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Performance of Different Light Sources for the Absolute Calibration of Radiation Thermometers

M. J. Martín[1] · J. M. Mantilla[1] · D. del Campo[1] · M. L. Hernanz[2] · A. Pons[2] · J. Campos[2]

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Abstract The evolving mise en pratique for the definition of the kelvin (MeP-K) [1,2] will, in its forthcoming edition, encourage the realization and dissemination of the thermodynamic temperature either directly (primary thermometry) or indirectly (relative primary thermometry) via fixed points with assigned reference thermodynamic temperatures. In the last years, the Centro Español de Metrología (CEM), in collaboration with the Instituto de Óptica of Consejo Superior de Investigaciones Científicas (IO-CSIC), has developed several setups for absolute calibration of standard radiation thermometers using the radiance method to allow CEM the direct dissemination of the thermodynamic temperature and the assignment of the thermodynamic temperatures to several fixed points. Different calibration facilities based on a monochromator and/or a laser and an integrating sphere have been developed to calibrate CEM's standard radiation thermometers (KE-LP2 and KE-LP4) and filter radiometer (FIRA2). This system is based on the one described in [3] placed in IO-CSIC. Different light sources have been tried and tested for measuring absolute spectral radiance responsivity: a Xe-Hg 500 W lamp, a supercontinuum laser NKT SuperK-EXR20 and a diode laser emitting at 6473 nm with a typical maximum power of 120 mW. Their advantages and disadvantages have been studied such as sensitivity to interferences generated by the laser inside the filter, flux stability generated by the radiant sources and so forth. This paper describes the setups used, the uncertainty budgets and the results obtained for

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✉ M. J. Martín
mjmartinh@cem.minetur.es

1 Centro Español de Metrología, Tres Cantos, Spain

2 Consejo Superior de Investigaciones Científicas, Instituto de Óptica, Madrid, Spain

the absolute temperatures of Cu, Co-C, Pt-C and Re-C fixed points, measured with the three thermometers with central wavelengths around 650 nm.

Keywords Absolute radiometry · Radiance method · Radiometer · Standard radiation thermometer · Thermodynamic temperature · Uncertainty

1 Introduction

The redefinition of kelvin, unit of thermodynamic temperature, will be broad enough to encompass any form of thermometry [2]. In the past, CEM performed the absolute radiance responsivity calibration of a standard radiation thermometer for the determination of thermodynamic temperatures, traceable to the Spanish standard electrical substitution cryogenic radiometer, in a lamp–monochromator-based facility at the Instituto de Óptica which is part of the Spanish Research Council (IO-CSIC) [3].

The capability of measuring thermodynamic temperatures allowed both institutions participated in the international campaign for the assignment of the thermodynamic temperatures of the Co-C, Pt-C and Re-C eutectic high temperature fixed points part of the European Union funded InK project [4].

However, the uncertainties obtained were higher than expected and similar to the ones obtained using ITS-90, so the experimental setups presented in [3] have being improved in a new facility which is now located in CEM in order to avoid the transportation of the standard filter radiometers between calibration and temperature measurements.

Since the most significant sources of uncertainty come from the stability and homogeneity of the light source, the need to improve it becomes apparent. Different light sources could be chosen to reduce these contributions having, each one, advantages and disadvantages, assessed in this paper, for the absolute calibration of radiometers and radiation thermometers using radiance method. The final uncertainty achieved is lower than in the previous setup [3].

2 Experimental Apparatus and Procedures

2.1 Relative Spectral Calibration

The relative spectral responsivity of three radiation thermometers/imaging radiometers has been measured, namely a commercial KE-LP2, a commercial KE-LP4 and a homemade imaging radiometer FIRA2 [6]. The method is described with more details in [3], and it is based on knowing the relative change of the radiometer's responsivity from one wavelength to another, taken the peak wavelength as reference. Similar to the one at IO-CSIC [3], a new setup showed in Fig. 1a has been laid at CEM. In this case, an automated translation stage with the reference detector (Si) is used instead of a rotation stage. In addition, an optical rail allows having several radiometers/thermometers to be measured at the experiment.

An image of the exit slit of a monochromator has been used as source for these measurements. A single monochromator (model SPEX 750) with its corresponding second-order blocking filter was illuminated with a halogen incandescent lamp whose electrical current was kept constant within ± 0.5 mA.

