

SPECTRAL CHARACTERISATION OF $V(\lambda)$ FILTERS FOR CANDELA REALIZATION

*Luciana Castro Alves*¹, *Carla Thereza Coelho*¹, *Thiago Ferreira da Silva*¹, *Thiago Menegotto*¹,
*Miguel Angelo Catharina Torres*¹, *Muriel Aparecida de Souza*², *Ana Paula Dornelles de Alvarenga*²

¹ Inmetro / Dimci / Diopt / Laraf, Duque de Caxias, Brazil, laraf@inmetro.gov.br

² Inmetro / Dimci / Diopt / Laco, Duque de Caxias, Brazil, laco@inmetro.gov.br

Abstract: Four $V(\lambda)$ filters used in the standard photometers based on trap detector specially constructed for the candela realization were characterised for spectral transmittance in a calibrated spectrophotometer. The filters were thermalized and the temperature dependence of their transmittance was analyzed. These measurements are a step in the national realization of the candela at Inmetro.

Key words: spectral transmittance, photometer, filter, candela.

1. INTRODUCTION

The candela, the base unit of luminous intensity of the International System of Units (SI), according to the adopted definition by the *Conférence Générale des Poids et Mesures* (CGPM) since 1979, has been defined in terms of the watt [1]:

“The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian”

Since 1979, the candela has been realized by many National Metrology Institutes (NMI) following the detector-based method, deduced from the illuminance provided by calibrated detector and the distance from light source to the photometer, whose relative spectral responsivity $s(\lambda)_{rel}$ has been adapted to the spectral luminous efficiency function $V(\lambda)$.

The spectral responsivity of the photometer is mainly determined by the wavelength-selective $V(\lambda)$ filter, which represents the relative spectral responsivity of the human eye under daylight illumination levels [2]. The spectral responsivity is then the product of the spectral responsivity of the photodiode and the spectral transmittance of the $V(\lambda)$ filter, which can be determined by two different ways: measured directly i.e. calibrated as an entity to account for interreflections between the filter and the detector or calculated as product of its components characterized separately.

In this article, we present the spectral characterization of $V(\lambda)$ filters used in the standard photometers based on trap

detector specially constructed for the materialization of the luminous intensity scale at Inmetro. Each photometer is consisted by a silicon 3-reflection trap detector, which consists of three windowless Hamamatsu S1337-11 photodiodes, a $V(\lambda)$ filter and a precision aperture. The filters were characterized under different temperatures.

1.1. Principle of realization

A standard photometer consists of a silicon photodiode, a $V(\lambda)$ filter, and a precision aperture [3]. The luminous responsivity s_v (A/lm) of the photometer is determined by

$$s_v = \frac{i}{\phi_v} \quad (1)$$

where i (A) is the output photocurrent and $\phi_v(\lambda)$ (lm), the luminous flux. The output photocurrent i (A) of the photometer is given by

$$i = \int \phi_e(\lambda) s(\lambda) d\lambda \quad (2)$$

where $\phi_e(\lambda)$ (W/nm) is the incident spectral radiant flux and $s(\lambda)$ (A/W) is the spectral responsivity of the photodiode. Normalizing $s(\lambda)$ in relation to $s(\lambda)$ at 555 nm, as well as the function $V(\lambda)$, then $s_n(\lambda)$ is given by the following equation

$$s(\lambda) = s(555) s_n(\lambda) \quad (3)$$

The luminous flux $\phi_v(\lambda)$, i.e., the luminous energy emitted by the source per unit time, is defined in relation to the corresponding radiometric quantity

$$\phi_v = K_m \int \phi_e(\lambda) V(\lambda) d\lambda \quad (4)$$

where $\phi_e(\lambda)$ (W/nm) is the incident spectral radiant flux and $K_m = 683$ lm/W is the spectral luminous efficacy function for photopic function, defined by *Commission Internationale de L'Éclairage* (CIE). The illuminance E_v (lux = lm/m²) at the opening of area A (m²) is determined when the entire area of the aperture is uniformly illuminated. The output photocurrent i is then proportional to the illuminance E_v .

$$E_v = \frac{\phi_v}{A} = \frac{K_m F i}{s(555)A} \quad (5)$$

The photometer measures the luminous intensity I_v (cd) when used with a point light source at a distance r from the aperture plane. The luminous intensity I_v is then determined from the following equation

$$I_v = E_v r^2 = K_m \frac{i}{s(555)(A/r^2)} F \quad (6)$$

where i is the output photocurrent, in A; K_m is the maximum spectral luminous efficacy, equal to 683 lm/W; $s(555)$ is the spectral responsivity $s(\lambda)$ a 555 nm, in A/W; A is the aperture area of the photometer, in m^2 ; r is the distance from the point light source to the aperture plane, in m; F is the spectral mismatch factor given by [4].

