SPECTRAL CHARACTERISATION OF THE LINEAR PYROMETER OF INMETRO

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Abstract: A linear pyrometer operating at 650 nm and 900 nm used for the maintenance of the International Temperature Scale of 1990 (ITS-90) at the Pyrometry Laboratory (Lapir) of the Thermal Metrology Division (Diter) was characterised for spectral responsivity at the Radiometry and Photometry Laboratory (Laraf) of the Optical Metrology Division (Diopt) of Inmetro. Direct measurements and indirect measurements were performed with a monochromatic beam in the spectral responsivity measurement facility. Results of the relative spectral responsivity of the linear pyrometer at 650 nm and 900 nm agreed with those from the previous evaluation performed in 2005, considering their uncertainties, to about 0.1 nm.

Key words: spectral responsivity, pyrometer.

1. INTRODUCTION

In the range above the freezing point of silver 1234.93 K (961.78°C), the International Temperature Scale (ITS-90) [1] states that the temperature T_{90} is defined by the equation:

$$\frac{L_\lambda(T_{90})}{L_\lambda[T_{90}(X)]} = \frac{\exp\left(c_2\left[\lambda T_{90}(X)\right]^{-1}\right)-1}{\exp\left(c_2\left[\lambda T_{90}\right]^{-1}\right)-1} \qquad (1)$$

where $T_{90}(X)$ refers to any one of the silver $\{T_{90}(\mathrm{Ag}) = 1234.93\ \mathrm{K}\}$, the gold $\{T_{90}(\mathrm{Au}) = 1337.33\ \mathrm{K}\}$ or the copper $\{T_{90}(\mathrm{Cu}) = 1357.77\ \mathrm{K}\}$ freezing points and in which $L_\lambda\ (T_{90})$ and $L_\lambda\ [T_{90}(X)]$ are the spectral concentrations of the radiance of a blackbody at the wavelength (in vacuo) λ at T_{90} and at $T_{90}(X)$ respectively, and $c_2 = 0.014388$ m K.

Three basic operations are necessary for the realisation of ITS-90 above the freezing point of silver [2]: the fixed-point calibration, the spectral characterisation of the thermometer and the measurement of the non-linearity of the detector.

The spectral responsivity of an optical pyrometer is principally determined by the narrow bandpass filters, being the product of the spectral responsivity of the detector and the spectral transmittance of the interference filter and of the other optical components such as lenses and neutral density filters. The relative spectral responsivity of an optical pyrometer can be determined by two ways: measured directly i.e. calibrated as an entity to account for interreflections (direct measurement) or calculated as product of its components characterized *in situ* so as to avoid errors due to different positioning and orientation (indirect measurement) [3].

In this article, it is presented the spectral characterisation of the primary standard radiation thermometer used for the maintenance of the ITS-90 at high temperatures at Inmetro. The radiation thermometer under test is a linear pyrometer, model LP3, manufactured by KE Technologie GmbH, Germany.

2. THE LINEAR PYROMETER

The linear pyrometer LP3 has a front lens of 400 mm of focal length and a rear one of 200 mm. The combination of these lenses permits focusing at a distance between 410 mm to 1010 mm, with a target diameter of 0.6 mm to 1.4 mm. The LP3 pyrometer has a collimator lens of f50/17. The numerical aperture of the LP3 pyrometer is f/8.2. Two narrow band interference filters can be inserted on its optical path: one at 650 nm and the other at 900 nm with half-height bandwidth of 10 nm and 13.6 nm, respectively. A single silicon photodiode S1336-18BK from Hamamatsu is used as radiation detector. The optical arrangement of the LP3 pyrometer [4] is shown in figure 1.