The monochromator wavelength scale was calibrated following the same procedure described in [3] obtaining similar results.

The relative responsivity is given by the ratio of the radiometer response, $I_{ph,RT}$ to a standard silicon detector response, $I_{ph,Si}$, times the spectral silicon detector responsivity $S_{Si}(\lambda)$, normalized lately to the maximum value.

2.2 Absolute Radiance Calibration

Three systems have been used to perform the absolute calibrations (see Fig. 1b, c, d) based on the one described in [3]:

– A monochromator-based integrating sphere facility in combination with :

- A high-stability, high-power Xe-Hg discharge lamp manufactured by Hamamatsu placed inside a housing with an optical objective imaging the lamp's arc on the entrance slit of the single monochromator. See Fig.1b.
- A supercontinuum (SC) laser NKT SuperK EXR20, with a typical total power of 8 W working in a feedback mode with power stability better than 0.01 % in the observed spectral band. See Fig. 1c. A dispersive prism is used to reduce the light power at the entrance slit of the monochromator. In order to use the power stability mode at the SC laser, a monitor Si detector is placed looking at the exit port of the integrating sphere. The signal of this detector is measured with an electrometer and fed back to the SC laser control unit.

The monochromator output goes directly to the entrance port of a 5.2-cm-diameter integrating sphere.

– A laser-based integrating sphere facility using a CW Coherent diode laser OBIS model 648 nm (Fig. 1d), with a 120 mW typical maximum power. The laser output goes directly to the entrance port of a 5.2-cm-diameter integrating sphere

When a laser light is used, a rotating diffuser plate is placed before the entrance port of the integrating sphere to reduce speckle. This diffuser is placed in an enclosure to avoid stray light from it.

The diffraction grating used at the monochromator is 1200 grooves/mm. The entrance and exit slits widths of the monochromator are set to 0.9 mm resulting in a 1 nm FWHM bandwidth. The maximum signal-to-noise ratio is 0.08 % or better for the standard thermometers under test and it is considered in the uncertainty budget.

To measure the radiance of the source, a radiance meter is used. This system has been improved too, in comparison with the one used in [3]. Now, it is a fixed ensemble of two temperature-controlled high-precision apertures and a Si-trap detector, traceable to the primary cryogenic radiometer of IO-CSIC. Knowing the effective areas of the apertures and the distance between them, the geometric factor of the radiance measurement can be calculated and then the spectral radiance of the sphere's aperture obtained.

