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Approximation function of spectral irradiance of standard lamps

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Abstract. Band filter radiometry has recently become popular. Its application for detector-based spectral-irradiance measurements requires improved characterization of standard lamps. This paper presents an approximation function for the spectral irradiance of NPL/GEC and FEL lamp data, reported in the 1990 international comparison measurements of the Consultative Committee for Photometry and Radiometry (CCPR). Characterization with a minimum number of parameters, applicable within the visible spectral range, is attempted. Since the spectral emissivity of tungsten is nearly linear in the spectral range from 400 nm to 900 nm, the irradiance of the standard lamps was approximated with three parameters, representing a linear polynomial multiplied by the Planck function. The same linear polynomial was used for each lamp of the same type, and was fitted only for temperature and intensity. The average difference between the measured and the approximated data was found to be less than 0.085 % for the NPL/GEC lamps and less than 0.095 % for the FEL lamps. This means that the relative spectral emissivity of each lamp of the same type is practically the same. The temperature fitting was characterized by the average difference between the measured and approximated data in the ultraviolet and infrared spectral ranges.

1. Introduction

The application of filter radiometers makes it possible to realize a detector-based absolute spectral irradiance scale [1]. This has been demonstrated by measurements using a high-temperature variable black body (HTVBB) as a standard irradiance source [2]. Since the HTVBB has an emissivity close to unity, the spectral irradiance is almost Planckian. However, it is common practice to use FEL lamps as standards. The spectral irradiance of these lamps departs from the ideal Planckian distribution, and is generally approximated by multiplying the Planck function by a fifth-order polynomial [3]. The application of this approximation to the filter-radiometer-based spectral-irradiance measurements requires the determination of six constants. The goal of this paper is to present a simpler approximation, requiring only two or three constants, applicable in the visible spectral range from 400 nm to 800 nm. This is feasible because the emissivity of tungsten is nearly linear over the visible spectral range. The present calculation method uses the published data of the 1990 CCPR international comparision of spectral irradiance [4].

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2. CCPR comparison data

Twelve national metrology institutes participated in the 1990 star-type international comparison of spectral irradiance. The measurements were made on twenty-six NPL/GEC lamps and eight FEL lamps in the general range from 250 nm to 2400 nm, at eleven ultraviolet (UV), eight visible (VIS) and twelve infrared (IR) wavelengths. The NPL/GEC lamps are single coil, and the FEL lamps double-coil, tungsten-halogen standard lamps. The measurements of some institutes covered less than the full spectral range, so the available data in the spectral ranges from 250 nm to 300 nm and 1600 nm to 2400 nm are sparse. The approximation function presented here uses the data from the pilot laboratory, the US National Institute of Standards and Technology (NIST), because its data for all lamps were recorded with the same reference instrumentation. According to the NIST irradiance measurement procedure [3], this data base results from fitting the measurement data calculated for each lamp.

3. Calculation method

The measured spectral irradiance $E(\lambda)$ was approximated by the $F(\lambda)$ function:

$$F(\lambda) = (1 + A_1 \lambda) \cdot \exp(A_0 + B/\lambda) \cdot \lambda^{-5}, \qquad (1)$$

where λ is the wavelength and A_0, A_1, and B are the fitting parameters. In (1) the expression

$\exp\,(A_0 + B/\lambda)\cdot\lambda^{-5}$ is an approximation to the Planck function. The parameters were determined for each lamp with a three-step iteration:

First, a best fit for the parameters was found by minimizing the average relative differences $[D\,(A_0;\,A_1;\,B)]$ between the measured $E\,(\lambda_i)$ and the calculated $F\,(\lambda_i)$ values. This was carried out by the least-squares method in the spectral range from 400 nm to 800 nm. The average relative difference is given as

$$D\,(A_0;\,A_1;\,B) = \sum_i [(F\,(\lambda_i) - E\,(\lambda_i))/E\,(\lambda_i)]^2. \tag{2}$$

Based on the results of the least-squares fitting for each lamp, a correction factor $C_j\,(\lambda_i)$ was calculated in the spectral range over which the lamp had measured data. This correction factor is

$$C_j\,(\lambda_i) = E_j\,(\lambda_i)/F_j\,(\lambda_i), \tag{3}$$

where j identifies the lamp number. These $C_j\,(\lambda_i)$ correction factors for both lamp types were averaged, and average correction factors $C_{\mathrm{FEL}}\,(\lambda_i)$ and $C_{\mathrm{GEC}}\,(\lambda_i)$ were defined for the two types of lamp in the wavelength range from 250 nm to 2400 nm.

Next, the least-squares fitting was repeated for each lamp by minimizing the average relative difference between the measured and calculated values in the spectral range from 250 nm to 800 nm UV-VIS. The modified error function $DGC_j\,(A_0;\,A_1;\,B)$ is given by

$$DGC_j\,(A_0;\,A_1;\,B) = \sum_i G\,(\lambda_i)\,[(F_i\,(\lambda_i) - C\,(\lambda_i))/F\,(\lambda_i)]^2, \tag{4}$$

where $G\,(\lambda_i)$ is a weighting factor for the wavelength-dependent measurement accuracy, and $C\,(\lambda_i)$ refers to the type of lamp, either $C_{\mathrm{FEL}}\,(\lambda_i)$ or $C_{\mathrm{GEC}}\,(\lambda_i)$. With these revised values for the parameters, new correction factors $C_j\,(\lambda_i)$ were determined for each lamp, and were averaged as before. The fitted A_{1j} values were averaged for both lamp types as well, resulting in values for $A_{1\mathrm{FEL}}$ and $A_{1\mathrm{GEC}}$.