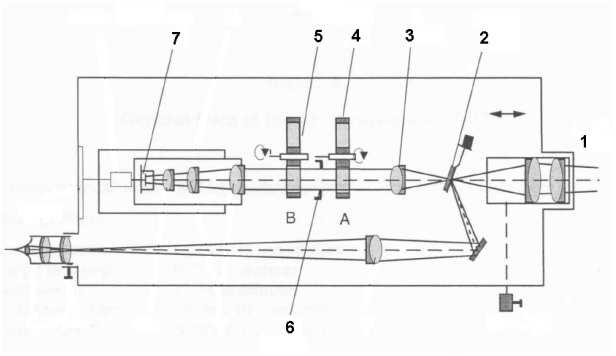

Fig. 1. Optical arrangement of the LP3 pyrometer: objective lens (1); measuring field stop (2); collimator lens (3); filter wheels A (4) and B (5); aperture stop (6) and detector (7).

3. EXPERIMENTAL SET-UP

The measurement system used for calibration of optical pyrometer was the existing spectral responsivity measurement facility at Inmetro. The heart of the system was a single grating monochromator of 250 mm focal length

with an f/4.1 numerical aperture. A holographic grating of 1200 grooves/mm and spectral dispersion of 3 nm/mm at 500 nm was used in the spectral range from 400 nm to 1300 nm. The wavelength calibration of the monochromator was performed using spectral lamps.

Figure 2 shows the experimental set-up, which consisted of a tungsten halogen lamp as radiation source. The filament of this lamp was imaged on the entrance slit of the monochromator and GG395 and RG695 colored glass filters were used to suppress higher orders. The entrance and exit slits of the monochromator were adjusted to a width corresponding to the bandpass equal to 0.8 nm. Considering that the numerical apertures of monochromator and LP3 pyrometer were not the same, an optical arrangement between both equipments was used in order to reach the maximum flux, adjusting the numerical aperture of monochromator to the pyrometer.

The image of the exit slit was set over the third photodiode of a 3-reflection silicon trap detector used as reference detector with LNE-INM traceability. The trap detector was mounted on an optical rail with a computer-controlled XY axis translation stage. An aperture with a diameter approximately equal to 3 mm was placed in the optical path in front of the trap detector. Photocurrents generated by the trap detector were amplified with calibrated Vinculum SP042 current to voltage converter and the voltage was measured with calibrated Hewlett Packard 34401A digital multimeter. The amplifier conversion factor used for the trap detector was typically 10^6 V/A.

Taking into account the normal conditions of use of the linear pyrometer, the measurement mode used was power mode, underfilled. Both detectors were covered by a light-tight enclosure and all the measurements were carried out under dark environment conditions. The temperature and the relative humidity during measurements were controlled and did not vary more than 0.6°C and 1.6%, respectively.

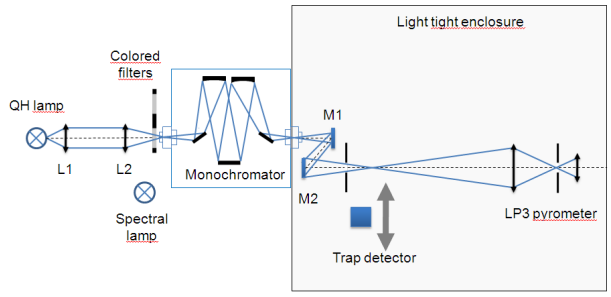

Fig. 2. Experimental setup for spectral responsivity.

3.1. Relative spectral responsivity measurements

The relative spectral responsivity of the LP3 pyrometer was measured directly, performed with the lenses and interference filters in position. For the filter centered at 650 nm, some spectral scans, identified as June 2010, were carried out in the spectral range from 633.0 nm to 672.9 nm. In the central region from 643.0 nm to 663.5 nm where the spectral responsivity changes substantially, the measurements were performed at intervals of 0.25 nm, using 0.5 nm intervals in the measurements made in the side wings.

Additional scans, identified as December 2010, were performed in the spectral range from 590.1 nm to 717.9 nm at intervals of 0.5 nm in the central region from 640.0 nm to 668.0 nm and of 5 nm in the side wings. The relative spectral responsivity was measured directly and it was also calculated as product of its components characterized *in situ*, in the spectral range from 638.0 nm to 672.9 nm at intervals of 0.5 nm for the filter centered at 650 nm. The transmittance curve of the interference filter was determined from the output of the LP3 pyrometer while scanning the monochromator through the filter transmission band with and without the interference filter in position. The spectral response of the photodiode was determined by direct measurement.