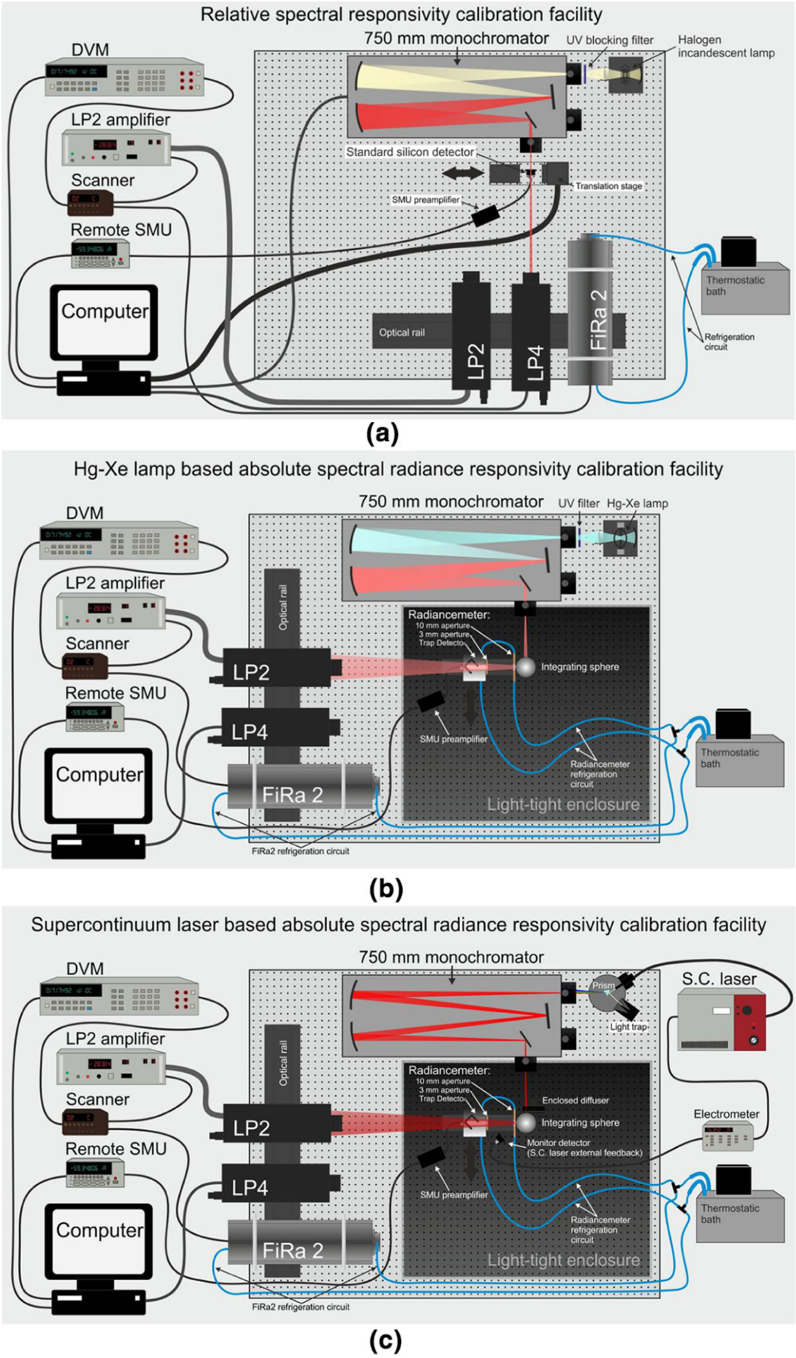
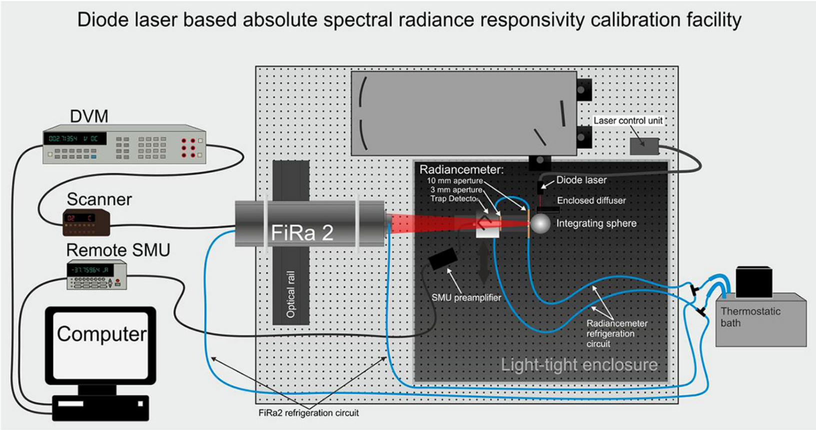


Fig. 1 Schematic diagram of the setups used for radiation thermometer calibration: (a) relative spectral response measurements and (b), (c) and (d) absolute spectral response measurements. DVM, digital voltmeter; SMU, source-meter unit



(d)

