

A CCPR international comparison of spectral radiance measurements in the air-ultraviolet

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Abstract. An international comparison of the spectral radiance scales of the National Physical Laboratory (NPL), the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB) was carried out in 1993 and 1994, under the auspices of the Comité Consultatif de Photométrie et Radiométrie (CCPR) of the Comité International des Poids et Mesures (CIPM). The comparison covered the spectral range 200 nm to 350 nm. The transfer standards were deuterium discharge lamps, with examples of the lamps used at each of the participating laboratories included in the comparison to aid in the identification of systematic errors and to gather information on their relative performance. The scales of the laboratories agreed within the combined uncertainties. However, the combined uncertainties were high (an expanded uncertainty with a coverage factor of $k = 2$ of up to 8 %), and further work is required to reduce the uncertainties associated with the spectral radiance scales of each laboratory. Little difference was observed in the performance of the three different transfer standard sources used.

1. Introduction

The applications of spectroradiometric measurements in the air-ultraviolet are wide-ranging. Many applications, including the monitoring of terrestrial ultraviolet radiation levels and those involving international trade, require results that are accepted internationally. It is therefore important that the level of agreement between national scales is known, not least so that discrepancies can be reduced through further work.

The major industrial and environmental requirement for source measurement in the air-ultraviolet is for measurement of spectral irradiance, but in many cases this scale is derived from national spectral radiance scales. The CCPR Working Group on Air-Ultraviolet Spectral Radiometry therefore recommended that an international comparison of national spectral radiance scales should be undertaken [1]. The comparison included the NPL (UK), the NIST (USA) and the PTB (Germany). The results of the comparison have been presented to the CCPR [2] and are summarized here.

2. Arrangements for the comparison

The national scales were compared by measurement of the spectral radiance of a group of nine deuterium lamps. Deuterium lamps are used extensively to maintain scales of both spectral radiance and spectral irradiance in the ultraviolet, including those of national standards laboratories. The minimum wavelength range compared was 220 nm to 400 nm at 10 nm intervals with a bandwidth of 2 nm. However there is some line emission superimposed on the continuum output of deuterium lamps at wavelengths longer than 350 nm. As a consequence, measurement results are extremely sensitive to small differences in bandwidth and wavelength setting, making it difficult to carry out a direct comparison of national scales. For this reason, the results presented are restricted to the wavelength range 200 nm to 350 nm.

The area of the source selected for measurement was a central circular area of diameter 0.6 mm, measured with a radiation collection solid angle not exceeding 4.0×10^{-4} sr.

Each of the participating laboratories provided three examples of the deuterium lamp in use as a transfer standard at that laboratory. The NPL supplied three Cathodeon V04 lamps, the NIST three lamps manufactured by Hamamatsu, and the PTB three lamps manufactured by Heraeus. All lamps were nominally 30 W, operated with a discharge current of 300 mA and with a reduced voltage to the heater during operation to improve stability. The Cathodeon deuterium lamps

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were aligned using the lamp front window, whereas the Hamamatsu and Heraeus lamps were aligned using an alignment jig inserted into the lamp mount in front of the lamp and then removed before measurement.

The comparison was carried out in the round-robin style, the order of measurement being NPL-NIST-PTB-NPL. The initial measurements at the NPL were made in May 1993 and the final measurements at the NPL in July 1994.

3. Basis of national spectral radiance scale and measurement procedure for each laboratory

3.1 The NPL

The NPL scale of spectral radiance was realized by comparison with two primary standards.

The relative spectral power scale over the wavelength range 200 nm to 350 nm was realized by comparison of a group of 30 W deuterium lamps with the electron synchrotron at Daresbury in the UK [3]. Four working standard lamps of the same type, calibrated by reference to the group measured at Daresbury, were used in the calibration of the comparison lamps.

