Publication II

Y. J. Liu, G. Xu, M. Ojanen, and E. Ikonen. 2009. Spectral irradiance comparison using a multi-wavelength filter radiometer. Metrologia, volume 46, number 4, pages S181-S185.

http://www.iop.org/journals/met
http://stacks.iop.org/met/46/S181

IOP Publishing Metrologia

Metrologia **46** (2009) S181–S185 doi:10.1088/0026-1394/46/4/S09

Spectral irradiance comparison using a multi-wavelength filter radiometer

Y J Liu[1,4], **G Xu**[1], **M Ojanen**[2] **and E Ikonen**[2,3]

[1] National Metrology Centre, Agency for Science and Technology Research (A*STAR), Singapore
[2] Metrology Research Institute, Helsinki University of Technology (TKK), Finland
[3] Centre for Metrology and Accreditation (MIKES), Finland

E-mail: liu_yuanjie@nmc.a-star.edu.sg

Received 15 October 2008, in final form 2 January 2009
Published 2 June 2009

Abstract

An automatic multi-wavelength filter radiometer (MWFR) was developed at the National Metrology Centre (NMC) of Singapore to realize the spectral irradiance scale in the wavelength range from 250 nm to 1600 nm. The UV–VIS range (250 nm to 900 nm) is covered by a silicon trap detector with 17 filters, while the near IR range (900 nm to 1600 nm) is covered by an InGaAs photodiode with 7 filters. A complete run of measurements at all 24 wavelength points takes only 12 min. The spectral irradiance scales of NMC and MIKES/TKK (Finland) in the spectral range from 280 nm to 900 nm were compared successfully using this instrument. Measurement results of three standard lamps calculated using MIKES/TKK's algorithm showed excellent repeatability and very good agreement with their assigned values. It is concluded that, compared with the conventional monochromator based spectroradiometers, a properly designed MWFR with sufficient spectral coverage is a good alternative instrument for spectral irradiance comparison owing to its faster speed and better short-term reproducibility.

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

1. Introduction

Spectral irradiance scales at national metrology institutes (NMIs) are normally realized using a high temperature blackbody together with a few filter radiometers measuring the temperature of the blackbody [1–3]. The benefit of this type of realization is that the blackbody, once its temperature is determined, provides theoretically known continuous spectral irradiance values in the wavelength range covered. However, this approach requires substantial resources.

The excellent performance of silicon trap-detector based filter radiometers leads to the true detector-based realization of the spectral irradiance scale at several NMIs [4, 5]. This method measures the spectral irradiance generated by a tungsten halogen lamp directly using a large number of filter radiometers operating at different wavelengths. As the results are calculated based on the spectral responsivity of the radiometer, the spectral transmittance of the filters and the aperture area without using a blackbody, the method greatly simplifies the realization process of a spectral irradiance scale. In the actual measurement process, however, to replace one filter radiometer by another is rather inconvenient and time consuming. It can be a problem if many filter radiometers are used.

This paper first describes an automatic multi-wavelength filter radiometer (MWFR) designed for an independent realization of the spectral irradiance scale at the NMC. Results of a bilateral comparison on spectral irradiance scales between NMC and MIKES/TKK carried out using this new instrument are reported next. The results presented in this paper cover only the wavelength range from 280 nm to 900 nm, which is currently the range of the MIKES/TKK spectral irradiance scale.

2. The multi-wavelength filter radiometer

The structure of the MWFR and the measurement set-up are shown in figure 1.

All the key optical components are housed in a light-tight container with the temperature controlled at 28 °C ± 0.1 °C. A precision aperture with a nominal diameter of 4 mm is

---

[4] Author to whom any correspondence should be addressed.

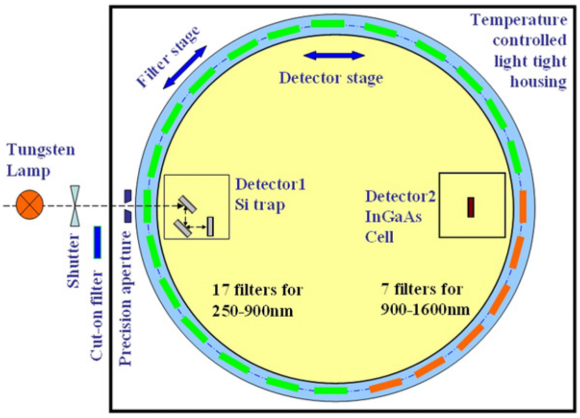

Figure 1. The MWFR.