$$F = \frac{\int \phi_e(\lambda) V(\lambda) d\lambda}{\int \phi_e(\lambda) s_n(\lambda) d\lambda} \quad (7).$$

1.2. $V(\lambda)$ filters

Four $V(\lambda)$ filters with 12 mm of diameter and 2.5 mm of thickness were measured. All filters, hereafter numbered from 1 to 4, were manufactured by LMT Lichtmesstechnik GmbH and made by superposition of different types of colored glass layer as shown in Figure 1. According to the manufacturer, the spectral matching of these filters to the $V(\lambda)$ function f_1 was 2.2%, measured with Hamamatsu S1227-66 photodiode, which has peak sensitivity wavelength at 720 nm.

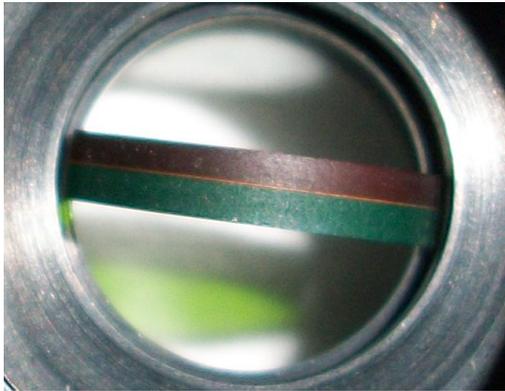


Fig. 1. $V(\lambda)$ filter made of different types of glass.

1.3 Temperature controller

The $V(\lambda)$ filter thermalization was performed with a PID temperature controller acting on an annular thermoelectric Peltier element, which heats or cools the filter according to the temperature read through a 10 k Ω thermistor. One side of the Peltier was in contact with the heat sink, and the other one was in contact with the copper oven insulated from the

heat sink by a plastic layer. Therefore the copper oven, the $V(\lambda)$ filter and the precision aperture were at equal temperatures. The temperature-controlled filter holder manufactured by AS Rantell was specially designed to be coupled to the trap detector front end. Figure 2 shows the temperature-controlled filter holder used on filter radiometers (photometers) based on trap detectors. A data acquisition program developed in the LabView graphical language was used to monitor temperature of the filter assembly. The accuracy of the whole temperature controller is about 0.3°C (PID temperature controller accuracy given by manufacturer is 0.002°C).

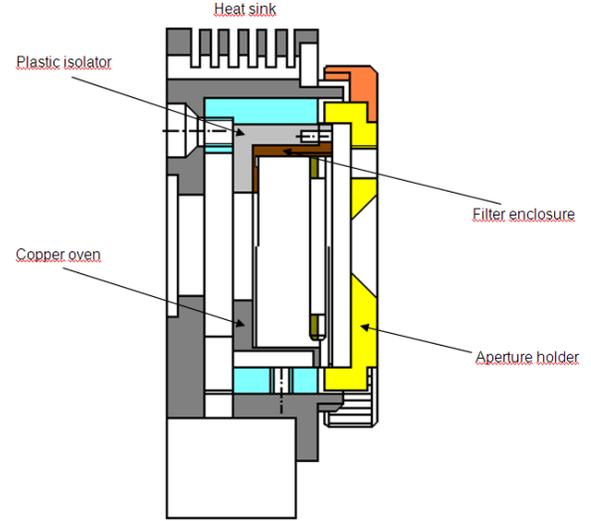


Fig. 2. Cross-section of the temperature-controlled filter holder.

2. SPECTROPHOTOMETRIC MEASUREMENTS

The spectral transmittance of the $V(\lambda)$ filters has been measured since 2000 using the high accuracy reference spectrophotometer, a double-grating monochromator, Lambda 19 manufactured by Perkin Elmer. In this study, a new high resolution Cary 5000 by Varian was used. This spectrophotometer has dual beam, dual monochromator, and works in the range of wavelength of 175 nm to 3300 nm. The light source used in the ultraviolet (UV) spectral range is a deuterium lamp and in the visible and near infrared (VIS/NIR) spectral range, a tungsten halogen lamp is used. The detection system consists of a photomultiplier (UV/VIS) and a PbS detector (NIR). Both spectrophotometric measurement facilities are periodically full characterized. The same temperature controller system used for lamp measurements on the photometric bench was adapted for the transmittance measurements, thus ensure the same temperature and orientation in both measurements. A brief description of the spectrophotometer is presented in figure 3, having wavelength repeatability better than 0.005 nm.