The absolute spectral radiance scale over the wavelength range 340 nm to 400 nm was realized by comparison of gas-filled tungsten strip lamps with a primary standard black-body source operated at a calibrated temperature. The lamps used – type 25/G, developed at the NPL and manufactured by Polaron Special Lamps (formerly General Electric Company (UK)) – had a 1.6 mm wide tungsten strip. Three working standard lamps of this type were used in the calibration of the comparison lamps.

The full calibration of each comparison lamp consisted of the measurement of relative spectral radiance over the wavelength range 200 nm to 400 nm against the deuterium and tungsten lamp working standards, followed by the measurement of absolute spectral radiance against the tungsten lamp working standards with the monochromator set at 350 nm.

The measurement system consisted of a double 1200 lines/mm grating monochromator manufactured by Hilger-Watts, linked to a 9635QB photomultiplier with an S20 photocathode. The monochromator wavelength scale and bandpass were calibrated by reference to two emission lines from a low-pressure mercury penray source at 253.65 nm and 334.15 nm. The instrumental bandwidth (full width at half maximum) was approximately 2 nm. A solar blocking filter (Schott type UG5) was used in the optical path when comparing deuterium and tungsten sources in order to reduce the effect of stray light from the visible portion of the spectrum.

The input optical arrangement consisted of a spherical mirror used to form a 1:1 image of the emitting area of the lamp on to a high-precision pinhole

aperture of diameter 0.6 mm. The deuterium lamps were centred on to the pinhole aperture by adjusting for maximum signal at 350 nm, and the tungsten lamps were positioned visually using a pointer enclosed within the lamp envelope. A mask was positioned over the mirror to reduce the collection angle to approximately 1.7×10^{-4} sr. All radiation passing through the pinhole aperture was imaged into the monochromator using a second spherical mirror.

3.2 The NIST

The NIST scale of spectral radiance was realized by a traceable calibration chain to a gold-point black body, the temperature of which was determined using the NIST High Accuracy Cryogenic Radiometer [4] and Planck's radiation law.

A gold-point black body was used to determine the radiance temperature of a high-stability vacuum lamp, the radiance temperature of which was approximately 1337 K. This lamp was, in turn, used to determine the radiance temperature of another high-stability vacuum lamp operating at a higher radiance temperature of approximately 1528 K. This lamp was used to determine the radiance temperature of a variable-temperature black body, the radiance temperature of which could be set over the range 900 K to 2700 K. The estimated emissivity of the 2 mm aperture in the black body was 0.999. The variable-temperature black body was used to calibrate a set of working standard 30 W deuterium lamps for spectral radiance over the wavelength range 220 nm to 400 nm. The spectral radiance of the comparison lamps was determined by reference to the set of working standard deuterium lamps.

All measurements were performed using the NIST Facility for Automated Spectroradiometric Calibrations (FASCAL) spectroradiometer [5]. The NIST-designed spectroradiometer used the monochromator from a CARY 14 spectrophotometer. The monochromator was a prism/grating double monochromator. The measured bandwidth of the monochromator was 1.8 nm at 250 nm and 2.6 nm at 330 nm. The detector used to measure the optical power from the monochromator was a cooled (-15°C) S-20 photomultiplier tube (EMI 9659QB) with a quartz window. The current from the photomultiplier tube was measured using a dc current amplifier and a high-accuracy digital multimeter.

The circular entrance aperture of the monochromator was 0.6 mm in diameter and the solid angle of the entrance optics was 4×10^{-4} sr. The comparison lamps were aligned to the aperture by maximizing the signal at 400 nm.

3.3 The PTB

The PTB scale of spectral radiance used in the comparison was based on the calculable synchrotron radiation of the electron storage ring BESSY.

An electron storage ring is a primary standard [6] of spectral radiant flux and of spectral irradiance, and so additional geometric quantities were measured in order to calculate the spectral radiance. The calculable spectral radiant flux of the electron storage ring was used to calibrate the measurement equipment (described below) which was, in turn, used to determine the spectral radiance of the comparison lamps.