Table 1. Filter–detector combinations at each wavelength.

Filter nominal wavelength/nm	Detector used
254, 260, 280, 300, 310, 330, 340, 360, 380, 400, 450, 500, 550, 600, 650, 700, 800	Si trap
900, 1050	Si trap and InGaAs
1100, 1200, 1300, 1550, 1600	InGaAs

mounted on the input port. The detectors (an Si trap and an InGaAs photodiode) and 24 interference filters (from Melles Griot) with a nominal bandpass of 10 nm full width at half maximum (FWHM) are mounted on two motorized rotating stages separately to allow different filter–detector combinations. Mechanically any of these combinations is possible for measurement. The actual filter–detector arrangement for the measurement range of 250 nm to 1600 nm is shown in table 1. In the range 900 nm to 1050 nm both detectors can be used so that counter checking of various effects due to alignment, beam geometry, stray light, inter-reflection, etc can be carried out.

As shown in figure 1, the reference plane of the lamp to be measured is positioned 500 mm away from the aperture. A shutter in the optical path is used to measure the 'dark' signal to correct for background and scattered radiation and cut-on filters are used to make a correction for out-of-band leaks.

The optical components of the multi-filter spectroradiometer are calibrated separately. The opening area of the precision aperture is calibrated by KRISS (Korea) using Gaussian beam superposition and optical edge detection methods. The spectral responsivity of the two detectors and the spectral transmittance of the 24 interference filters are all calibrated against NMC's reference standards at 28 °C, the working temperature of the MWFR.

3. Measurement principle

When the *k*th filter is used in the measurement, we have

$$i_k = A \int E(\lambda) R(\lambda) \tau_k(\lambda)\, \mathrm{d}\lambda, \qquad (1)$$

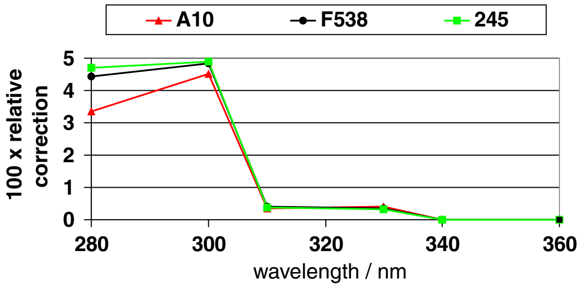

Figure 2. Corrections for out-of-band leaks of the interference filters (100 × relative correction).

where i_k is the photocurrent produced by the photodetector in response to the direct radiation from the lamp through the pass band of the *k*th filter, A is the opening area of the aperture, λ is the radiation wavelength in air, $E(\lambda)$ is the spectral irradiance produced by the lamp on the plane of the aperture, $R(\lambda)$ is the spectral responsivity of the detector and $\tau_k(\lambda)$ is the spectral transmittance of the *k*th filter.

Three corrections are made to obtain the correct i_k value. The first is the 'dark' signal, which is the measured photocurrent when the shutter between the lamp and the MWFR is closed. This signal is due to the actual dark current of the detector, together with that caused by the scattered light from the lamp and other light sources such as the computer screen.

The second is the correction for out-of-band leaks. The spectral transmittances of all the interference filters are measured within the responsive range of the detectors to be used with them (250 nm to 1200 nm for the silicon detector and 800 nm to 1700 nm for the InGaAs detector). No out-of-band transmittance more than 10^{-3} of the peak transmittance of any filter was observed. For filters used at shorter wavelengths, leaks of this order of magnitude can still be significant because the spectral irradiance of tungsten lamps at the shorter wavelengths is much lower than at the longer wavelengths. Cut-on filters are used to make the correction for out-of-band leaks in the same way as they are used for stray light correction for a monochromator-based spectroradiometer [6].

Two cut-on filters with nominal wavelengths of 335 nm and 395 nm are used for the wavelength range of 280 nm to 900 nm. The former is used to assess the out-of-band leaks for interference filters of 280 nm and 300 nm whereas the latter is used for interference filters of 310 nm and 330 nm. No correction is made for other interference filters. The amount of correction required for the measured photocurrent with the *k*th filter is

$$i_{\mathrm{correction},k} = i_{\mathrm{leak},k} / \tau_{\text{cut-on}}, \qquad (2)$$

where $i_{\mathrm{leak},k}$ is the measured photocurrent when both the cut-on filter and the *k*th filter are in the optical path and $\tau_{\text{cut-on}}$ is the averaged spectral transmittance of the cut-on filter in its pass band. Figure 2 shows the relative correction for the out-of-band leaks for three tungsten halogen lamps measured in the spectral range from 280 nm to 900 nm. More details of these lamps are given in section 5.

