MeP-K absolute primary radiometric thermometry

Section 1: Absolute (spectral-band) radiometry (radiation thermometry)

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Introduction
The determination of thermodynamic temperatures through absolute primary radiometry requires the following:
- A blackbody with a known (high) spectral emissivity.
- A measurement of the spectral radiance of the blackbody traceable to the units of the SI.

Blackbody sources

The spectral radiance of a blackbody, $L_{\text{b},\lambda}$[1], that is the power emitted per unit area per solid angle per unit wavelength interval, is given by Planck's law:

$$L_{\text{b},\lambda}\left(\lambda,T\right)d\lambda = \varepsilon\left(\lambda,T\right)\left(\frac{2hc^2}{n^2\lambda^5}\right)\frac{d\lambda}{\exp\left(hc/n\lambda kT\right)-1}, \tag{1}$$

where T is the thermodynamic temperature, k is the Boltzmann constant, h is the Planck constant, c the speed of light in a vacuum, n is the refractive index of the gas in the optical path, λ is the wavelength in that gas, and $\varepsilon\left(\lambda,T\right)$ is the spectral emissivity of the blackbody. The units of the spectral radiance are W m^{-2} sr^{-1} nm^{-1}

The measurement of thermodynamic temperature by absolute primary filter radiometry

Traceability to fundamental units
The implementation of absolute primary radiometry requires that the quantities involved are traceable to the units of the SI. Hence, the power measurement must be traceable to the definition of the watt; wavelength, area and distance to the definition of the metre.

Basic principles of absolute primary radiometry
The components of a radiometric system for the measurement of thermodynamic temperatures are a blackbody source and a detector with a known spectral responsivity. The source and the detector areas are limited by co-aligned, circular

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[1] The subscript λ in this case indicates that the value is per unit wavelength, not a wavelength dependency.

apertures with radii r_1 and r_2, respectively, separated by distance d. The incident spectral power, $\Phi_\lambda(\lambda)$, at the detector is given by

$$\Phi_\lambda(\lambda) = \Theta L_\lambda(\lambda), \tag{2}$$

where L_λ is the spectral radiance of the source and Θ is the throughput of the setup. The throughput is related to the configuration factor (also known as the geometric or form factor), F, and the source aperture area, A_1

$$\Theta = \pi A_1 F_{A_1 - A_2}, \tag{3}$$

where the configuration factor is

$$F_{A_1 - A_2} = \frac{1}{2}\left(\frac{(r_2^2 + r_1^2 + d^2) - \sqrt{\left(r_2^2 + r_1^2 + d^2\right)^2 - 4r_1^2 r_2^2}}{r_1^2} \right). \tag{4}$$

The term $g = A_1 F_{A_1 - A_2}$ is also known as the 'geometric factor' in the literature.

The spectral irradiance, E_λ, is simply given by the incident power at the plane of the detector aperture divided by the detector aperture area, $A_2 = \pi r_2^2$,

$$E_\lambda(\lambda) = \Phi_\lambda(\lambda)/A_2. \tag{5}$$

Absolute primary spectral-band (or filter) radiometry
The spectral power is determined using a detector of known spectral responsivity in a particular waveband and in a defined solid angle. In principle, there are a number of different filter radiometry implementations. But in practice the filter radiometer is comprised of a detector, a spectrally selective filter and a geometric/optical system with at least one defining aperture; in addition, at least one lens has to be added for imaging systems.

Different practical implementations of absolute primary spectral-band radiometry are possible, but all require the following common calibration infrastructure:
- A trap detector calibrated at distinct wavelengths by monochromatic radiation from a laser or monochromator, using a cryogenic electrical substitution radiometer and a continuous spectral power responsivity scale obtained by interpolating these values by a physical model. This provides power traceability to the watt.
- The calibration of the spectral responsivity, at discrete wavelengths, of the filter radiometer by comparison with the trap detector. This requires a monochromatic source, tuneable across the bandwidth of the filter radiometer. This is often achieved using a tuneable laser illuminating an integrating sphere or, alternatively, a monochromator-based source. For a spectral radiance responsivity calibration, the source must be Lambertian. The wavelength

determination of the laser, or the wavelength scale calibration of the monochromator, provides traceability to the metre.

- Two precision circular apertures with known diameter and separation. The areas of these apertures and separation distance provide traceability to the metre.

Examples of practical implementations of absolute primary spectral-band radiometry are described below, each having a slightly different calibration method. These are given as a guide only, and the realisation of an absolute primary thermometry scale will depend on local requirements and constraints.

The first two methods are non-imaging, and the third and fourth use optics to facilitate the measurement of small sources.

Non-imaging methods

The power mode
If the radiometer is calibrated for spectral power responsivity, $s_\Phi(\lambda)$, the photocurrent measured by the radiometer is

$$i = \int s_\Phi(\lambda)\Phi_\lambda(\lambda)d\lambda . \tag{6}$$

The power responsivity is determined by calibration against a source that underfills the radiometer, and then a geometric system with two apertures is added to measure the radiance of the blackbody (see Figure 1). For this method the homogeneity of the detector is very important.

a) Calibration   b) Use
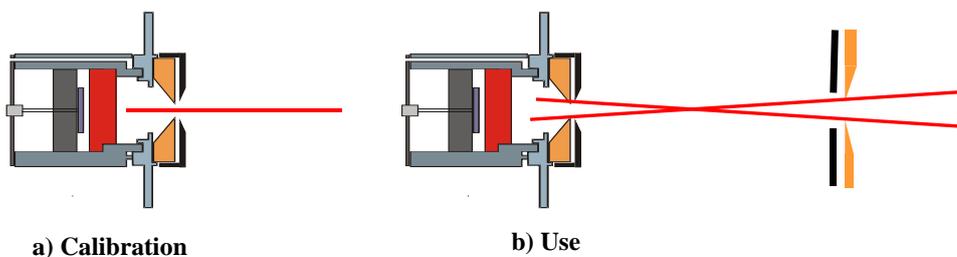
Figure 1: The power method.