For the filter centered at 900 nm, the spectral responsivity measurements were carried out in the spectral range from 681.0 nm to 1025.2 nm at intervals of 1 nm in the central region from 880.5 nm to 925.4 nm and of 10 nm in the side wings.

4. MEASUREMENTS RESULTS

The relative spectral responsivity of the LP3 pyrometer measured directly is shown in logarithmic scale in figure 3. The ratio of signals at the extremities of the wings to the peak signal was 10^{-4} and 10^{-5}, in June 2010 and in December 2010, respectively. Figure 4 presents the relative spectral responsivity measured in June 2010 and its uncertainty. The maximum uncertainty of relative spectral responsivity was about 5.3×10^{-2} at the edge of the spectral band.

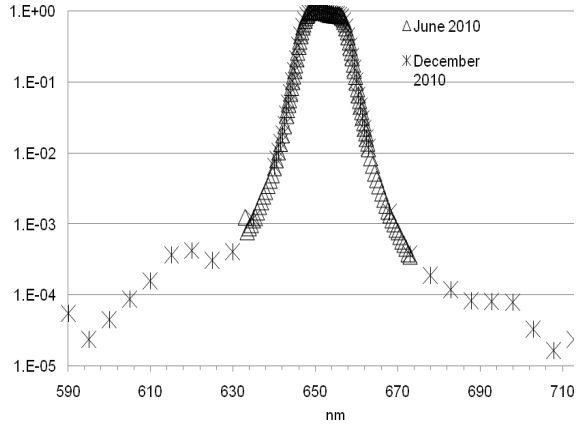

Fig. 3. Relative spectral responsivity of the LP3 pyrometer at 650 nm measured in June and December of 2010.

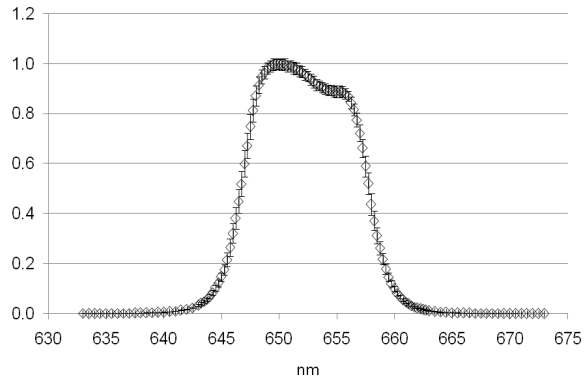

Fig. 4. Relative spectral responsivity of the LP3 pyrometer at 650 nm and associated expanded uncertainties measured in June 2010.

The relative spectral responsivity of the LP3 pyrometer measured directly and calculated as product of its components characterized *in situ* is shown in figure 5 and the relative difference between them is shown in figure 6. In figure 7 is shown the relative spectral responsivity calculated as product of its components characterized *in situ* and using the manufacturer typical data of spectral response of a S1336-18BK silicon photodiode. The relative difference between these responses is shown in figure 8.

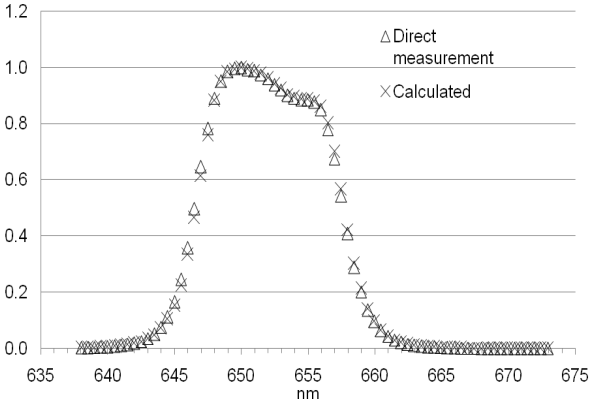

Fig. 5. Relative spectral responsivity of the LP3 pyrometer at 650 nm measured directly and calculated as product of its components.