Fig. 1 continued

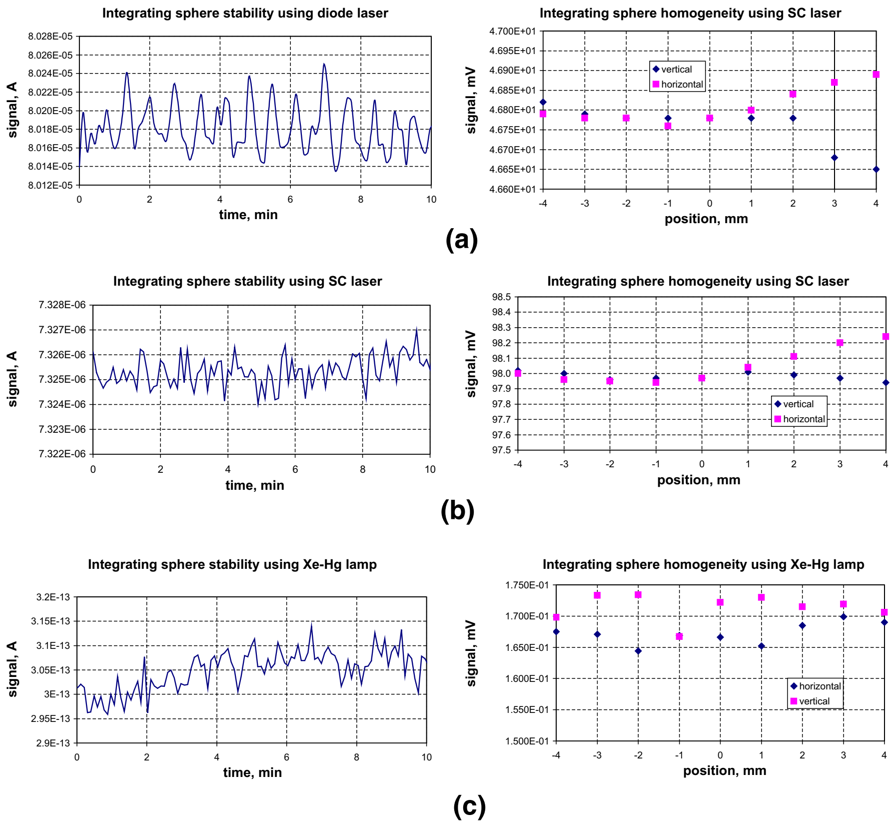


Fig. 2 Stability and homogeneity of the integrating sphere with the different light sources used: (a) diode laser, (b) supercontinuum laser and (c) Xe-Hg lamp

Table 1 Integrating sphere stability and homogeneity with different light sources

Light source	Stability as standard deviation, %	Homogeneity as standard deviation, %
Diode laser	0.04	0.12
SC laser	0.01	0.10
Xe-Hg lamp	1.00	1.13

The diameter of the precision apertures and the distance between them are measured by CEM's length division using a Mitutoyo ® Ultra Quick Vision coordinate measuring machine ® [7], which counts on a non-contact vision module based on a Revishaw TP-200 touch-trigger probe. Both systems are referenced to the scales the machine has for each axis and they have traceability to the national length standards maintained by CEM. This allows measuring the precision apertures diameter with a non-contact method and the distance with a contact method, much more accurately than in [3].

The signal of the Si-trap detector is measured with a source-meter unit (SMU) 6430 from Keithley. It has a remote preamplifier to be set near the detector to reduce noise. The electrical signals from the FIRA2 and KE-LP2 in volts are measured with a digital voltmeter (DVM) HP3458A, while the radiation thermometer KE-LP4 measures photocurrent directly.

The stability of the sources has been estimated by recording the Si-trap detector's signal, while the homogeneity has been estimated by mapping the output port of the sphere with the radiation thermometer KE-LP2. The results are shown graphically in Fig. 2 and numerically in Table 1.

Commercial radiation thermometers (KE-LP2 and KE-LP4) can only be calibrated by using incoherent sources to avoid interference fringes as those shown in Fig. 3. When the supercontinuun laser is used to calibrate them, interference fringes are not seen at first sight, as expected since its coherence length is much shorter than that of the diode laser. However, to discard any interference effects, the response of the KE-LP4 versus wavelength was recorded pointing directly to the exit slit of the monochromator, spectrally scanning with different bandwidths and a constant sampling step of 0.01 nm. The ripple of the recorded signal due to interference should decrease as the bandwidth would increase, being negligible over a certain bandwidth threshold. Results of these scans are shown in Fig. 4a. It can be seen that interference effects may be considered negligible in KE-LP4 for bandwidths larger than 0.5 nm. The same test was done for KE-LP2 and the results obtained (see Fig. 4b) are as those of KE-LP4. Even more the differences between the relative spectral responses are less than 0.02 which is negligible.

The homemade radiometer FIRA2 was designed to avoid inter-reflections between the detector and filter [6], so that interference effects should be smaller than in the thermometers. In fact, interference fringes are not seen at first sight in the focal plane of the radiometer when using laser sources. Nevertheless FIRA2 was subjected to the same test. The record of its response is shown in Fig. 4c. Ripple is smaller than