The measurement system [7] consisted of an ultrahigh-vacuum 1 m McPherson-type monochromator with a 15° deviation between the incoming and diffracted beams. A 600 lines/mm grating was used with a linear dispersion of 1.667 nm/mm. The detector was a photomultiplier tube with a fused-silica window and a bialkali photocathode (EMI type 9635QB). Measurements in the spectral region 200 nm to 360 nm were made with bandwidths of 1.6 nm and 3.2 nm; no significant variation in the spectral radiance results were observed. Measurements in the spectral region 360 nm to 400 nm were made with a bandwidth of 0.4 nm and the results corrected to a nominal bandwidth of 2.0 nm using a mathematical smoothing procedure. The stray light of the system was checked prior to measurement using a series of cut-on and cut-off filters. Filters in front of the entrance slit were used to suppress the second-order diffraction contribution above 320 nm.

The comparison lamps were measured for a central circular area of 0.6 mm diameter, aligned by setting the peak signal from the lamp at 220 nm. The acceptance solid angle was 1.70×10^{-5} sr.

4. Results

Figure 1 presents the difference between the measurement results obtained at the NPL in July 1994 and May

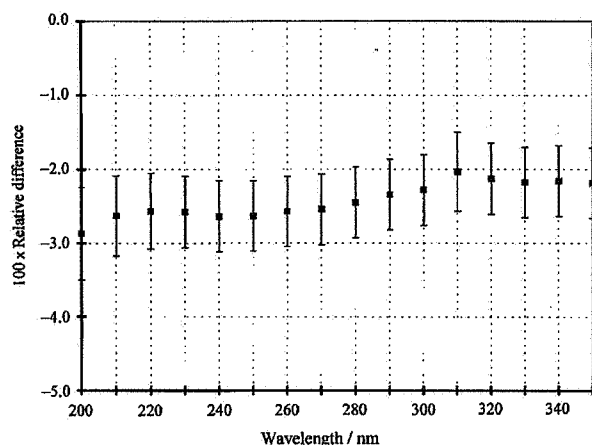


Figure 1. Relative difference between spectral radiance measurements made at the NPL in July 1994 (post circulation of lamps) and those made at the NPL in May 1993 (pre circulation of lamps). The error bars indicate the calculated standard deviation of the mean for all nine transfer standard lamps.

1993. The error bars show the standard deviation of the mean of the nine lamps.

These results show that the stability of the set of nine lamps was no better than 2 % over the period of the comparison, due to a combination of the reproducibility and ageing of the deuterium lamps. There was a great deal of variability in stability from lamp to lamp, and so the results of the spectral radiance measurements made at each of the other participating laboratories, $L_{\lambda, \text{laboratory}}$, were referred to the average of the measurements made at the NPL, $L_{\lambda, \text{NPL average}}$, using (1) below:

Relative difference =

$$(L_{\lambda, \text{laboratory}} - L_{\lambda, \text{NPL average}}) / L_{\lambda, \text{NPL average}} \quad (1)$$

Figure 2 gives a summary of the results. The graph shows the difference between laboratories, based on the average difference for all nine deuterium lamps included in the comparison, together with the limits of the combined uncertainty. The uncertainties associated with the measurements carried out at each laboratory are given in Table 1. These were added arithmetically to give the combined uncertainties of the comparison, also included in the table. All uncertainties are expanded with a coverage factor of $k = 2$, providing a confidence level of approximately 95 % (2σ). The error bars show the calculated standard deviation of the mean of the nine deuterium lamps, included to illustrate the spread in results.

