Construction of UV-A radiometer for irradiance measurements

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Abstract. This work presents preliminary results aiming on providing Inmetro with a radiometric transfer standard in the UV-A spectral range. A broadband UV radiometer head was constructed using an UV photodiode, a commercially available UV-A optical filter and a precision aperture. These components have been characterized in the calibration and measurement facilities available at Inmetro. The preliminary characterization of the assembled UV broadband radiometer was carried out and the results are presented and discussed in this text.

1. Introduction

Ultraviolet (UV) light has many applications in materials processing, inspections of products and health care. These applications can require accurate monitoring of radiation levels [1-3]. Broadband UV radiation can be measured using filter radiometers whose spectral responsivities are matched to the desired spectral function. The UV-A spectral function is a rectangular-shape response function ranging from 315 nm to 400 nm which was standardized by the Commission Internationale de l’Eclairage (CIE) [4]. UV-A radiometers can be constructed using semiconductor photodiode, passband filters and a limiting aperture (figure 1). They are technically simple to construct and easy to use, however it is usually difficult to obtain good matching between its response function and the standardized spectral function [5].

![Figure 1. Exploded view of a typical radiometer.](image)

This study reports introductory results aiming on providing Inmetro with a radiometric transfer standard in the UV-A spectral range. A broadband UV radiometer was assembled. The preliminary
The characterization of this broadband radiometer was carried out according to the guidelines elaborated within the Working Group of the Thematic Network for Ultraviolet Measurements [6].

2. Experimental procedure
Each element of the UV radiometer was characterized separately assuming that inter-reflections between filter and photodiode were negligible. The spectral transmittance of the optical filter was previously measured. The selected type of UV photodiode (GaAsP Schottky) used for the construction of the transfer standard was characterized with respect to spectral responsivity and spatial uniformity in the ultraviolet and visible spectral regions [7]. The power spectral responsivity values were measured with suitable transfer standards traceable to Inmetro’s cryogenic radiometer. A precision aperture with cylindrical edge and nominal area of 0.5 cm² was used in the UV broadband radiometer to define the area of the input flux for irradiance measurement. A non-contact technique was used for measuring the aperture area with an expanded uncertainty of $2.8 \times 10^{-2}$ mm² ($k = 2$) [8].

The power spectral responsivity of the UV-A radiometer was then calculated from the product of the measured regular spectral transmittance of the UV-A optical filter and the power spectral responsivity of the UV photodiode.

The assembled radiometer was characterized in order to determine its performance according to reference [9]. A brief description of each characterized parameter as well as the measurement procedure is given under the following subsections. These parameters contribute to the uncertainty of measurement of the radiometer.

2.1. Directional response
The directional response describes the radiometer responsivity with respect to radiation incident at angles other than perpendicular. The ideal response would be a cosine function.

The measurement of directional response was performed under overfilled conditions using the output of a 1 kW FEL lamp as a radiation source. Lamp and radiometer were placed 1 m apart. The radiometer head was rotated about the axis passing by the center of the head aperture in the vertical direction (in the plane formed by the aperture surface) as shown in figure 2. The signal was acquired every 5° step. The characteristic function $f_\phi$ describing the directional response was calculated according reference [9].

![Figure 2. Setup for the measurement of the directional response.](image)

2.2. Radiometer Linearity
The linearity describes the variation of the response of the radiometer with respect to different levels of radiation.

For measuring this property, a set of neutral density (ND) filters whose nominal transmittances were 12 %, 15 %, 20 % and 40 % were used. The radiation of a 1 kW FEL lamp was directly measured by the radiometer (100 % signal) followed by attenuation of the beam by each of the filters. At the end of the cycle, the stability of the lamp was checked by measuring again the non-attenuated beam. This procedure allowed testing the linearity in the range from 0.5 mW/cm² to 5.5 mW/cm².
The linearity is described by function $f_3$ \cite{9}, which express the maximum deviation of the linear behavior of the radiometer output when compared to the expected value calculated from the known transmittances of the ND filters.

2.3. Radiometer Fatigue
The fatigue describes a reversible change of the radiometer responsivity due to submission to radiation.

The fatigue of the UV-A radiometer was measured using the UV output of a 1 kW FEL lamp. The distance of the lamp to the radiometer reference plane was one meter. The output signal (photocurrent) was measured as a function of the irradiation period keeping the lamp operating conditions constant. Furthermore, in order to follow the recommended procedure \cite{9}, the radiometer head was not exposed to radiation for at least 24 hours before starting the test. The characterization was carried out in irradiance mode and the fatigue was tested over an elapsed time of 30 minutes.

2.4. Response uniformity
The response uniformity describes the influence of non-uniform irradiation of radiometers. This parameter was evaluated by clipping the beam to a size of 2.7 mm diameter. The signal of this beam was measured in five regions in the active area: at center, and more four positions located at 90° intervals around the center of the acceptance aperture as depicted in figure 3.

