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Comparison of a Detector-Based Near-IR Radiance Scale to an ITS-90 Calibrated Radiation Thermometer

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Abstract Integrating-sphere-input InGaAs radiometers (ISIR) have been developed at the National Institute of Standards and Technology (NIST) to extend the detector-based calibration of radiation thermometers from the Si range to the near-infrared (NIR). These near-infrared radiometers are used to determine the reference spectral irradiance responsivity scale based on the primary-standard cryogenic radiometer. The irradiance responsivity scale is then propagated to spectral radiance at the exit port of an integrating sphere. The near-infrared radiation thermometer (NIRT) is calibrated using this detector-based radiance scale. The first phase of this research work is reported here where the relative spectral radiance responsivity of the NIRT has been determined using a monochromator-based system. Thereafter, the relative spectral responsivity of the NIRT is converted into an absolute responsivity using the radiances from the Zn fixed point blackbody. Then, the NIRT is used to extend these calibrations for temperature measurements between 157 °C and 1000 °C. The NIRT has also been calibrated in this temperature range using the five, fixed point blackbodies of the ITS-90. The two different calibration approaches for temperature measurements are compared.

Keywords InGaAs detector · Irradiance responsivity · ITS-90 · Near-infrared · Optical radiation · Radiance · Radiance temperature · Radiation thermometer · Spectral responsivity · Temperature scales

1 Introduction

Although thermodynamic radiation thermometry in the wavelength range of Si detectors is well established, the rapidly decreasing spectral radiances with decreasing

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temperatures restrict the temperature range of measurements with Si-based radiation thermometers. To extend the temperature range to lower temperatures, radiance temperature measurements must be performed with near-infrared detectors. Such extension to lower temperatures has two objectives: (1) the comparisons of the radiometric scale against the calibrations obtained using the International Temperature Scale of 1990 (ITS-90) which would validate the infrared responsivity scale for use in satellite sensors for climate change applications; and (2) if the uncertainties of the thermodynamic radiation thermometry were sufficiently low, then these measurements could be used to determine systematic differences between fixed points of the ITS-90. Although the lowest uncertainties are better achieved with the use of laser-based facilities, the process of radiometric transfer can still be examined using traditional monochromator-based facilities with larger uncertainties.

Near-infrared radiometers developed at the National Institute of Standards and Technology (NIST) are used to realize a reference spectral irradiance responsivity scale at the Spectral Comparator Facility (SCF) which is traceable to the primary-standard cryogenic radiometer. The irradiance responsivity scale is then propagated to spectral radiance at the exit port of a sphere source. A separate monochromator setup is used for this scale transfer. A near-infrared radiation thermometer (NIRT) is calibrated against this detector-based radiance scale. The first phase of this research work is described here where the relative spectral radiance responsivity of the NIRT has been determined using the separate monochromator setup. Thereafter, the relative spectral responsivity of the NIRT is converted into an absolute responsivity using the radiances from the Zn fixed point blackbody. Then, the NIRT is used to extend these calibrations for temperature measurements between 157 °C and 1000 °C. The NIRT has also been calibrated in this temperature range using the five, fixed point blackbodies of the ITS-90. The two different calibration approaches for temperature measurements are compared.

2 Reference Near-Infrared Radiometers

Integrating-sphere-input InGaAs radiometers (ISIR) have been developed at the NIST [1] to realize a low-uncertainty reference irradiance responsivity scale for the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources facility (SIRCUS) [2]. Briefly, the ISIR is a sphere-input detector with a unique geometrical arrangement which can convert the radiant-power responsivity obtained from the primary-standard cryogenic radiometer into irradiance responsivity. The scale conversion uncertainty is dominated by the two largest uncertainty components produced by the ISIR itself: (1) the spatial nonuniformity of responsivity in the power measurement mode and (2) the angular responsivity deviation from the cosine function in the irradiance measurement mode. These two uncertainty components are kept smaller than 0.05 % ($k = 2$) [1] to avoid limiting the uncertainty of the spectral radiance between 1500 nm and 1600 nm derived from the reference irradiance responsivity scale. These small uncertainty components are equal to the uncertainties of Si tunnel-trap detectors [3] used for the visible wavelength range and are the results of a tilted input aperture (relative to the sphere axis) and four symmetrically positioned detectors (around the