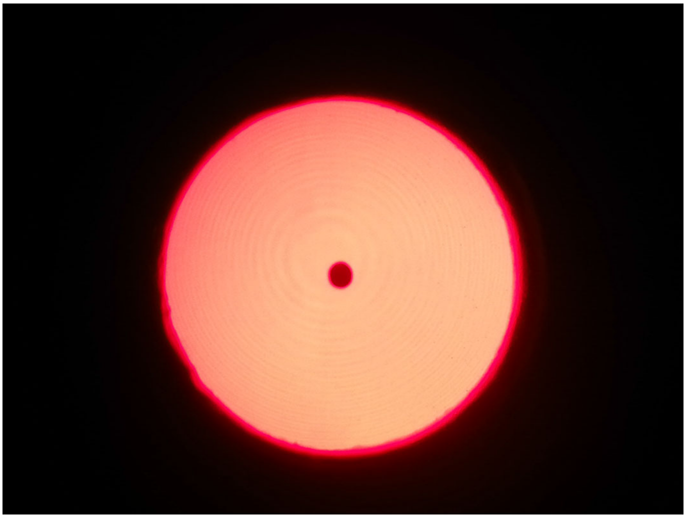


Fig. 3 Interference fringes seen by KE-LP2 when a coherent light is used

that of thermometers and negligible too. The negligibility of this effect is supported by the comparison on temperature measurement results got with this radiometer that was calibrated by using the SC laser and the diode laser (see table 3). The difference between temperature results is well below the calibration uncertainty, so the interference effect, which in principle is more important when calibrated with the diode laser than when the SC laser is used, is considered negligible compared to other uncertainty sources.

Finally, the absolute spectral radiance of the sphere measured with the radiance meter is compared with the photocurrent generated at the radiation thermometer to determine the absolute spectral radiance responsivity of the radiation thermometer, using the equations shown in [3]. From the absolute spectral radiance responsivity, the thermodynamic temperature is obtained from the photocurrent values measured at the fixed points (see [3]).

2.3 Temperature Measurements

The furnaces used for the measurements of the three eutectics fixed points (Co-C, Pt-C and Re-C manufactured by CHINO, diameter aperture of 3 mm) and the Cu fixed point were described in [3]. Different melt–freeze cycles have been performed for each fixed point to estimate its repeatability.

3 Results

The absolute calibrations were performed at 651.8 nm (KE-LP2); 646.5 nm (KE-LP4) and 647.3 nm (FIRA2) which are wavelengths where the responsivity of the radiation