The third correction necessary for equation (1) is the correction for inter-reflection effects between the interference filter and the detector. For this purpose the spectral

Table 2. Detailed measurement uncertainty budget of the MWFR.

Source of uncertainty	100× relative standard uncertainty													
Effective wavelength/nm	283	303	311	342	360	400	452	501	550	603	651	699	800	902
Detector responsivity	0.88	0.87	0.82	0.83	0.86	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.86
Filter transmittance	0.80	0.70	0.50	0.40	0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.40
Distance	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Lamp current	0.12	0.11	0.11	0.10	0.10	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04
Photocurrent	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Aperture area	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Inter-reflection	0.23	0.23	0.12	0.12	0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Out-of-band leaks	0.58	0.58	0.06	0.06	0.06	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Interpolation [4]	0.57	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Reproducibility	0.05	0.03	0.03	0.04	0.07	0.09	0.08	0.07	0.05	0.04	0.05	0.09	0.21	0.21
Combined standard uncertainty	**1.47**	**1.32**	**1.02**	**0.99**	**1.01**	**0.41**	**0.40**	**0.40**	**0.40**	**0.39**	**0.39**	**0.40**	**0.44**	**1.02**
Expanded uncertainty (k=2)	**2.9**	**2.6**	**2.0**	**2.0**	**2.0**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**	**2.0**

reflectance of each interference filter facing the detector is measured within the responsive range of the detectors. The spectral reflectance data of the trap detector are provided by MIKES/TKK as detailed in [7]. This correction is applied to the spectral transmittance of each interference filter at each wavelength:

$$\tau_k(\lambda) = \tau'_k(\lambda)/(1 - \rho_k(\lambda)\rho_{\mathrm{d}}(\lambda)), \tag{3}$$

where $\tau_k(\lambda)$ is the corrected spectral transmittance of the kth interference filter used in equation (1), $\tau'_k(\lambda)$ is the measured spectral transmittance, $\rho_k(\lambda)$ is the spectral reflectance of the kth interference filter at the side facing the detector and $\rho_{\mathrm{d}}(\lambda)$ is the spectral reflectance of the detector.

A lamp is measured four times in a complete cycle: first with the shutter closed, then with the shutter opened and finally two measurements with the two cut-on filters. The measurements with cut-on filters need to be done only once for each lamp. Therefore, only the shutter open/closed data are needed for each lamp on the repeat measurement runs. The time for one measurement run is about 6 min for all the interference filters working with the trap detector.

The spectral power distribution of a tungsten lamp can be presented as a modified Planck's radiator at temperature T [4]:

$$E(\lambda) = \frac{Bc_1\varepsilon'(\lambda)}{\lambda^5[\exp(c_2/\lambda T) - 1]}, \tag{4}$$

where B is an auxiliary factor, $\varepsilon'(\lambda)$ is the effective emissivity of the lamp and c_1 and c_2 are the first and second radiation constants defined by the CIE.

For N as the number of filters, a difference function can be calculated:

$$\Delta = \sum_{k=1}^{N}[(i_{\mathrm{m},k}/i_{\mathrm{c},k}) - 1]^2, \tag{5}$$

where $i_{\mathrm{m},k}$ is the measured photocurrent at the kth filter and $i_{\mathrm{c},k}$ is the expected photocurrent calculated using equations (1) and (4). The difference function is minimized by optimizing the parameters in equation (4). The optimization algorithm is developed by MIKES/TKK and is detailed in [4]. Once the parameters are optimized, equation (4) can be used to obtain the continuous spectral irradiance of the lamp.

4. Uncertainty budget

The uncertainty budget for the measurement of the spectral irradiance of a tungsten lamp at various wavelengths using the MWFR is presented in table 2.

The calibration uncertainty for the detector responsivity increases drastically outside the visible wavelength range. This is because the transfer of the absolute responsivity scale from the visible to the UV and IR ranges relies on a pyroelectric detector, working in the ac mode, which introduces a large uncertainty. The uncertainty associated with the filter transmittance measurement includes the wavelength uncertainty of the spectrophotometer used. The distance uncertainty is estimated to be 1 mm over the required distance of 500 mm. The uncertainty caused by the lamp current setting is estimated based on a 0.04% measurement uncertainty of the lamp current. The calibration uncertainty of the digital voltmeter used for the photocurrent measurement is taken directly as its measurement uncertainty.