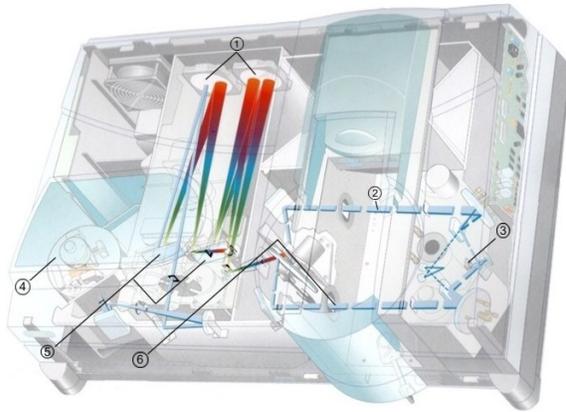


Fig. 3. Spectrophotometer system: 1 - mirrors; 2 - reference beam; 3 - detector; 4 - radiation source; 5 - gratings; 6 - sample beam [5].

The wavelength expanded uncertainty of the spectrophotometer is estimated to be equal to 0.13 nm ($k = 2.02$). The bandwidth of the spectrophotometer was 1 nm.

2.1. Spectral regular transmittance measurements

The temperature dependence of the $V(\lambda)$ filter transmittance was investigated measuring the spectral transmittance of the $V(\lambda)$ filters at different temperatures ranging from 19°C to 30°C. Spectral scans were carried out in the spectral range from 380 nm to 780 nm with step of 0.1 nm. Additional scans were performed in the spectral range from 200 nm to 1100 nm at intervals of 1 nm. The spectral transmittance at the side wings of the $V(\lambda)$ filters was investigated at the temperature of 25°C, taking into account the normal conditions of the photometric measurements. Some transmittance measurements were performed in previous years made on both sides of the filters. In this study, the filters were measured with the incidence of optical radiation in the green glass layer.

Measurements were carried out under dark environment conditions. The ambient and inner temperature and relative humidity were monitored with thermo-hygrometers during measurements and varied less than 0.4°C and 1.0% (1σ).

3. MEASUREMENTS RESULTS

The measured percentual spectral transmittance curves of the $V(\lambda)$ filter 1 and the standard deviation of the measurements are shown in figures 4 and 5, respectively. The variation of spectral transmittance in the expanded spectral region is presented in figure 6. The extinction ratio between the peak and out-of-band signals was 10^5 . All studied $V(\lambda)$ filters showed similar behavior.

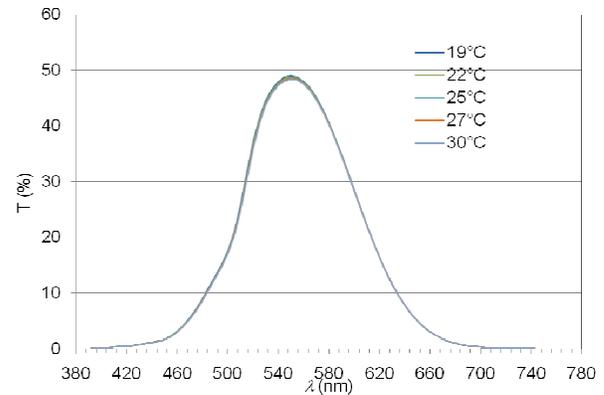


Fig. 4. Percentual spectral transmittance of the $V(\lambda)$ filter 1 measured in different temperatures.

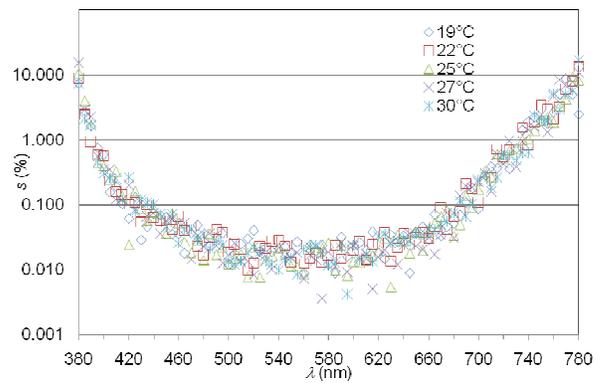


Fig. 5. The standard deviation of the measurements of spectral transmittance of the $V(\lambda)$ filter 1 in different temperatures.