As the final step, the fitting was carried out according to (4), but A_1 was chosen to be either $A_{1\mathrm{FEL}}$ or $A_{1\mathrm{GEC}}$ (depending on the type of lamp) and was not a variable in the calculation. The parameters obtained for each lamp-type from this minimization were considered to be the final results.

4. Results

The quality of the approximation function was characterized for each lamp by the calculated $C_j\,(\lambda_i)$ correction factor of (3). At each wavelength these correction factors were averaged $[C_{\mathrm{FEL}}\,(\lambda_i)$ and $C_{\mathrm{GEC}}\,(\lambda_i)]$ and their standard uncertainty was calculated for both types of lamp $[s\,C_{\mathrm{FEL}}\,(\lambda_i)$ and $s\,C_{\mathrm{GEC}}\,(\lambda_i)]$. These results are shown in Table 1 and Figure 1. In the spectral range from 400 nm to 800 nm the average relative difference between the measured and calculated data was ± 0.085 % for the NPL/GEC lamps and ± 0.0895 % for the FEL lamps for a coverage factor of $k = 1$ [5]. The relative standard uncertainty of the correction factors over the entire UV range remains below 0.5 % for both types of lamps. This is achievable only if the effective emissivity is similar for all lamps of the same type, and if the temperature fitting of the lamps can be characterized with reasonable accuracy by a single temperature. However, in the spectral range above 1600 nm, the relative standard uncertainties for the NPL/GEC lamps are as high as 5 %. It may be possible to reduce the uncertainty by extending the parameter fitting into the IR range in the second step.

Table 1. Average C_{FEL} and C_{GEC} correction factors and their $s\,C_{\mathrm{FEL}}$ and $s\,C_{\mathrm{GEC}}$ standard uncertainties, calculated for eight FEL and twenty-six NPL/GEC lamps.

Wave-length/nm	C_{FEL} correction factor	$s\,C_{\mathrm{FEL}}$ uncertainty	C_{GEC} correction factor	$s\,C_{\mathrm{GEC}}$ uncertainty
250	0.886	0.003	0.900	0.005
260	0.922	0.002	0.923	0.004
270	0.950	0.002	0.941	0.003
280	0.966	0.001	0.953	0.004
290	0.976	0.000	0.964	0.003
300	0.983	0.001	0.971	0.003
310	0.987	0.001	0.980	0.001
320	0.992	0.001	0.987	0.001
330	0.993	0.001	0.988	0.002
340	0.995	0.001	0.992	0.002
350	0.997	0.001	0.995	0.002
400	1.000	0.000	1.000	0.001
450	0.999	0.001	1.000	0.001
500	1.000	0.001	1.001	0.001
555	1.001	0.001	1.000	0.001
600	1.000	0.001	1.000	0.001
654.6	1.000	0.001	1.000	0.001
700	0.999	0.001	1.000	0.001
800	1.000	0.001	1.000	0.002
900	1.009	0.004	1.006	0.004
1050	1.011	0.003	1.005	0.005
1150	1.018	0.005	1.014	0.004
1200	1.002	0.004	1.016	0.006
1300	1.030	0.004	1.026	0.007
1540	1.061	0.005	1.064	0.010
1600	1.080	0.006	1.087	0.011
1700	1.085	0.005	1.101	0.013
2000	1.146	0.008	1.195	0.020
2100	1.186	0.012	1.254	0.024
2300	1.220	0.015	1.326	0.030
2400	1.251	0.008	1.381	0.053

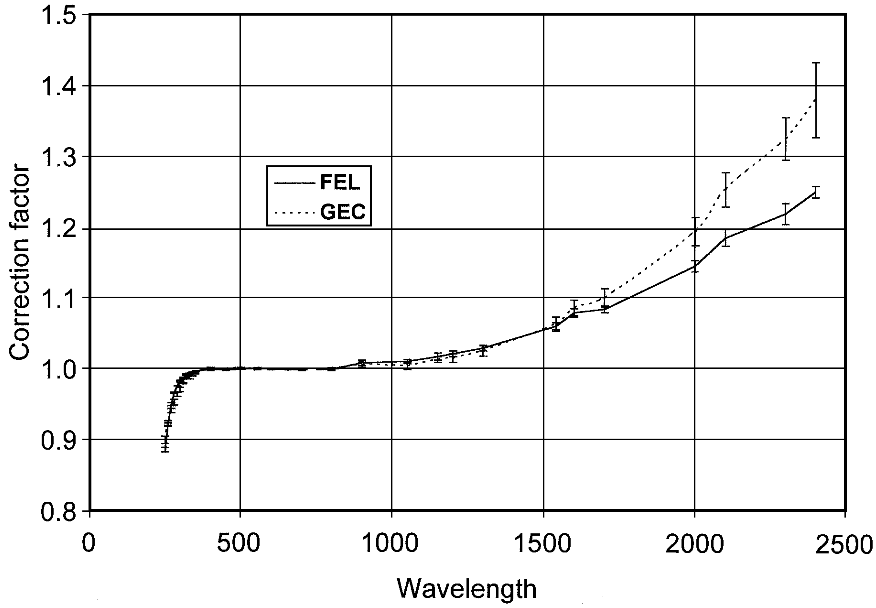

Figure 1. Average C_{FEL} and C_{GEC} correction factors indicated with their $s\,C_{\mathrm{FEL}}$ and $s\,C_{\mathrm{GEC}}$ standard uncertainties, calculated for eight FEL and twenty-six NPL/GEC lamps.

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