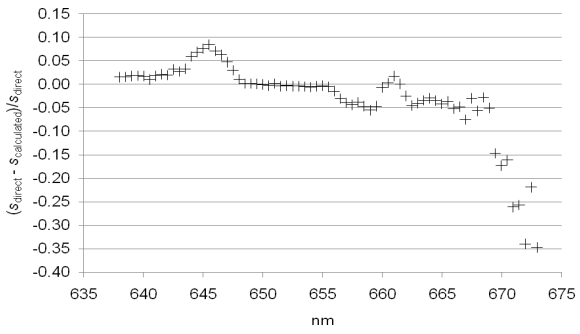

Fig. 6. Relative difference between relative spectral responsivity of the LP3 pyrometer at 650 nm measured directly and calculated as product of its components.

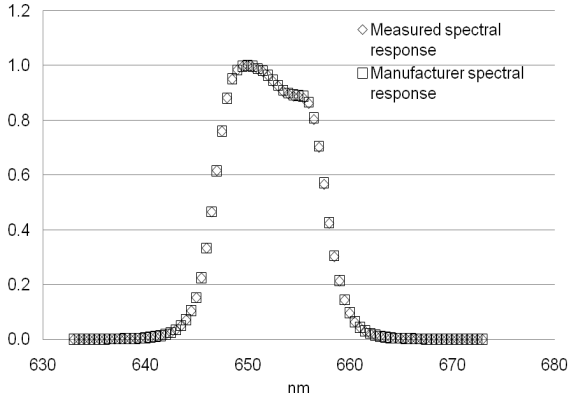

Fig. 7. Relative spectral responsivity of the LP3 pyrometer at 650 nm calculated as product of its components measured separately and using the manufacturer spectral response of photodiode.

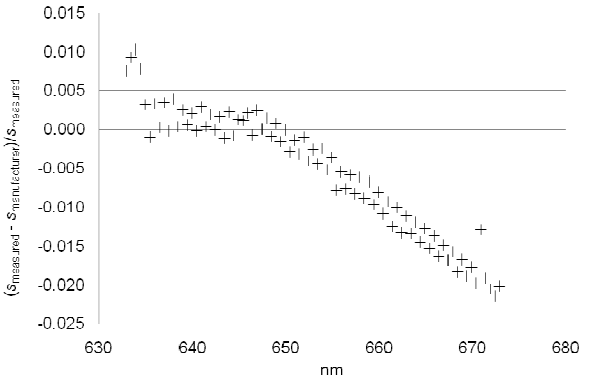

Fig. 8. Relative difference between relative spectral responsivity of the LP3 pyrometer at 650 nm calculated as product of its components measured separately and using the manufacturer spectral response of photodiode.

In figure 9 the relative spectral responsivity at 900 nm of the LP3 pyrometer measured directly is shown. The ratio of signals at the ends of the wings to the peak signal was 10^{-6}, in December 2010. Figure 10 presents the relative spectral responsivity measured in December 2010 and its uncertainty. The maximum uncertainty of relative spectral responsivity was about 4.3×10^{-2} at the edge of the spectral band.

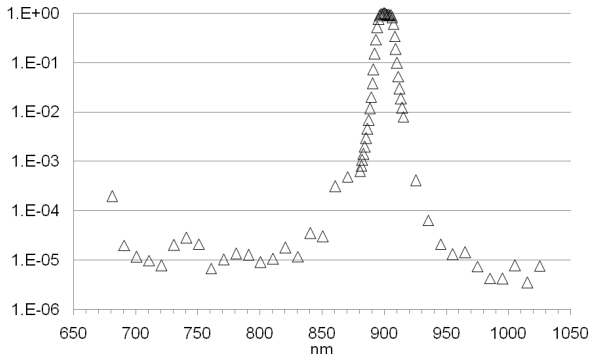

Fig. 9. Relative spectral responsivity of the LP3 pyrometer at 900 nm measured in December of 2010.

