New data-reduction method in detector-based spectral-irradiance measurements

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Abstract. Detector-based bandfilter radiometry has recently become increasingly popular in the fields of absolute spectral-irradiance measurements, black-body temperature determination and comparison with source-based measurements. This paper introduces an advanced data-reduction method which handles all bandfilter measurements together. An analytical function approximation is used on Planckian radiation multiplied by a polynomial emissivity.

1. Introduction

Since the long-term stability of a silicon-photodiode trap detector [1] is better than that of spectral irradiance and luminous-intensity standard lamps, absolute spectral-irradiance measurements were developed based on a trap detector, bandfilters, and area and distance measurements, as described elsewhere [2-6]. The advantage of this method is its simplicity, allowing absolute scale realization for small countries. However, the applied data-reduction methods [2, 4, 6] give only one spectral irradiance value for each filter and its effective wavelength, and these assigned values or wavelengths may well be significantly in error. The aim of this paper is to present a new data-reduction method for irradiance based on an approximation in analytical form whose applicability has been proved [7].

The approximation also has a physical meaning: Planckian radiation multiplied by a polynomial emissivity.

2. Measurement

The purpose is to determine the spectral irradiance $E(\lambda)$ of a standard lamp at a distance d as a function of wavelength. The measurement arrangement has been described [4, 6]. The irradiance of the lamp is measured with a detector unit consisting of an entrance aperture with area A, a filter wheel with seven band filters used consecutively, and a trap detector. The output signals are the seven measured photocurrents $I_{\mathrm{m},\,i}$ of the trap detector.

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3. Calculation

The spectral irradiance is defined as

$$E(\lambda) = \phi(\lambda)/A, \tag{1}$$

where $\phi(\lambda)$ is the radiant power at wavelength λ behind the aperture area A.

The area A of the aperture is readily measured. Thus the calculation is reduced to determining $\phi(\lambda)$.

Supposing the radiant power $\phi(\lambda)$ was known, the $I_{\mathrm{c},\,i}$ output photocurrents of the filter radiometer measured with the seven bandfilters could be calculated as follows:

$$I_{\mathrm{c},\,i} = \int_\lambda \phi(\lambda) \cdot \tau_i(\lambda) \cdot R_{\mathrm{Si}}(\lambda) \cdot \mathrm{d}\lambda, \tag{2}$$

where $i = (1, 2, \ldots, 7)$, $R_{\mathrm{Si}}(\lambda)$ is the spectral response of the silicon detector, and $\tau_i(\lambda)$ is the spectral transmittance of bandfilter i.

In (2) the only unknown quantity is $\phi(\lambda)$, the spectral radiant power. In the wavelength range 250 nm to 2500 nm the irradiance standards are either tungsten lamps or high-temperature large-area black bodies, whose spectral irradiance can be given in the following analytical form:

$$\phi_\lambda = \frac{A_3 \cdot \lambda^3 + A_2 \cdot \lambda^2 + A_1 \cdot \lambda + A_0}{\exp(B/\lambda) \cdot \lambda^5}. \tag{3}$$

The approximation (3) is used as the National Institute of Standards and Technology (NIST) for radiance and irradiance standard lamps [7]. Substituting (3) in (2), for the seven values of $I_{\mathrm{c},\,i}$ we obtain seven equations with five variables $(A_0;\ A_1;\ A_2;\ A_3;\ B)$ in the form

$$I_{\mathrm{c},\,i} = \int_\lambda \frac{A_3 \cdot \lambda^3 + A_2 \cdot \lambda^2 + A_1 \cdot \lambda + A_0}{\exp(B/\lambda) \cdot \lambda^5} \cdot \tau_i(\lambda) \cdot R_{\mathrm{Si}}(\lambda) \cdot \mathrm{d}(\lambda). \tag{4}$$

We look for the solution of the equation in a form that minimizes the relative errors between the measured and calculated values of the photocurrents, $I_{\mathrm{m},\,i}$ and $I_{\mathrm{c},\,i}$, with least-squares fitting:

$$\begin{aligned}&\mathrm{Error}\,(A_0,\,A_1,\,A_2,\,A_3,\,B)\\&=\sum_{i=1}^{7}\left(\frac{I_{\mathrm{m},\,i}-I_{\mathrm{c},\,i}}{I_{\mathrm{m},\,i}}\right)^2\\&=\mathrm{minimum}.\end{aligned} \tag{5}$$

Substituting for $I_{\mathrm{c},\,i}$ in (5):

$$\begin{aligned}&\mathrm{Error}\\&=\sum_{i=1}^{7}\left(\frac{\left\{\begin{array}{l}I_{\mathrm{m},\,i}-\int_{\lambda}\frac{A_3\cdot\lambda^3+A_2\cdot\lambda^2+A_1\cdot\lambda+A_0}{\exp\,(B/\lambda)\cdot\lambda^5}\\\cdot\,\tau_i\,(\lambda)\cdot R_{\mathrm{Si}}\,(\lambda)\cdot\mathrm{d}\,(\lambda)\end{array}\right\}}{I_{\mathrm{m},\,i}}\right)^2\\&=\mathrm{minimum}.\end{aligned} \tag{6}$$

Unfortunately it is difficult to determine the minimum of this function due to the exponential term. We recommend the following iteration:

(a) First, we set $A_1 = A_2 = A_3 = 0$ and determine A_{01} and B_1, such that the error function is minimized. Then, keeping these A_{01} and B_1 values fixed, we look for the best-fit values for A_{11}, A_{21} and A_{31} such that the error function is again minimized.

(b) Keeping these values for A_{11}, A_{21} and A_{31} fixed, we determine A_{02} and B_2 such that the error function is minimized. Then, keeping these values for A_{02} and B_2 fixed, we look for the best-fit values for A_{12}, A_{22} and A_{32} when the error function is minimized.

This iteration is continued until ΔE becomes less than the required limit. If the error function does not reach this limit, it means that the measurement uncertainties are higher than was supposed and we have to accept a higher error. If the error function reaches the required ΔE value in two or three iterations, it means that we have chosen too high a limit, and we should reduce it.

Band filters having different stabilities or accuracies can be given a weighting function G_i such that

$$\begin{aligned}&\mathrm{Error}\,(A_0,\,A_1,\,A_2,\,A_3,\,B)\\&=\sum_{i=1}^{7}G_i\left(\frac{I_{\mathrm{m},\,i}-I_{\mathrm{c},\,i}}{I_{\mathrm{m},\,i}}\right)^2\\&=\mathrm{minimum}.\end{aligned} \tag{7}$$

Other quantities (luminous intensity, correlated colour temperature) may also be calculated from spectral irradiance. In these cases, when the spectral irradiance is calculated, the use of a weighting function corresponding to the particular application is recommended.

4. Application limits

The data-reduction method described has the following application limits:

(a) The method works only for black-body sources or incandescent lamps without significant absorption or emission lines.

(b) The spectral range of the irradiance calculations is limited by the wavelength interval between the shortest and the longest wavelength bandfilters.

(c) At least six bandfilters are needed for the calculation of the five parameters $(A_0,\,A_1,\,A_2,\,A_3,B)$; seven or more are recommended.

5. Advantages of the method

(a) The calculated spectral irradiance is available as a mathematical function.

(b) Both the illuminance and the luminous intensity of the measured lamp may be derived from the calculated spectral irradiance. Similarly, the colour temperature of the lamp may be calculated.

(c) The method works best for black-body temperature determinations.

(d) The method, in a modified version, is suitable for the analysis of errors of bandfilter measurements.

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