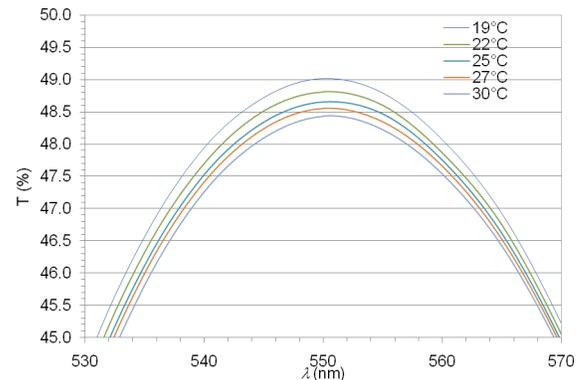


Fig. 6. Variation of spectral transmittance in the expanded spectral region of $V(\lambda)$ filter 1.

Within the passbands, the spectral transmittance of the filters were measured at temperatures of 19°C, 22°C, 25°C, 27°C and 30°C. Figure 7 shows the temperature coefficient of the $V(\lambda)$ filter transmittance as a function of wavelength. The temperature stability was better than 0.1°C. At 25°C, the transmittance of the $V(\lambda)$ filters 1, 2, 3 and 4 at 555 nm, was 48.47 %, 47.87 %, 48.23 % and 48.294 %, with an relative standard uncertainty of 2.9×10^{-3} , respectively. The typical temperature coefficient at the peak wavelength of the

filter transmittance is about $5.2 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$, resulting in a relative standard uncertainty of 2.1×10^{-4} in the photometer responsivity at 555 nm.

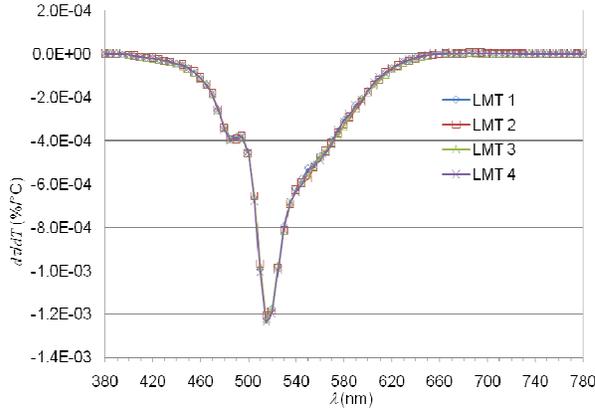


Fig. 7. Temperature coefficient of the $V(\lambda)$ filter transmittance.

Broad scans were performed from 200 nm to 1100 nm to determine the out-of-band blocking of the $V(\lambda)$ filters. Outside the passbands, in the ultraviolet and near-infrared spectral ranges, from 200 nm to 400 nm and from 830 nm to 1100 nm, the transmittance is less than 8.1×10^{-4} and 4.4×10^{-4} , respectively. No leakages were found outside the passbands of all four filters.

Four independent photometers were constructed for the realization of the luminous intensity scale at Inmetro. The individual spectral responsivity of each photometer was determined by the convolution of the spectral transmittance of the $V(\lambda)$ filter with the spectral responsivity of the trap detector. The relative spectral responsivity of the photometer $s_n(\lambda)$ and the spectral luminous efficiency function $V(\lambda)$ are presented in the figure 8. The spectral match between $s_n(\lambda)$ and $V(\lambda)$ functions is presented in figure 9 (for photometer built with $V(\lambda)$ filter 1). The spectral matching of the photometer head to the $V(\lambda)$ function f_1' [6] of 2.7% was found.

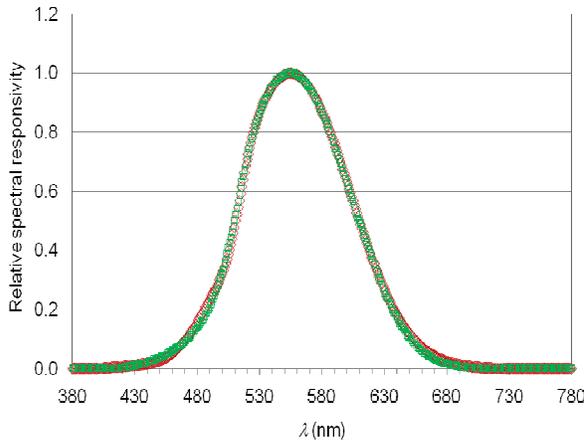


Fig. 8. The relative spectral responsivity of the photometer $s_n(\lambda)$ (\diamond) and the spectral luminous efficiency function $V(\lambda)$ (\square) of photometer built with $V(\lambda)$ filter 1.

