0.60 %
750	-0.98 %	0.63 %
800	-0.99 %	0.63 %
850	-0.88 %	0.62 %
900	-0.95 %	0.52 %
950	-0.99 %	0.52 %
1000	-0.93 %	0.58 %
1100	-0.93 %	1.27 %
1200	-0.89 %	1.11 %
1300	-1.02 %	1.53 %
1400	-0.96 %	1.96 %
1500	-0.64 %	1.62 %
1600	-0.41 %	1.28 %
1700	-0.70 %	1.55 %
1800	-1.06 %	1.61 %
1900	-0.71 %	1.92 %
2000	-1.13 %	2.24 %

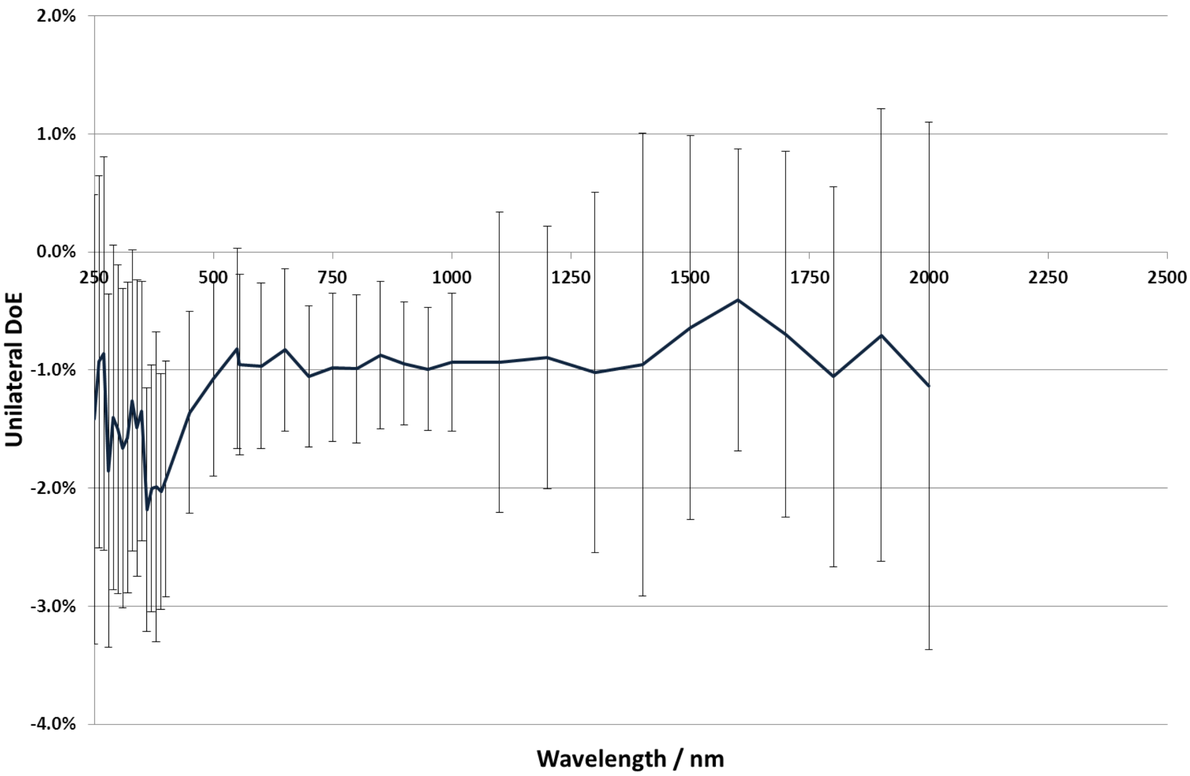

Figure 53. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for VSL.

APPENDIX D – RESULTS FROM CCPR K1.A KEY COMPARISON FOR NPL (2003 SCALE) AND PTB

Table 44 and Figure 54 below gives the DoE values and associated uncertainties for NPL (2003 scale) and PTB as given in the report of the CCPR K1.a Key Comparison. These are included for completeness; they were not determined as a result of this comparison.

Table 44. Unilateral DoE and associated uncertainties for NPL (2003 scale) and PTB as determined from the CCPR K1.a Key Comparison.