As discussed in the previous section, the inter-reflection between the filter and the detector is corrected for the shorter wavelength points. About 40% of the correction amount is taken as the residual uncertainty for this component. Similarly 40% of the correction for out-of-band leaks is taken as their uncertainty component. The standard uncertainty values shown in table 2 for the distance, lamp current, inter-reflection and out-of-band leaks are obtained by assuming rectangular probability distributions with numerical full width values given above. The reproducibility is taken as the average of the relative experimental standard deviations of the mean values of the three tungsten halogen lamps in two runs as shown in figure 3.

5. A bilateral comparison and results

To verify the performance of the new instrument, a bilateral comparison on the spectral irradiance between NMC and MIKES/TKK was carried out at the NMC using the MWFR on three tungsten halogen lamps, one from MIKES/TKK (1 kW, FEL, lamp ID: 245) and two from the NMC (one 1 kW FEL, lamp ID: F538 and one 400 W, Osram HLX64665,

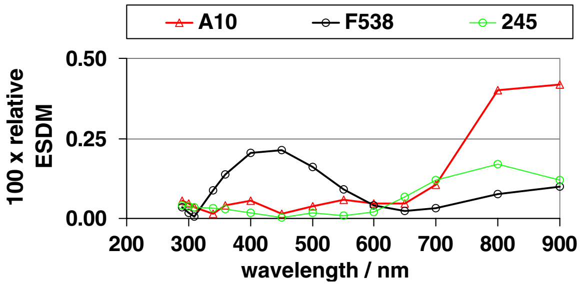

Figure 3. 100 × relative experimental standard deviation of the mean (ESDM) values of the measured spectral irradiance of each lamp in two independent runs.

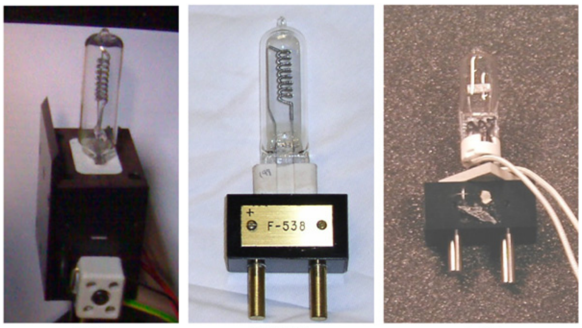
245 F538 A10

Figure 4. Photos of the three lamps used in the comparison.

lamp ID: A10). Figure 4 shows the images of these lamps.

The spectral irradiance of the MIKES/TKK lamp was first measured at MIKES/TKK before being hand-carried to NMC and then remeasured after it was back at MIKES/TKK, in the wavelength range of 280 nm to 900 nm, which is the range of the MIKES/TKK spectral irradiance scale. The measurement of the three lamps at NMC using an MWFR was jointly conducted by the MIKES/TKK and NMC staff.

In the bilateral comparison, each lamp was measured in two runs with re-alignment and power-up. The relative experimental standard deviation of the mean of each lamp in the two runs is shown in figure 3. It can be seen that the deviations are less than 0.25% in the UV and visible regions and less than 0.5% in the IR region. This result indicates good measurement reproducibility using the MWFR.

Figure 5 shows the relative deviation of the standard values from the measured spectral irradiance values obtained using the MWFR. The standard values are assigned to the lamps by MIKES/TKK (for lamp 245) and the NMC (for lamps F538 and A10) based on their national scales. The result for the NMC shown in figure 5 is the average of the two NMC lamps. The red (thicker) boundaries shown are expanded uncertainties ($k = 2$) for the difference between the MIKES/TKK results and the MWFR results. The black (thinner) boundaries are expanded uncertainties ($k = 2$) for the difference between the NMC existing scale and the MWFR. The agreements of the standard values assigned to the lamps by both NMIs with the measured values using the MWFR are well within their expanded measurement uncertainties.