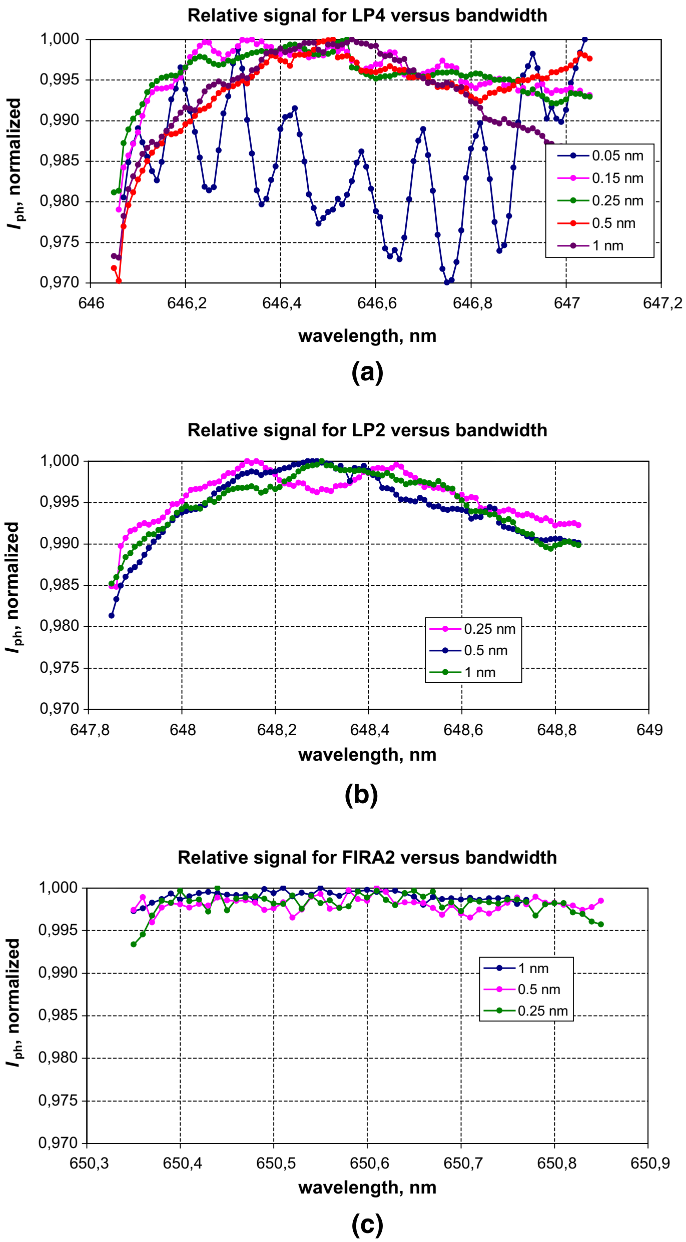


Fig. 4 Spectral relative response recorded at different bandwidths (with a sampling step of 0.01 nm) at the SC laser + monochromator setup. (a) LP4, bandwidths of 0.05 nm, 0.15 nm, 0.25 nm, 0.5 nm and 1 nm; (b) LP2, bandwidths of 0.25 nm, 0.5 nm and 1 nm and (c) FIRA2, bandwidths of 0.25 nm, 0.5 nm and 1 nm

thermometer is spectrally flat and, in consequence, less sensitive to the monochromator wavelength error and bandwidth. The absolute spectral radiance responsivity of the three thermometers/radiometers calculated from Eq. 1 is plotted in Fig. 5.

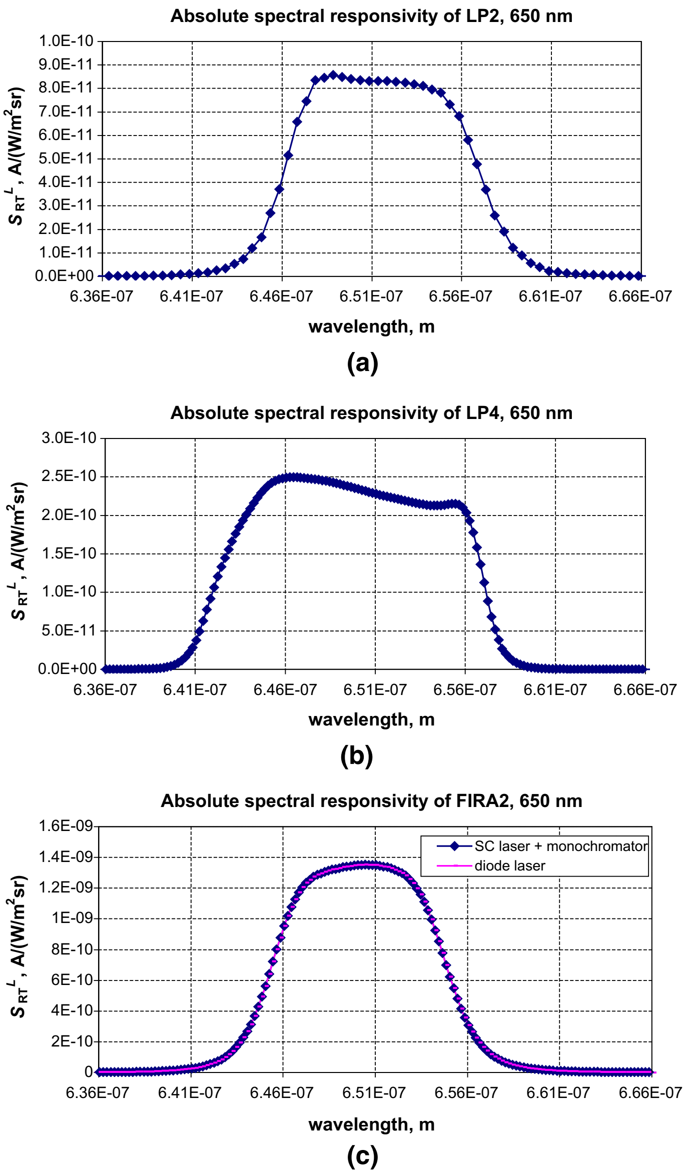


Fig. 5 Absolute spectral radiance responsivity of the radiometers: (a) KE-LP2, measured on the monochromator-based facility with SC laser (b) KE-LP4, measured on the monochromator-based facility with SC laser (c) FIRA2, measured on the monochromator-based facility with SC laser and diode laser facility

Two curves are given for the FIRA2 measured with the SC laser and the diode laser setups, respectively.