The irradiance mode
If the radiometer is calibrated for spectral irradiance responsivity, $s_E(\lambda)$, the photocurrent measured by the radiometer is

$$i = \int s_E(\lambda)E_\lambda(\lambda)d\lambda . \tag{7}$$

The spectral irradiance responsivity of the filter radiometer with mounted aperture is determined by comparison to a trap detector (calibrated *a priori* against a cryogenic radiometer) with a calibrated entrance aperture, defining the effective area of the trap

detector. The spectral irradiance responsivity can be determined with a monochromator-based or a laser-based system.

During measurement, an aperture at known distance from the radiometer aperture is added in front of the blackbody to create the geometric system needed to convert from irradiance to radiance, i.e. to define the solid angle (see Figure 2). However as diffraction losses increase drastically for a decreasing diameter of the blackbody aperture, so the method has been adapted, as below, for determining the temperature of small sources (e.g. HTFPs).
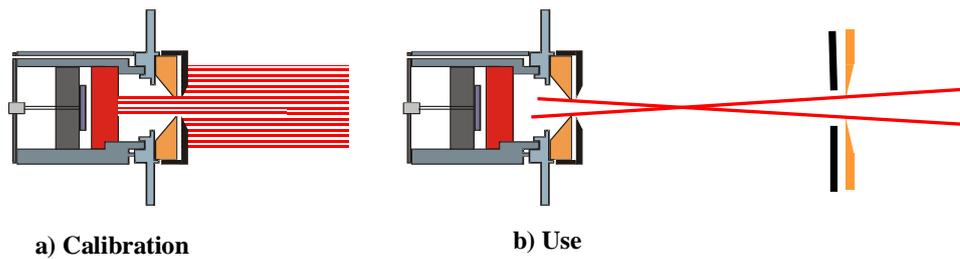
a) Calibration   b) Use

Figure 2: The irradiance method.

Imaging methods

The hybrid method (irradiance mode)
The irradiance approach can be applied to smaller blackbody cavities by introducing a single lens. The calibration is usually performed "in parts", with the irradiance responsivity of the filter radiometer determined as above, and the transmittance of the lens determined separately. An additional known aperture is added to the lens, at a known distance from the radiometer aperture, to form the geometric system for spectral radiance (see Figure 3). Formally, the method can be considered to be equivalent to the irradiance method (above) – but is capable of measuring sources with small apertures. The absolute size-of-source effect must be corrected for. The instrument can also be calibrated for use in radiance mode.

a) Calibration   b) Use
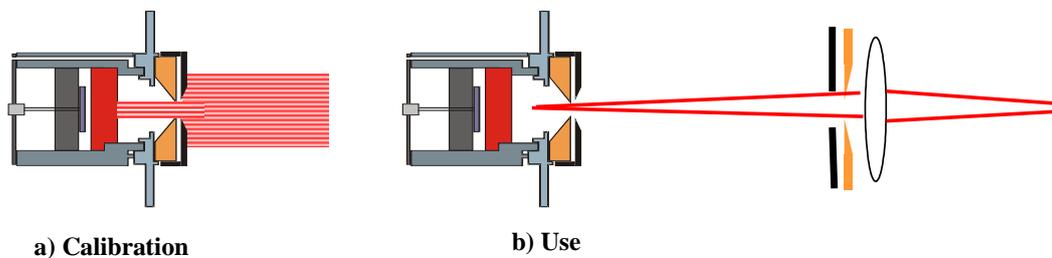
Figure 3: The hybrid method.

The radiance mode

An appropriately designed imaging radiometer can be calibrated traceable to primary units as a filter radiometer (see Figure 4). The more complex optical system of the thermometer (e.g. several lenses and appropriate baffling) can lead to an extremely low size-of-source effect.

If this imaging radiometer, or radiation thermometer, is calibrated for spectral radiance responsivity, $s_L(\lambda)$, the photocurrent measured by the radiometer is

$$i = \int s_L(\lambda)L_\lambda(\lambda)d\lambda . \qquad (8)$$

The calibration of such a system is by comparison with a source of known radiance. The instrument can then determine the blackbody radiance directly.
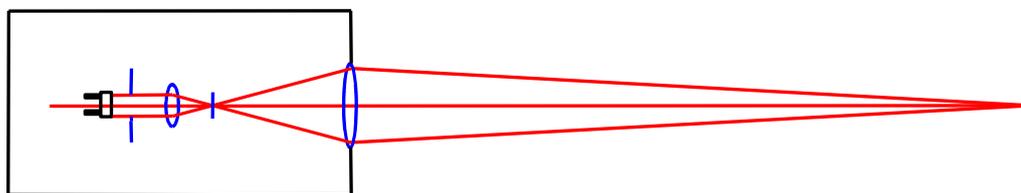
Calibration and Use

Figure 4: The radiance method.

Summary of absolute primary radiometry methods

Several different absolute primary radiometry methods could be employed to generate thermodynamic temperature, directly traceable to SI units. Four have been outlined here for illustrative purposes, but radiometrists should not be constrained by these methods and should use whichever variant their own laboratory circumstances permit.

By comparing ITS-90 with absolute primary radiometry [1, Annex 2], it is clear that for those laboratories capable of radiometry at the highest level, advantage will be gained through realising and disseminating T directly instead of the T_{90} proxy.

More details are to be found in [1, 2, 3, 4, 5] and references therein.

References

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