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The realization and the dissemination of thermodynamic temperature scales

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Abstract
Since the establishment of the International Temperature Scale of 1990 (ITS-90), much progress has been made in the development of radiometers and blackbody sources. Cryogenic electrical-substitution radiometry is widely used in detector and radiometer calibrations, and stable, high-temperature metal–carbon eutectic blackbodies are under development. Radiation thermometers can be calibrated for absolute radiance responsivity, and blackbody temperatures determined from the amount of optical power without the use of any fixed points to directly measure thermodynamic temperatures. These thermodynamic temperatures can be measured with lower final uncertainties than the ITS-90 derived temperatures, and these developments will directly impact future international temperature scales.

1. Introduction

Temperature can be measured by primary and secondary means [1]. Primary thermometry is defined as determining temperatures using equations of state and physical constants without any adjustable temperature-dependent parameters; some examples are constant-volume gas thermometry [2], speed-of-sound measurements in gases [3] and noise thermometry [4]. Primary measurements based on measurements using gases are limited in temperature range due to deviation of the gas from ideal behaviour and other experimental limitations [5], and noise thermometry is limited due to the long measurement times needed for averaging [6].

Other types of primary thermometers are the total and the spectral radiometers, calibrated using electrical substitution radiometry and used in conjunction with a blackbody. Such systems have been used in the past to determine the Stefan–Boltzmann constant using the wavelength-integrated Planck's radiance law to a relative combined uncertainty of 0.013% [7]. If only a narrow spectral region is selected by the use of spectral filters, then the spectral radiometer can be used to determine the temperatures of blackbodies with the use of Planck's radiation within the spectrally selected region.

Since primary thermometers are not easily transportable and are difficult to use, secondary thermometers have been developed as transfer devices. Because of the difficulties in maintaining primary thermometers for routine calibrations, the International Temperature Scale of 1990 (ITS-90) fixed the phase-transition temperatures of various pure materials based upon the best thermodynamic-temperature determinations at the time of specifying the scale [8]. Secondary interpolating thermometers are based upon these fixed points and require transducers whose changes with temperature are calibrated using primary thermometers.

In the ITS-90, temperatures above the freezing temperature of silver are determined with radiation thermometers calibrated using the Planck radiance law and spectral radiance ratios to one of the Ag-, Au- or Cu-freezing temperature blackbodies. However, due to the use of spectral radiance ratios, the temperature uncertainties of the ITS-90 increase as the square of the temperature ratios, and recent acoustic-thermometry measurements have also shown that the temperatures used in the radiance ratios in determining the Ag- and Au-fixed point temperatures could be in error [9]. Furthermore, as radiation thermometry is improved, the ITS-90 scale may be non-unique due to the choice of any one of the three fixed points as the basis for the scale.

Another strong impetus for the development of direct thermodynamic temperature measurements traceable to optical power has been the development of metal–carbon eutectic blackbodies [10]. A temperature scale could be generated from the use of these eutectics as interpolation points to be used by the radiation thermometer. Such a scheme would simplify radiation thermometer calibrations, especially transfer to the secondary laboratories. Thus far, one of the most pressing issues has been the lack of a sufficient number of thermodynamic temperature determinations of the metal–carbon eutectic transition temperatures at different national measurement institutes.

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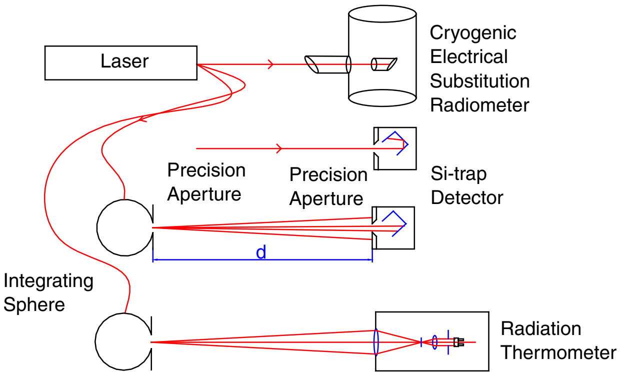

Figure 1. The sequence of calibrations to realize thermodynamic temperatures at NIST.

This paper will discuss how thermodynamic temperatures using detector-based radiation thermometers are realized. The techniques used at NIST for the realization of thermodynamic temperatures are described. We demonstrate that the total uncertainties in the thermodynamic temperatures are comparable to those in the ITS-90. Since well-characterized and stable radiometers are needed, the development of stable radiation thermometers with low size-of-source effect (SSE) is discussed. Possible detector-based replacements for the fixed-points using laser-diode-illuminated integrating spheres are also discussed.