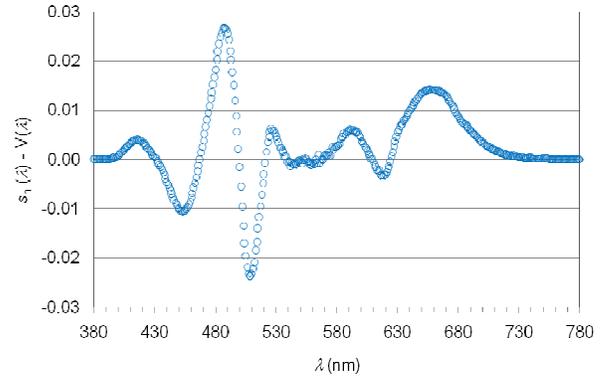


Fig. 9. The spectral match between $s_n(\lambda)$ and $V(\lambda)$ functions of the photometer built with $V(\lambda)$ filter 1.

The spectral mismatch factor F depends on the spectral radiant flux of the source through the detector aperture [7]. Considering the relative spectral power distribution of CIE illuminant A, the temperature dependence of F due to change of the filter transmittance was $0,007\%/^\circ\text{C}$.

4. DISCUSSION

Spectral transmittance as a function of temperature ranging from 19°C to 30°C was measured for all filters, and the typical temperature coefficient at the peak wavelength of the filter transmittance is about $5.2 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$. There was no indication of the existence of out-of-band transmittance within the spectral range. The approximation of the spectral response of the photometer to the CIE $V(\lambda)$ function was also evaluated. The difference between the f_1' can be easily explained taking into consideration the different typical curves of spectral responsivity of S1226-66, S1337-11 photodiodes and S1337-11 3-reflection trap detector. The S1337-11 photodiode has peak sensitivity wavelength at 960 nm while S1226-66, at 720 nm.

5. CONCLUSION

The study of the temperature dependence of the transmittance of the $V(\lambda)$ filters is an important step in the full characterization of the photometers for the candela realization. Future characterization of filters in terms of spectral reflectance, polarization-dependence, and angle-dependence will allow for the correction of the spectral transmittance. The spectral reflectance of the $V(\lambda)$ filters can be used to correct the effect of the interreflections between the filter and the trap detector, despite of the low reflectance of the trap detector. As a further remark, filters should be individually selected to achieve a better realization of the $V(\lambda)$ function i.e. the spectral transmittance optimized to match the spectral responsivity of the photometer to the $V(\lambda)$ function. Filters made to match Hamamatsu S-1337-11 photodiode must be acquired. Some new trap detectors based on Hamamatsu S-1227-1010BQ photodiodes will be soon assembled and characterized for photometric measurements. This

improvement will impact in the measurement results of the photometer spectral responsivity, contributing in the reduction of the overall luminous intensity measurement uncertainty.

ACKNOWLEDGEMENTS

The authors would like to acknowledge CETUC/PUC-Rio for providing the temperature controller and thermistor. A. D. Alvarenga acknowledge support from CNPq proc.# 307991/2008-3.

REFERENCES

- [1] P. Giacomo, “*News from the BIPM*”, *Metrologia*, Vol. 16, pp. 55-61, 1980.
- [2] CIE Publication 18.2, “*The Basis of Physical Photometry*”, 1983.
- [3] Y. Ohno, “*OSA Handbook of Applied Photometry*”, Chapter 3 – Photometric Standards, December 1, 1996.
- [4] C. L. Cromer, G. Eppeldauer, J. E. Hardis, T. C. Larason, Y. Ohno, and A. C. Parr, “*The NIST Detector-Based Luminous Intensity Scale*”, *Journal of Research of the National Institute of Standards and Technology*, Vol. 101, No. 2, pp. 109-132, March-April 1996.
- [5] Picture from “*UV-VIS-NIR / Varian Cary 4000, 5000, 6000i and Deep UV Spectrophotometers*” description brochure.
- [6] CIE Publication 53, “*Methods of Characterizing the Performance of Radiometers and Photometers*”, 1982.
- [7] E. Ikonen, P. Kärhä, A. Lassila, F. Manoochehri, H. Fagerlund and L. Liedquist, “*Radiometric realization of the candela with a trap detector*”, *Metrologia*, Vol. 32, pp. 689-692, 1995/96.