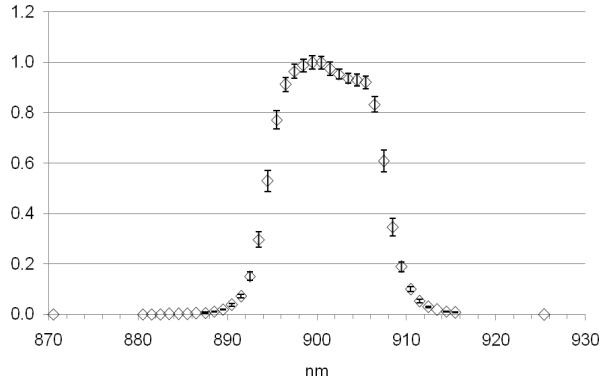

Fig. 10. Relative spectral responsivity of the LP3 pyrometer at 900 nm and associated expanded uncertainties measured in December 2010.

4.1. Uncertainty in the spectral responsivity measurements

The overall spectral responsivity of a linear pyrometer depends on the relative spectral response of the detector, the transmission profile of the interference filter and any other optical components [2]. The relative spectral responsivity of the LP3 pyrometer (measured as a unit) was calculated as the ratio of the output and input spectral curves. The wavelength uncertainty of the monochromator was estimated to be equal to 0.07 nm. The bandwidth of the monochromator of 0.8 nm was less than 1/10 of the bandpass of the filter. Despite this wasn't a significant proportion of the bandwidth of the LP3 pyrometer, an additional uncertainty caused by the bandwidth of the monochromator was also estimated. The estimated expanded uncertainty was greater in the cut-on and cut-off regions of both filters, where the responsivity curve is very steep. The contribution of the wavelength uncertainty to the measurement uncertainty was very significant in these two regions. The uncertainty due to the repeatability contributed significantly to the measurement uncertainty in the region out of the bandpass filter with poor signal to noise ratio. Other uncertainty components were considered in the overall measurement uncertainty: reproducibility of measurements, calibration of electronic equipment, calibration of reference detector, monochromator resolution, spectral responsivity uncertainty due to the wavelength uncertainty and drift of the reference detector. The uncertainty contributions in spectral responsivity measurements at 650 nm and 900 nm of the LP3 pyrometer are summarised in Tables 1 and 2.

Table 1. Uncertainty budget for spectral responsivity measurements at 650 nm of the LP3 pyrometer

Quantity	Relative standard uncertainty (%)
Repeatability and reproducibility (Type A)	0.7
Calibration of the current to voltage converter	0.001
Calibration of the reference detector	0.32
Spectral responsivity due to wavelength uncertainty	0.009
Calibration of multimeter	0.0004
Resolution of the wavelength	0.009
Bandwidth of the monochromator	0.00002
Long-term stability of the reference detector	0.0016
Combined standard uncertainty	0.77
Expanded standard uncertainty (k = 2.03)	1.6

Table 2. Uncertainty budget for spectral responsivity measurements at 900 nm of the LP3 pyrometer

Quantity	Relative standard uncertainty (%)
Repeatability and reproducibility (Type A)	0.8
Calibration of the current to voltage converter	0.001
Calibration of the reference detector	0.33
Spectral responsivity due to wavelength uncertainty	0.15
Calibration of multimeter	0.0004
Resolution of the wavelength	0.006
Bandwidth of the monochromator	0.0004
Long-term stability of the reference detector	0.002
Combined standard uncertainty	0.89
Expanded standard uncertainty (k = 2.03)	1.8

5. DISCUSSION

For the filter centered at 650 nm, a very narrow range was used in the runs taken in June 2010, if considering the ratio of signals at the extremities of the wings to the peak signal was 10^{-4}. In December 2010, some new broad scans were performed to determine the out-of-band blocking of both interferential filters. There was no indication of the existence of out-of-band transmittance within the spectral range.

