MEP-K ABSOLUTE PRIMARY RADIOMETRIC THERMOMETRY

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1. Introduction

The determination of thermodynamic temperatures through absolute primary (spectral) radiometric thermometry 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.

2. Blackbody sources

Primary (spectral) radiometric thermometry is based directly on Planck's equation (1). The spectral radiance of an ideal blackbody, $L_{\mathrm{b},\lambda}$[†], that is the power emitted per unit area per solid angle per unit wavelength interval, is given by Planck's law:

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

where T is the thermodynamic temperature, k is the Boltzmann constant, h is the Planck constant, c the speed of light *in vacuo*, and λ is the wavelength *in vacuo*. The unit of the spectral radiance is $\mathrm{W\ m^{-2} sr^{-1}\ nm^{-1}}$.

3. Traceability to SI units

The implementation of absolute primary radiometric thermometry 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.

4. Basic principles of absolute primary radiometric thermometry

The spectral power is determined using a detector of known (absolute) 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

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

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 radiometric thermometry are possible, but all require the following common calibration infrastructure:

- Usually a trap detector calibrated at distinct wavelengths by monochromatic radiation from a laser or monochromator is used as a reference detector, 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.

There are numerous examples of practical implementations of absolute primary radiometric thermometry, each having a slightly different calibration method – examples of these are given in the list of references.

5. Attainable uncertainties with absolute primary radiometry

In order to simplify the uncertainty analysis, incorporating the finite radiometer bandwidth while retaining the thermodynamic basis, the Planck form of the Sakuma–Hattori equation is used to model the signal measured by the radiometer – see document CCT/10-12 and Saunders (2011) for details. This model is written as a function of the mean wavelength, λ_0, and standard deviation, σ, (proportional to the width) of the relative spectral responsivity, and a parameter H, which is proportional to the area under the absolute spectral responsivity curve. Table 1 and Figure 1 give the current best uncertainty components for the laser-based calibration method.

Table 1. Standard uncertainty components for absolute primary radiometry for the case of laser-based radiance responsivity. The parameter *r* is the relative bandwidth ($r = \sigma / \lambda_0$), and the in-use *S* components are those associated with measuring the radiometer signal at the unknown temperature.

Uncertainty Component	**Value (Laser-based system)**
$\boldsymbol{\lambda_0}$ (650 nm)	
Wavelength	0.0003 nm
Drift	0.0003 nm
Total $\boldsymbol{\lambda_0}$	**0.00042 nm**
Total $\boldsymbol{\sigma}$ ($r = 0.01$)	**0.0000042 nm**
H	
Trap detector	0.015%
Aperture area	0.004%
Distance	0.01%
Sphere spatial and angular uniformity	0.025%
Amplifier gain	0.005%
Temperature coefficient of trap	0.002%
Temporal stability of trap	0.013%
Total *H*	**0.034%**
In-use *S*	
SSE (size of source effect)	0.01%
Non-linearity	0.005%
Gain ratios	0.01%
Ambient conditions	0.002%
Drift	0.01%
Repeatability	0.003%
Total in-use *S*	**0.018%**

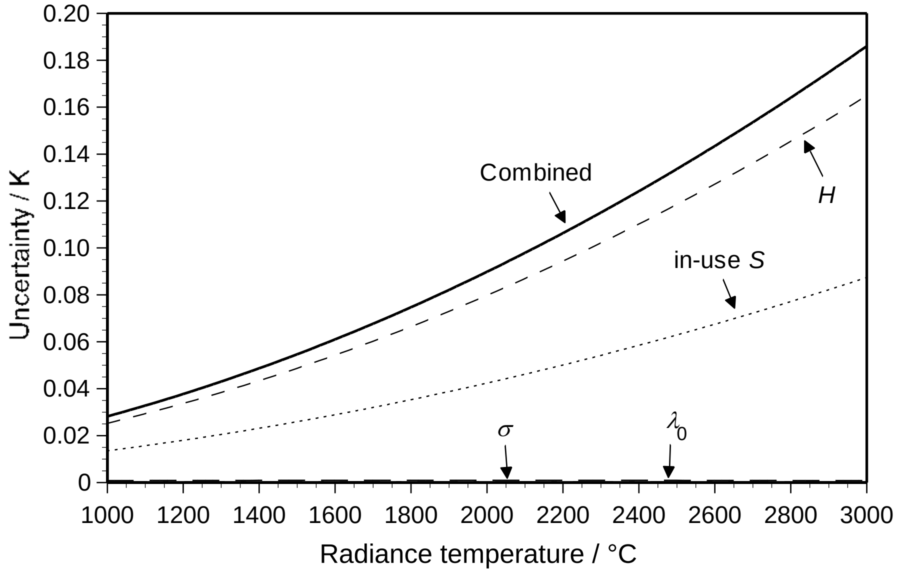

Figure 1. Uncertainty components and combined standard uncertainty for laser-based absolute primary radiometry.

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