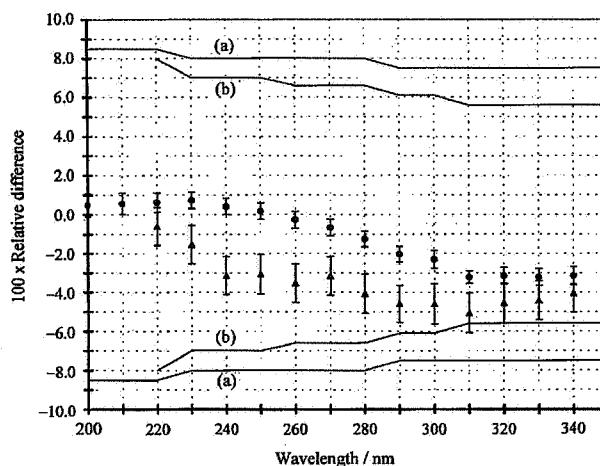


Figure 2. Relative difference between spectral radiance measurements made at the NIST and the PTB and the average of the measurements made at the NPL. The error bars indicate the calculated standard deviation of the mean for all nine transfer standard lamps. (a) PTB-NPL combined uncertainty (2σ); (b) NIST-NPL combined uncertainty (2σ); ● relative difference between PTB and average NPL result; ▲ relative difference between NIST and average NPL result.

Table 1. Expanded uncertainties ($k = 2$) of individual measurements and of comparison results.

Wavelength /nm	100 \times Rel. exp. uncertainty			100 \times Combined rel. exp. uncertainty	
	NPL	NIST	PTB	NIST-NPL	PTB-NPL
200	4.5	—	4.0	—	8.5
210	4.5	—	4.0	—	8.5
220	4.5	3.5	4.0	8.0	8.5
230	4.0	3.0	4.0	7.0	8.0
240	4.0	3.0	4.0	7.0	8.0
250	4.0	3.0	4.0	7.0	8.0
260	4.0	2.6	4.0	6.6	8.0
270	4.0	2.6	4.0	6.6	8.0
280	4.0	2.6	4.0	6.6	8.0
290	3.5	2.6	4.0	6.1	7.5
300	3.5	2.6	4.0	6.1	7.5
310	3.5	2.1	4.0	5.6	7.5
320	3.5	2.1	4.0	5.6	7.5
330	3.5	2.1	4.0	5.6	7.5
340	3.5	2.1	4.0	5.6	7.5
350	3.5	2.1	4.0	5.6	7.5

5. Conclusions

Referring to Figure 2, the measurements agree within the uncertainty of the comparison. However, the uncertainty was rather high, which may be masking real differences between the spectral radiance scales of the participating laboratories. This high uncertainty is mainly due to a combination of

- the difficulties associated with transferring the primary scale, which can often be calculated with a much lower uncertainty, to transfer standards such as deuterium lamps;
- the performance of the transfer standard deuterium lamps themselves. The absolute stability of the lamps during the comparison (shown in Figure 1) was poor, especially considering that the maximum burn time for any one lamp was 33 h. In addition, the error bars given in Figures 1 and 2 show that there was a large spread in the results for individual lamps, and that the main component of this spread was absolute rather than spectral. This concurs with previous experience with deuterium lamps, which indicated that the lamps are effective at maintaining a scale of relative spectral power, but can show large differences in absolute output from ignition to ignition.

It is therefore concluded that further work is necessary to

- reduce the uncertainties associated with the transfer of the primary scale to transfer standard sources, through improved techniques and equipment and a better understanding of the sources of error associated with the transfer;
- develop better transfer standard sources for this spectral region. This could be achieved through the use of deuterium lamps to maintain a scale of relative spectral power combined with a more stable source to provide an absolute level, by detector stabilization of the transfer standard source, by the introduction of completely different sources, or by a combination of all three methods.

Overall, the three types of deuterium lamp showed broadly similar performance, and it was not possible to identify a preferred transfer standard from this group.

Note. Certain commercial equipment, instruments or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by any of the organizations party to this paper, nor does it imply that the equipment, instruments or materials identified are necessarily the best available for the purpose.

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Received on 17 May 1999 and in revised form on 26 August 1999.