The uncertainty calculations were performed by using the method described in [4]. Table 2 shows the uncertainty budget associated with the calibration of the radiation

Table 2 Uncertainty budget for the radiation thermometers calibration (a) using a SC laser and (b) using a diode laser

Uncertainty component	Value	Uncertainty at Cu FP, K	Uncertainty at Co-C FP, K	Uncertainty at Pt-C FP, K	Uncertainty at Re-C FP, K
(a)					
λ_0: Wavelength	0.03 nm	0.025	0.027	0.029	0.027
Drift	0.05 nm	0.042	0.045	0.048	0.046
σ	0.02 nm	0.002	0.002	0.003	0.003
H:					
Trap detector	0.052 %	0.022	0.030	0.048	0.089
Aperture area	0.1 %	0.042	0.058	0.092	0.171
Distance	0.02 %	0.008	0.012	0.018	0.034
Sphere spatial uniformity	0.1 %	0.084	0.116	0.184	0.342
Source stability	0.01 %	0.008	0.012	0.018	0.034
Diffraction at apertures	0.01 %	0.002	0.003	0.005	0.010
Signal-to-noise ratio	0.08%	0.019	0.027	0.042	0.079
Stability of the trap	0.052 %	0.025	0.035	0.055	0.103
	Combined	**0.11**	**0.15**	**0.23**	**0.42**
(b)					
λ_0: laser calibration	0.002 nm	0.001	0.002	0.002	0.002
σ	0.02 nm	0.002	0.002	0.003	0.003
H:					
Trap detector	0.052 %	0.022	0.030	0.048	0.089
Aperture area	0.1 %	0.042	0.058	0.092	0.171
Distance	0.02 %	0.008	0.012	0.018	0.034
Sphere spatial uniformity	0.12 %	0.100	0.139	0.220	0.411
Source stability	0.04 %	0.033	0.046	0.073	0.137
Diffraction at apertures	0.01 %	0.002	0.003	0.005	0.010
Signal-to-noise ratio	0.08 %	0.019	0.027	0.042	0.079
Stability of the trap	0.052 %	0.025	0.035	0.055	0.103
	Combined	**0.12**	**0.17**	**0.26**	**0.49**

thermometers using a SC laser and using a diode laser. The uncertainty budget with the Xe-Hg lamp is not included because its lack of stability and homogeneity provides uncertainties ranging from 3 K to 11 K.

The uncertainties shown in Table 2 have been reduced in comparison with the ones in [3], due to the improvements in the setup. The main improvements are:

- The uncertainty associated with λ_0, defined in [5], in case a diode laser is used, it is estimated as the uncertainty due to the laser calibration, 1.5 ppm ($k = 1$) (λ_0 drift is considered negligible because it is calibrated just before the measurements).
- Aperture areas, estimated as 0.1 % from the calibration certificates of the CEM length department ($k = 2$).

Table 3 Thermodynamic temperature measurements

Fixed point, assigned temperature [4]	Thermodynamic temperature, K				Expanded uncertainty, K			
	KE-LP2 SC laser	KE-LP4 SC laser	FIRA2 SC laser	FIRA2 Diode laser	KE-LP2 SC laser	KE-LP4 SC laser	FIRA2 SC laser	FIRA2 Diode laser
Cu, 1357.80	1357.76	1357.72	1358.29	1358.25	0.23	0.23	0.26	0.27
Co-C, 1597.39	1597.18	1597.10	1598.04	1597.99	0.30	0.31	0.33	0.36
Pt-C, 2011.43	2011.19	2011.19	2012.41	2012.32	0.46	0.46	0.48	0.55
Re-C, 2747.84	2747.49	2746.64	2748.46	2748.30	0.84	0.84	0.86	1.00

The expanded uncertainty includes in use thermometer components (SSE, linearity and drift)