2. Experimental procedure

2.1. Radiometric calibration

The basis of the calibration of the radiation thermometer at NIST is the measurement of optical power using the cryogenic electrical substitution radiometer [11]. The steps of the calibrations are shown in figure 1.

Briefly, the NIST radiation thermometer, called the Absolute Pyrometer 1 (AP1), is calibrated against the cryogenic radiometer using silicon trap detectors which are calibrated from power responsivity at selected wavelengths. The full responsivity is then determined by interpolation. The spatial uniformity of the trap detector is utilized to obtain irradiance responsivity from the power responsivity in conjunction with a precision aperture. If the geometric parameters such as the aperture area and the distance between the integrating sphere and the trap detector are known, then the spectral irradiance of the sphere source can be assigned. If the area of the precision aperture on the integrating sphere is known, then the spectral radiance of the sphere can be determined. Radiation thermometers are calibrated as a system without separately measuring the transmittance of the lenses and characteristics of the components. The calibrations are performed at many different wavelengths with stabilized lasers. At NIST, these calibrations are performed in the facility called the NIST Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) [12].

2.2. Application of the radiometric calibration

Since the laser wavelengths and the instrument spectral shape can be determined with low uncertainties, the radiance responsivity of the radiation thermometer can be determined at SIRCUS with lower uncertainties than those from a monochromator-based facility. Figure 2 shows the radiance responsivity of the NIST radiation thermometer calibrated in the SIRCUS facility along with the Planck radiance at 1337.33 K.

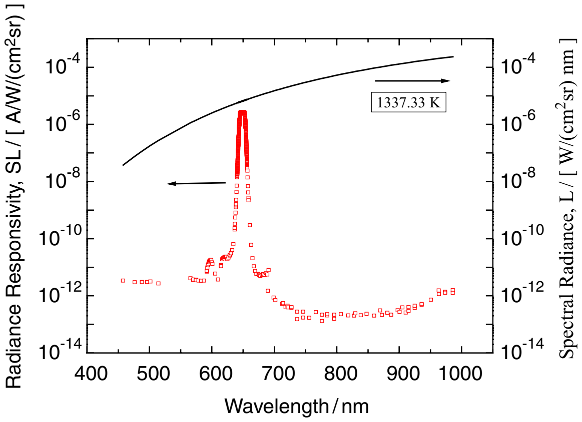

Figure 2. The absolute radiance responsivity of the AP1 along with the spectral radiance of a Planckian radiator at 1337.33 K.

The thermodynamic temperatures of blackbodies are found from the radiance responsivity and Planck's law by the use of

$$i_{\mathrm{c}} = \int S_L \cdot \varepsilon(\lambda)\, L(\lambda, T)\, \mathrm{d}\lambda, \tag{1}$$

where i_{c} is the calculated photocurrent, S_L is the absolute radiance responsivity, $L(\lambda, T)$ is the Planck radiance and $\varepsilon(\lambda)$ is the spectral emissivity. The Planck radiance is given by

$$L(\lambda, T) = \frac{c_{1L}}{n^2\lambda^5(\exp(h/(n\lambda ckT)) - 1)}, \tag{2}$$

where c_{1L} is the first radiation constant, T is the thermodynamic temperature, λ is the wavelength of the radiation, n is the refractive index of air, h is the Planck constant, c is the speed of light in a vacuum and k is the Boltzmann constant. For these calculations, the CODATA values [13] for the constants and the refractive index of air of $n = 1.000\,29$ were used. The spectral emissivity is set to 1.0 and corrections are applied for the specific, measured blackbody.

From the use of equations (1) and (2), a relationship between photocurrent and temperature can be established as shown in figure 3. Since the radiance responsivity calibrations were performed at specified gain settings of the transimpedance amplifier, the measurements at different gain settings should be scaled to the calibration setting.

For determining the temperatures of blackbodies, the measured signals are corrected prior to the application of equation (1) using

$$i = G\frac{\sigma}{\varepsilon} i_{\mathrm{m}}, \tag{3}$$

where i_{m} is the measured photocurrent, i is the corrected photocurrent, G is the gain correction, ε is the emissivity of the measured blackbody cavity and σ is the SSE correction. The calculated photocurrents are within the linear regime of the Si photodiode used in the AP1.

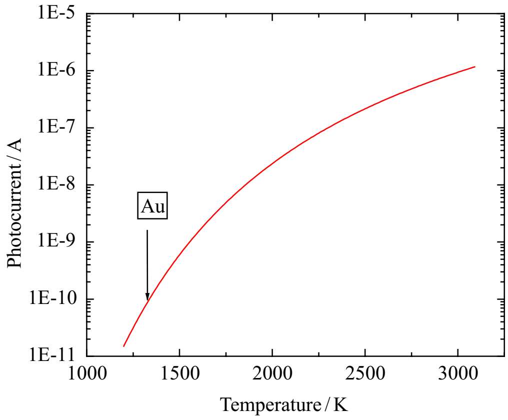

Figure 3. The temperature–photocurrent relationship as determined from the use of equations (1) and (2).