Wavelength / nm	NPL_{2003} DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)	PTB DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
250	0.50%	2.47%	-0.64%	0.84%
260	-0.12%	2.23%	-0.02%	0.71%
270	-0.98%	2.10%	-0.02%	0.66%
280	-0.65%	1.61%	-0.76%	0.69%
290	-0.81%	1.11%	-0.15%	0.68%
300	-0.42%	0.63%	-0.15%	0.67%
310	-0.28%	0.60%	0.00%	0.62%
320	0.03%	0.54%	-0.22%	0.59%
330	0.14%	0.51%	-0.28%	0.57%
340	0.22%	0.50%	-0.27%	0.56%
350	0.29%	0.50%	-0.14%	0.56%
360	0.27%	0.51%	-0.16%	0.49%
370	0.29%	0.52%	-0.15%	0.48%
380	0.27%	0.55%	-0.08%	0.47%
390	0.17%	0.53%	-0.15%	0.47%
400	0.16%	0.51%	-0.11%	0.47%
450	-0.18%	0.37%	-0.38%	0.44%
500	-0.30%	0.33%	-0.35%	0.42%
550	-0.25%	0.31%	-0.20%	0.41%
555	-0.29%	0.30%	-0.27%	0.40%
600	-0.31%	0.29%	-0.26%	0.40%
650	-0.16%	0.27%	-0.31%	0.42%
700	-0.11%	0.25%	-0.37%	0.41%
750	0.13%	0.23%	-0.30%	0.41%
800	0.16%	0.22%	-0.44%	0.41%
850	0.36%	0.25%	-0.31%	0.37%
900	0.43%	0.21%	-0.40%	0.34%
950	0.37%	0.22%	-0.24%	0.35%
1000	0.45%	0.21%	-0.35%	0.35%
1100	0.53%	0.21%	-0.44%	0.48%
1200	0.31%	0.22%	-0.42%	0.48%
1300	0.51%	0.24%	-0.74%	0.48%
1400	0.65%	0.26%	0.57%	1.10%
1500	0.63%	0.25%	-0.74%	1.09%
1600	0.78%	0.25%	-0.51%	1.09%

Wavelength / nm	NPL_{2003} DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)	PTB DoE to the CCPR KCRV	Uncertainty associated with DoE (*k*=1)
1700	0.84%	0.29%	-0.58%	1.09%
1800	1.00%	0.44%	-0.02%	1.10%
1900	0.77%	0.63%	0.70%	1.15%
2000	0.81%	0.73%	-0.64%	1.13%
2100	0.72%	0.79%	-0.56%	1.34%
2200	0.57%	0.89%	-1.50%	1.32%
2300	1.01%	1.17%	-1.04%	1.33%
2400	1.56%	1.48%	-0.13%	1.32%
2500	1.65%	1.83%	-0.09%	1.38%

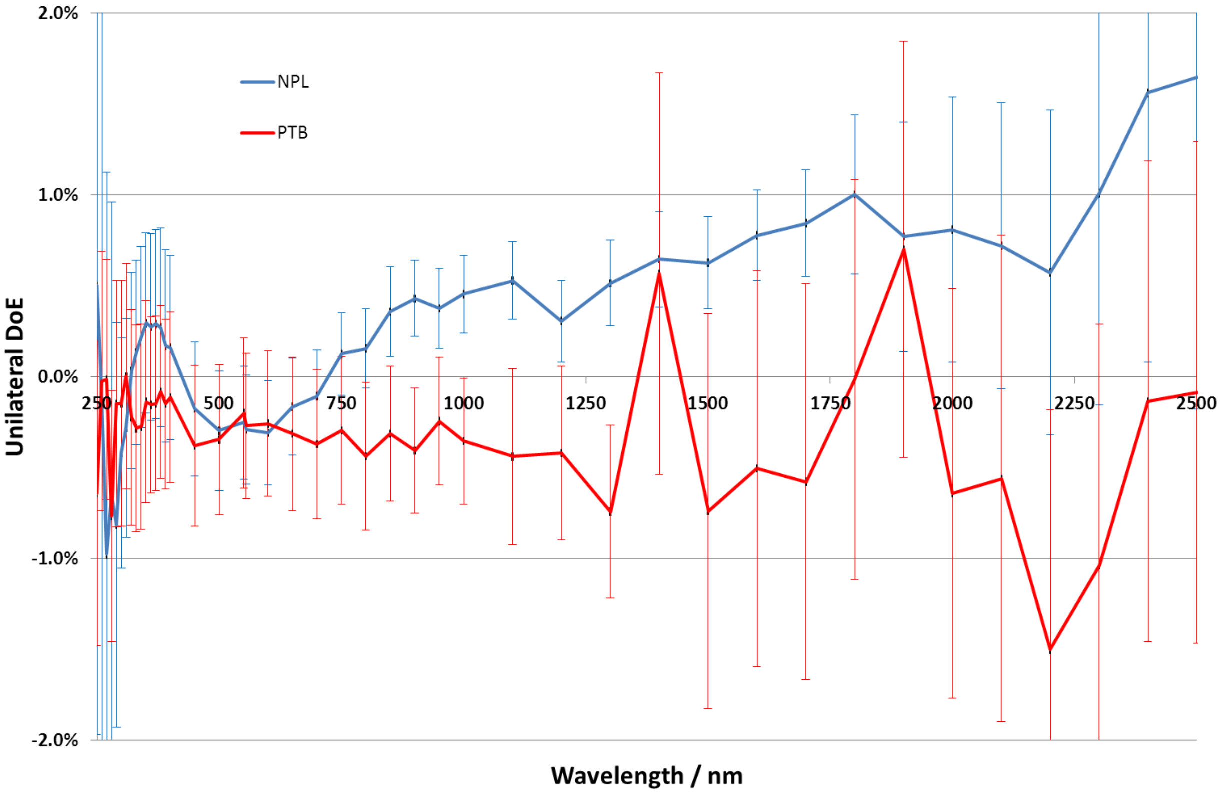

Figure 54. Unilateral DoE to CCPR KCRV and associated uncertainties (*k*=1) for NPL (2003 scale) and PTB, as given in report of CCPR K1.a Key Comparison.