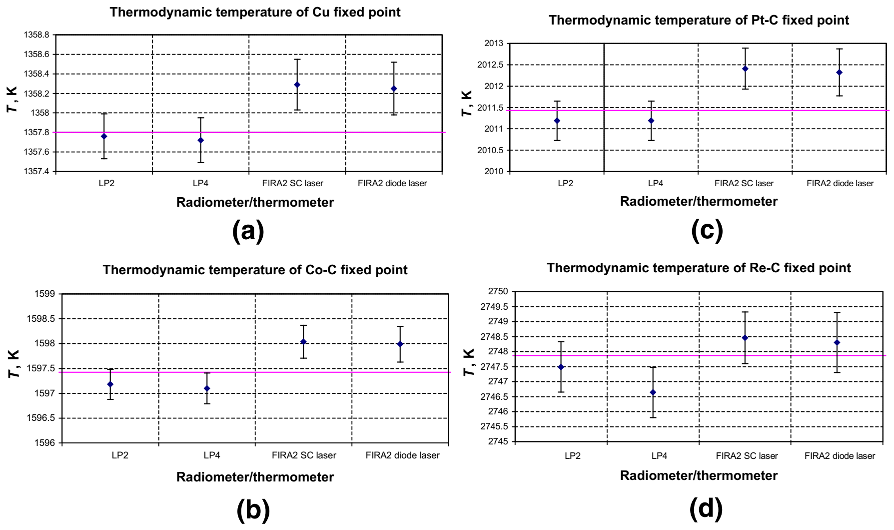


Fig. 6 Thermodynamic temperature measurements of (a) Cu, (b) Co-C, (c) Pt-C and (d) Re-C fixed points with KE-LP2, KE-LP4 and FIRA2. Straight lines at the graphs are the reference temperatures from [4]

- Distance, estimated as 0.02 % from the calibration certificate of the CEM length department ($k = 2$).
- Sphere spatial uniformity, taken from Table 1.
- Sphere stability, taken from Table 1.

The values obtained for the thermodynamic temperatures of the different fixed points measured are shown in Table 3 and Fig. 6. These results are close to the ones reported in [5], taking into account the uncertainty, except for Re-C with KE-LP4 and Cu, Co-C and Pt-C with FIRA2. FIRA 2 differences are due to some residual problems on the radiometer design (FIRA2 drifted by 0.2 °C at Co-C fixed point after measuring Re-C), but these present results are better than those obtained previously [6]. Even so, some modifications are required to improve this radiometer.

It is still unexplained the reason why the Re-C temperature is lower when measured with KE-LP4 and its difference bigger than the uncertainty, even though the uncertainty assigned to these measurements was higher because of the method used to obtain T (a Sakuma Hattori fitting). This effect has already been observed when KE-LP4 was used to measure absolute temperatures of a variable temperature blackbody up to 2500 °C [8].

4 Conclusions

Different light sources have been used for the absolute calibration of one filter radiometer and two radiation thermometers using the radiance method: a Xe-Hg lamp, a diode laser and a supercontinuum laser.

The following advantages and disadvantages of the different setups were found:

- *Xe-Hg lamp* It is the less expensive option; however, the emitted power is really low (see Fig. 2) and because of this the measurements for the stability and uniformity of the integrating sphere are not good enough. In consequence, the uncertainties when using this light source range from 3 K to 11 K due to these components.
- *Diode laser* The setup is much simpler because a monochromator is not needed, however, in commercial radiation thermometers (KE-LP2, KE-LP4) interference fringes are produced (see Fig. 3). It only could be used for the homemade radiometer FIRA2 designed for that purpose [6].
- *Supercontinuum laser* It is the most expensive option but it supplies enough light flux. A dispersive prism is needed at the entrance of the monochromator to limit the power inside it, so avoiding damaging the optical components. As this light source is not as coherent as the diode laser, interference fringes were not observed at KE-LP2 and KE-LP4 at the bandwidth used for the measurements. The laser gets an optimum stability when a power feedback is used.

Furthermore, two different methods have been used for the absolute calibration of FIRA2 giving compatible results for the absolute spectral radiance with temperature differences well below the calibration uncertainties: from 0.04 °C at the Cu fixed point to 0.16 °C at the Re-C fixed point (see graph c) at Fig. 4 and FIRA2 data in table 3.

The uncertainties obtained for both methods (SC + monochromator and diode laser) are similar (see table 2). The diode laser setup has less uncertainty in λ_0 because of the more accurate calibration of the laser wavelength. However, the stability and the homogeneity at the integrating sphere output is worse than in the SC laser + monochromator setup when the power feedback option is used.

Nevertheless, the uncertainties obtained in table 2, although better than in [3], are still high if compared with the ones of other NMIs (see [4]). This in mainly due to the inhomogeneity of the integrating sphere (see table 2). It is foreseen to change the current integrating sphere with a specially designed one, without frame at the exit port and with a baffle inside. It is expected that this will reduce the final uncertainty in radiance method calibrations at CEM making it comparable to other NMIs.

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