2.3. Validation of radiometric calibration using an ITS-90 fixed-point blackbody

A critical test of the radiometric calibration is the measurement of one of the ITS-90 fixed-point blackbodies. Due to the high aspect ratio (length to diameter) of the cavity along with the temperature uniformity provided by the molten metal, a freezing-point blackbody has high emissivity (0.9996) along with long-term stability of the freezing temperature. If care is taken to use high-purity metals, then the repeatability of the freezing-point temperatures is well established.

The AP1 has been used to measure the thermodynamic temperature of the freezing point of Au to determine the agreement with the current ITS-90 assignments. The thermodynamic temperatures of the Ag- and Au-freezing temperatures were determined to be 1234.956 K ± 0.110 K ($k = 2$) and 1337.344 K ± 0.129 K ($k = 2$), differing from the ITS-90 assigned values of 1234.93 K ± 0.080 K ($k = 2$) and 1337.33 K ± 0.090 K ($k = 2$) or $T - T_{90}$ of 26 mK and 14 mK, respectively. The differences are found to be within the combined uncertainties.

3. New designs of radiation thermometers

One of the barriers to thermodynamic temperature disseminations is the need for stable, well-characterized radiation thermometers. Additional radiation thermometers such as the Absolute Pyrometer 2 (AP2), shown in figure 4, have been constructed at NIST to achieve the objectives of small field-of-view, low SSE and long-term stability. The AP2 utilizes a temperature-stabilized filter and detector combination for long-term stability. The filter is constructed using ion-assisted deposition to form a hard, humidity-resistant coating on a wedged substrate to reduce the fringing effects. The AP2 also utilizes a low-scatter objective lens with a Lyot stop to reduce the SSE.

Since the SSE can result in one of the dominating sources of uncertainties in comparisons of sources, a systematic study of the contributions to the SSE was performed [14]. The study showed that the scatter from the objective lens could be the dominating source of the SSE and that re-imaging the objective lens onto a Lyot stop could lead to a reduction in the SSE by almost a factor of 20 as shown in figure 5.

4. Impact on future temperature scale

The need for developing a detector-based thermodynamic temperature scale is driven by the desire to reduce uncertainties in disseminated temperatures and by the need for the measurements of new metal–carbon eutectics [15]. If the thermodynamic temperatures of the selected metal–carbon eutectics from 1500 K to 3200 K can be measured with sufficiently low uncertainties, then the next international temperature scale could be disseminated using these calibrated fixed-points with almost a factor of five reduction in the uncertainties [16]. Although the metal–carbon eutectic blackbodies have been shown to be stable, the thermodynamic-temperature assignments require international efforts to achieve the lowest uncertainties. In recognition of such a need, the Working Group 5 of the Consultative Committee on Thermometry (CCT) has drafted a document [17] with the following three-phase work plan for

i. assessing the absolute thermometry capability of participating laboratories,
ii. assessing the reproducibility of eutectic cells and
iii. assigning thermodynamic temperatures,

with the work to be finished in the next seven years. The need for an improved temperature scale is also recognized by the CCT, passing the recommendation, T-2 (2005), 'that national laboratories initiate and continue experiments to determine values of thermodynamic temperatures…' [18].

5. Detector-based validation sources

For widespread practice and acceptance of detector-based thermodynamic temperature measurements, the calibration facilities should be relatively simple and inexpensive. Since large laser-based facilities can be prohibitively expensive for some of the small national measurement institutes (NMI) to develop and maintain for radiometer calibrations, it might be possible to utilize small, tunable-diode lasers (TDL) to develop spectral sources for detector-based radiation thermometry as shown in figure 6. An additional benefit is that one of the major difficulties in disseminating the low uncertainties achievable with modern cryogenic radiometers is that filter radiometers and radiation thermometers can change due to environmental and ageing effects in the filter transmittance. Such portable radiance calibrators could be used for on-site calibrations. Since hermetically-sealed silicon diodes have demonstrated long-term stability of $< 0.01\%$/year at 650 nm over a ten-year period [19], it might be possible to use these detectors in conjunction with TDLs to develop spectral sources with similar long-term stability. Such sources have the potential to replace the metal fixed-points which have been thus far used to measure the stability of the radiation thermometers.

These TDL radiance sources would be fitted with precision apertures to determine the spectral irradiance using a Si-trap detector. The calculated spectral radiance can then be used to calibrate the monitor diode. Any changes in the sphere throughput or diode-laser output can then be scaled by the signal from the monitor diode with low uncertainties.