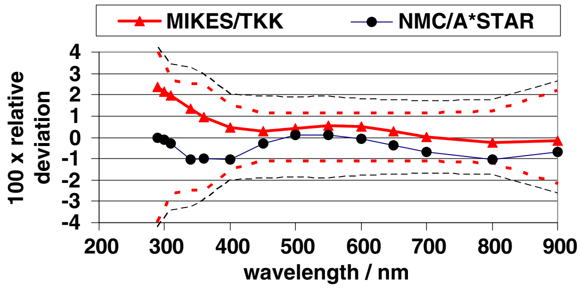

Figure 5. 100 × relative deviation of the lamps' assigned values from the corresponding measurement results using an MWFR. The boundaries shown are expanded uncertainties ($k = 2$) for the two measurements taking into account contributions of the MWFR and the uncertainties of the assigned values of the lamps.

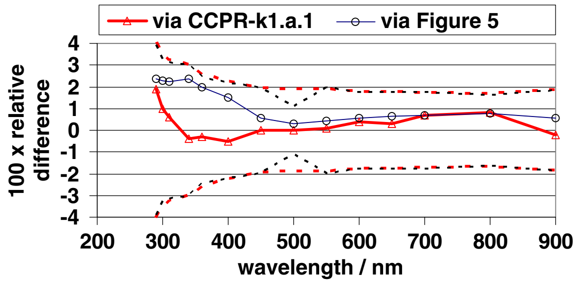

Figure 6. 100 × relative difference of the national spectral irradiance scales (MIKES/TKK versus NMC) obtained by CCPR-K1.a.1 and MWFR. The boundaries shown are expanded uncertainties ($k = 2$) of the bilateral comparisons.

Figure 6 shows the differences (degrees of equivalence) between the national scales of the two NMIs obtained via figure 5 and via CCPR-K1.a [8] and CCPR-K1.a.1 [9] as listed in the BIPM KCDB (MIKES/TKK and NMC/A*STAR are referred to as HUT and SPRING, respectively, in the KCDB). The boundaries shown indicate the expanded uncertainty taking into account contributions of the two NMIs ($k = 2$). The transfer uncertainty of the MWFR has not been included because it is negligible compared with the combined uncertainty.

The degrees of equivalence of the two NMIs obtained from these two comparison routes are very close except for the wavelength region below 400 nm where the relative difference is about 2%. A larger difference in this region is expected as the uncertainty in the UV range is generally larger.

6. Discussions and conclusions

An automatic, MWFR for 24 interference filters is constructed and characterized at the NMC for the direct measurement of the spectral irradiance of tungsten lamps in the wavelength range of 250 nm to 1600 nm. The MWFR is used to measure the spectral irradiance of three standard lamps in the wavelength range of 280 nm to 900 nm. The measurement results are compared with the specified irradiance values of these standard lamps which are traceable to the existing national scales held at the NMC and MIKES/TKK, respectively. This exercise not only verifies the performance of the MWFR but also compares, at the same time, the two national scales held at the two NMIs.

The good agreement between the measured values and the standard values indicates that the MWFR is capable of realizing the spectral irradiance scale in the tested wavelength range. The excellent short-term reproducibility and fast measurement speed suggest that this kind of radiometer is a good alternative for spectral irradiance comparisons as compared with conventional monochromator-based spectroradiometers. The effect of long term stability of the interference filters used on the performance of the MWFR is yet to be studied.

References

[1] White M *et al* 1995/96 The characterization of a high-temperature black body as the basis for the NPL spectral-irradiance scale *Metrologia* **32** 431–4

[2] Sperfeld P *et al* 1995/96 Spectral-irradiance scale based on radiometric black-body temperature measurement *Metrologia* **32** 435–9

[3] Yoon H *et al* 2003 The realization of the NIST spectral irradiance scale *Metrologia* **40** S172–6

[4] Kubarsepp T *et al* 2000 Spectral irradiance measurement of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm *Metrologia* **37** 305–12

[5] Durak M *et al* 2004 Realization of a filter radiometer-based irradiance scale with high accuracy in the region from 286 nm to 901 nm *Metrologia* **41** 401–6

[6] ASTM E387-84 1995 Standard test method for estimating stray radiant power ratio of spectrophotometers by opaque filter method *ASTM Standards* pp 755–64

[7] Haapalinna A *et al* 1998 Spectral reflectance of silicon photodiodes *Appl. Opt.* **37** 729–32

[8] Woolliams E R *et al* 2006 Final report on CCPR K1-a: spectral irradiance from 250 nm to 2500 nm *Metrologia* **43** (Tech. Suppl.) 02003

[9] Wilkinson F *et al* 2006 Final report on CCPR-K1.a.1: bilateral comparison of spectral irradiance between NMIA (Australia) and SPRING (Singapore) *Metrologia* **43** (Tech. Suppl.) 02002