The calculated centroid wavelengths for filter at 650 nm were equal to 652.12 nm and 652.07 nm, in June and December 2010, respectively. For filter at 900 nm, it was equal to 901.04 nm, in December 2010. The effect of the ends (side wings) was analyzed by calculating the centroid wavelength with and without wings. Taking the data from December 2010, excluding the ends, the centroid wavelengths were equal to 652.09 nm and 901.12 nm, a contribution of (0.014 nm) and (0.081 nm), for 650 nm and 900 nm filters, respectively.

The centroid wavelengths were equal to 652.00 nm and 652.07 nm, respectively, taking the data obtained from direct measurement and calculated as product of its components. Whereas using the manufacturer spectral response, the centroid wavelength was 652.08 nm. The results show small shift, less than 0.1 nm, in the centroid wavelength of the LP3 pyrometer at 650 nm calibrated as an entity in comparison with by separate calibrations of the detector and the interference filter, despite all interreflections between optical components.

The shape of the spectral responsivity curves obtained in 2010 seems to be very similar to that previous obtained in September of 2005 [5]. Figures 11 and 12 show the relative spectral response of LP3 pyrometer at 650 nm and 900 nm measured in 2005 and 2010.

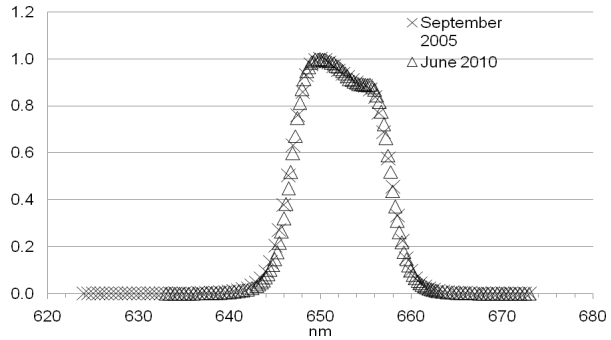

Fig. 11. Relative spectral responsivity of the LP3 pyrometer at 650 nm measured in September 2005 and June 2010.

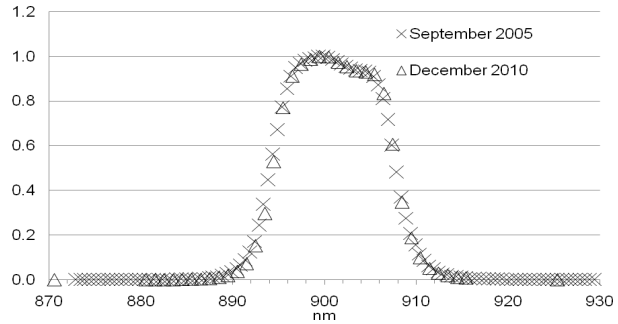

Fig. 12. Relative spectral responsivity of the LP3 pyrometer at 900 nm measured in September 2005 and December 2010.

Regarding the calculated centroid wavelengths when compared to those first obtained in 2005 [5], the discrepancy is equal to 0.05 nm and 0.04 nm, for 650 nm and 900 nm filters, respectively. According to the manual LP3 pyrometer [4], the transmittance declared by the manufacturer for the 650 nm filter is 58%. Analyzing the data obtained in 2005 and 2010, the maximum transmittance was around 29.7% and 29.3%, respectively.

6. CONCLUSION

From the results of the spectral responsivity of the linear pyrometer, it can be stated that a good agreement was observed using different methods, direct measurement and separate measurements. Results of relative spectral responsivity of the LP3 pyrometer at 650 nm and 900 nm over the period from 2005 to 2010 agree to about 0.1 nm.

A future improvement in the spectral responsivity measurement system will be the use of a new monochromator with better resolution and greater focal length will allow the reduction of the wavelength uncertainty. This improvement will concern in the measurement results of the pyrometer spectral responsivity, contributing for the reduction of the overall temperature measurement uncertainty.

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