Since the TDL can only be operated over a 10 nm to 15 nm wavelength region, the spectral scan over a wide

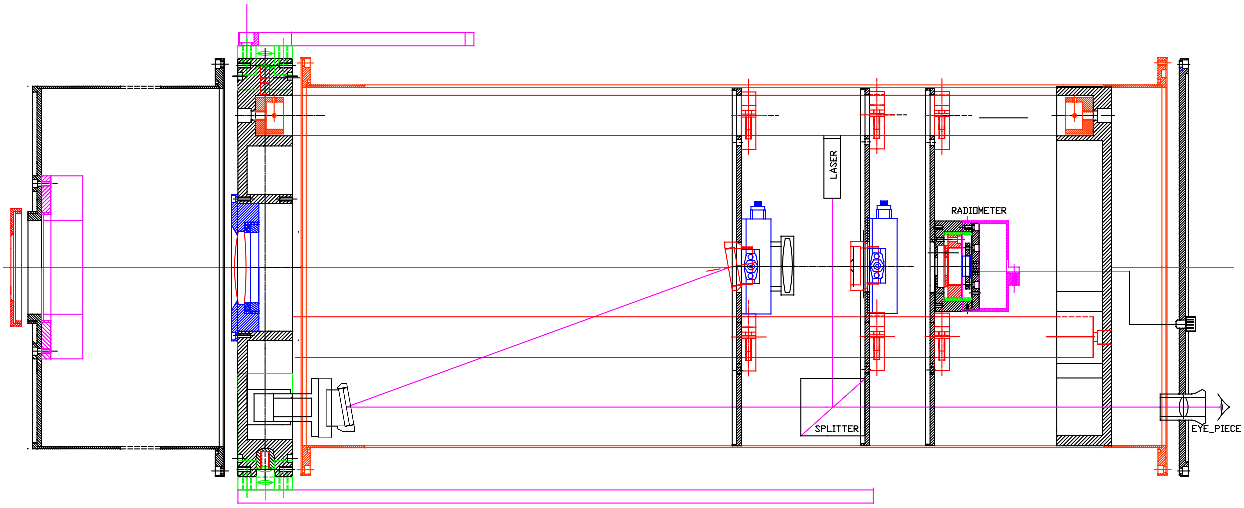

Figure 4. The design of the NIST AP2 with $< 5 \times 10^{-5}$ SSE with a 50 mm diameter source.

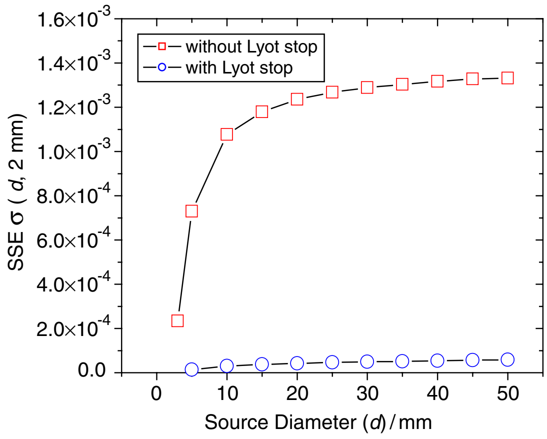

Figure 5. The SSE measured with and without the Lyot stop.

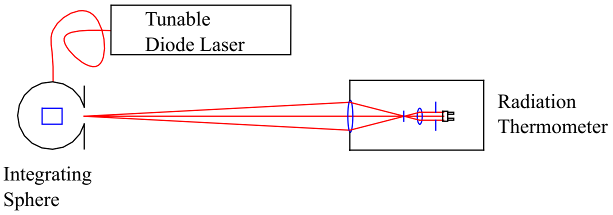

Figure 6. Portable detector-based radiance source using TDL. The small square on the sphere denotes the reference-monitor photodiode.

spectral region could be performed using a monochromator-based facility and then the lower uncertainty spectral scans can be performed in the peak spectral region. The out-of-band radiance responsivity could also be measured with the monochromator-based facility with a broad bandpass to enhance the signal-to-noise of the measurements.

6. Conclusions

The detector-based calibration of radiation thermometers to directly determine thermodynamic temperatures not based on any blackbodies was described. Radiation thermometers have been constructed and used to determine the freezing temperature of the ITS-90 fixed-point blackbodies with agreement in the measured temperatures within the combined uncertainties. New radiation thermometer designs were proposed to improve the long-term stability and reduce the SSE. The international consensus on the need for further thermodynamic temperature measurements was discussed. Compact radiance sources which rely on stable Si photodiodes could be developed to realize the detector-based radiance temperature scale at small NMIs.

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