![Figure 3](image_url)

Figure 3. Radiometer front view displaying the active area (blue) delimited by the aperture (gray). The clipped beam was measured over the active area in the five indicated regions, one at a time.

2.5. Short and long wavelength responses
These parameters describe the responsivity of the radiometer outside the UV-A range.

The experiment was held using optical filters with known spectral transmittances, WG305 and GG420. The radiation from a 1 kW lamp was filtered and the short and long wavelength range responses were determined.

3. Results and discussion
The spectral responsivity of the radiometer was calculated from the measured spectral responsivity of the photodiode and the transmittance of the optical filter. The results are shown in figure 4.
Figure 4. Calculated spectral responsivity for the broadband UV radiometer alongside the CIE UV-A spectral function.

Figure 4 also displays the CIE UV-A spectral function. It is clear that there is a large spectral mismatch of the radiometer responsivity to the proposed spectral function. Construction of UV radiometers with low spectral mismatch is challenging because of the rectangular shape of the response functions [5].

Figure 4 also indicates that there is a strong dependence of the power measured with the radiometer head on the spectral distribution of the source being measured. This poses a problem whenever the radiometer is calibrated with a kind of source and is used to measure radiation emitted by a source with distinct spectral distribution. The spectral mismatch correction factor $F$ tries to account for and correct this problem. Table 1 shows this factor calculated for a set of commonly used UV lamps. The calculation was performed as described in [6] using the spectral responsivity of the radiometer and the nominal spectral distribution of the lamps [9]. The spectral mismatch correction factor can exceed 70% when the radiometer is calibrated with a low pressure Hg lamp and used to measure a Xe lamp. Although table 1 displays rather high correction factors, those values are consistent with results found elsewhere [5,10].

| Test Lamp | Calibration lamp |
|-----------|-----------------|
| Xe        | 1               |
| LPHg      | 0.5794          |
| MPHg      | 0.7111          |
| QTH       | 0.9517          |
|           | Xe              |
|           | 1.7259          |
|           | 1.4063          |
|           | 1.0508          |
|           | LPHg            |
|           | 1               |
|           | 0.8149          |
|           | 0.6088          |
|           | MPHg            |
|           | 1.2272          |
|           | 1               |
|           | 0.7472          |
|           | QTH             |
|           | 1.6425          |
|           | 1.3384          |
|           | 1               |

Additionally, it is also possible to calculate the spectral mismatch factor, $f_i'$, which accounts for the mismatch of the radiometer head responsivity to the desired spectral function [9]. This parameter cannot be used for correcting measurements. Considering the relative spectral distributions of the xenon arc lamp and the quartz-tungsten halogen lamp (QTH), the calculated $f_i'$ for the assembled UV-A radiometer head were 0.3621 and 0.3925. The former result is consistent with $f_i'$ values reported for commercial UV-A radiometers [10,11].
Table 2 presents the characterization results of the parameters presented in section 2 for the filter radiometer.

| Parameter                  | Symbol | Value       |
|----------------------------|--------|-------------|
| Directional response       | \( f_2 \) | \( 8.6 \times 10^{-1} \) |
| Linearity                  | \( f_3 \) | \( 5.5 \times 10^{-2} \) |
| Fatigue (30 min)           | \( f_5 \) | \( 8.0 \times 10^{-4} \) |
| Uniformity                 | \( f_9 \) | \( 1.7 \times 10^{-3} \) |
| Short wavelength response  | \( u \) | \( 5.0 \times 10^{-2} \) |
| Long wavelength response   | \( r \) | \( 4.9 \times 10^{-2} \) |

The directional response is high when compared to the other parameters. This indicates that the radiometer response is strongly dissimilar to the cosine response. Such high values for this parameter have also been reported for commercial UV radiometers [10]. A diffuser can be used to improve the directional response of this radiometer with the drawback that it usually deteriorates the uniformity, which is rather good for the current construction, as can be realized from the magnitude of \( f_9 \) in table 2.

4. Conclusion
A special UV-A radiometer head was assembled with characterized components. The spectral responsivity of the radiometer was calculated using the spectral transmittance of the filter and the responsivity of the photodiode. This allowed estimating the spectral mismatch correction factor, \( F \), for a set of commonly used UV lamps, as well as the spectral mismatch factor, \( f_i' \). Additionally, the assembled UV-A radiometer was experimentally characterized in order to evaluate the performance regarding to directional response, linearity, fatigue, uniformity, short and long wavelength responses.

The results indicate the difficulties of constructing this kind of radiometers with good spectral mismatch between its spectral responsivity and the standardized response function. This is essentially a consequence of the rectangular shape of the response function for the UV-A.

The constructed device display performance parameters similar to commercially available UV-A radiometers. However, the high value of the directional response indicates the need of using a cosine corrector (diffuser).

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