The Realization and the Dissemination of Thermodynamic Temperature Scales

H. W. Yoon
NIST, Gaithersburg, MD, USA

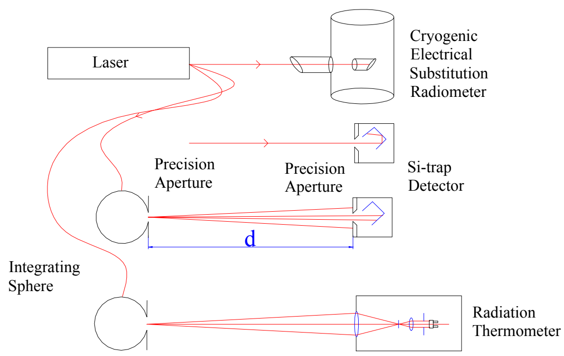
Abstract. Since the establishment of the International Temperature Scale of 1990 (ITS-90), much progress has been made in the development of radiometers and blackbody sources. Cryogenic electrical-substitution radiometry is widely used in detector and radiometer calibrations, and stable, high-temperature 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. These temperatures can be measured with lower final uncertainties than the ITS-90 derived temperatures. Just as the definition the photometric base unit, the candela, has been changed to one of optical power, the thermodynamic temperatures can be directly realized from optical power and length units. Because of these developments, any future international temperature scale should be revised so that a thermodynamic temperature scale can be directly disseminated with transfer standard sources or radiation thermometers.

Introduction

In the ITS-90, temperatures above the freezing temperature of silver are determined with radiation thermometers calibrated using spectral radiance ratios to one of the Ag-, Au- or Cu-freezing temperature blackbodies and the Planck radiance law. 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. 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. 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 the different NMIs.

This talk will review the different techniques for realizing thermodynamic temperature and why detector-based radiance temperature has proven to be so useful. Some of the smaller NMIs are beginning to develop the capabilities for such measurements. The techniques used at NIST for the realization of thermodynamic temperatures will be reviewed. The development of stable radiation thermometers with low size-of-source effect will be discussed. Possible detector-based replacements for the fixed-points using light-emitting diodes will be discussed.



Experimental Setup

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

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

The traceability to the length unit is necessary for the measurements of distances and the aperture areas in the second and the third steps in the realization.

One of the barriers to thermodynamic temperature dissemination is the need for radiometric characterizations of radiation thermometers. Radiation thermometers have been constructed at NIST to achieve the desired imaging, low size-of-source effect, and long-term stability. Figure 2 shows the schematic of one of the NIST radiation thermometer designs.

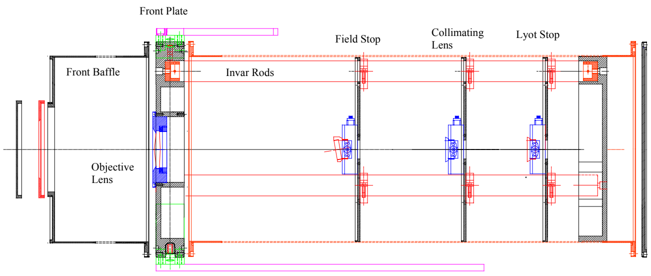


Figure 2. NIST Absolute Pyrometer 2 (AP2) design utilizing Invar rods for structural stability.

The AP2 utilizes temperature-stabilized filters and detectors for long-term stability. The AP2 also utilizes a low-scatter objective lens with a Lyot stop to reduce the size-of-source effect (SSE). A comparison of the radiation thermometer with and without the Lyot stop is shown in Fig. 3.

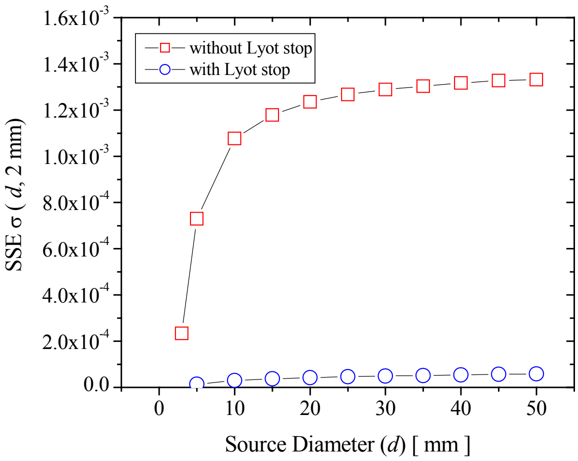


Figure 3. The SSE measured with and without the Lyot stop.

Irradiance Mode Radiation Thermometers

Since the procedure for the detector-based candela realization can be also used for the characterization of irradiance mode filter radiometers, these filter radiometers can also be used to measure thermodynamic temperatures. Some of the NMIs use a monochromator-based facility since laser-based spectral irradiance or radiance responsivity calibration facilities can be prohibitively expensive.

The difficulties in utilizing monochromator-based calibrations will be discussed. The non-imaging filter radiometer also suffers from a "size-of-source" effect arising from the uncertainties in the diffraction corrections from the source aperture when used with fixed-point cavities with small openings.

Detector-based Validation Sources

One of the major difficulties in disseminating the low uncertainties achievable with modern cryogenic radiometers is that filter radiometers and radiation thermometers change due to environmental and aging effects primarily due to the change in the filter transmittance. Hermetically sealed silicon diodes have demonstrated long-term stability of < 0.02 % from 450 nm to 900 nm over a ten-year period and it might be possible to use these detectors in conjunction with light-emitting diodes (LED) 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. Signal-to-noise comparisons of the LED sources with the Au freezing-temperature blackbody will be discussed.

Discussion

The needs for developing detector-based thermodynamic temperatures are driven by the desire to reduce the uncertainties in the disseminated temperatures and for the measurements of new metal-carbon eutectics. In recognition of such a need, the Consultative Committee on Temperature passed a recommendation, T-2 (2005), "that national laboratories initiate and continue experiments to determine values of thermodynamic temperatures…".