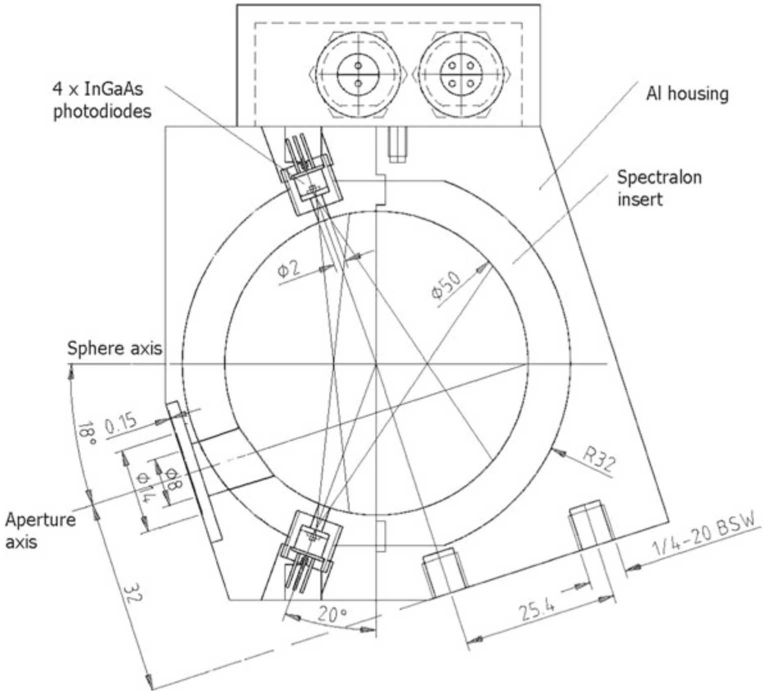

Fig. 1 Cross section of the sphere-InGaAs (ISIR) reference radiometer

incident beam spot in the sphere). The cross section of one of the two ISIRs is shown in Fig. 1. The tilt angle of the aperture axis is 6° for the first and 18° for the second ISIR. The tilt was necessary to keep the reflected radiation inside the sphere after the first bounce of the incident radiation. If the specular reflection escapes through the entrance port, this results in a flattened angular response. At 18°, the first back reflection from the sphere wall is entirely trapped since it cannot escape through the input aperture as is possible with the traditional entrance-port geometry where the opening is perpendicular to the geometric center. The housing is temperature controlled with a thermoelectric (TE) cooler/heater attached to the back of the Al-housing of the ISIR. A heat sink is attached to the back side of the TE cooler/heater. The four parallel connected 1 mm diameter InGaAs detectors are selected for an equal shunt resistance of 200 MΩ. The detectors are symmetrically positioned around the incident beam produced "hot" spot such that they cannot see each other. The detectors are temperature stabilized at the 26 °C temperature of the ISIR-housing through the thermal conductance from the exterior metal cases of the detectors.

With this design, the ISIR characteristics will not limit the lowest achievable uncertainty of the reference irradiance responsivity scale realization. The uncertainty required for the spectral radiance responsivity (which is directly derived from the spectral irradiance responsivity) between 1500 nm and 1600 nm is 0.05 % ($k = 2$) in order to obtain a thermodynamic temperature uncertainty of 10 mK ($k = 2$) at 157 °C, the freezing temperature of the In fixed point blackbody. This uncertainty can

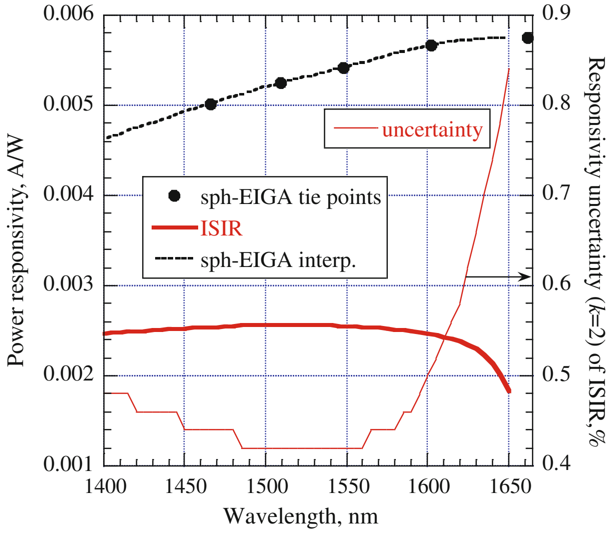

Fig. 2 Spectral power responsivity of the ISIR based on the interpolated SIRCUS tie points of a sphere-input extended-InGaAs (sph-EIGA) detector

be achieved in the SIRCUS facility with the new ISIR where similar scale derivations have been performed in the silicon wavelength range [4]. However, since the full SIRCUS calibrations could not be accomplished for this work, we show here a simple monochromator-based method to determine the relative spectral radiance responsivity of a NIRT.

One of the critical aspects of using integrating sphere systems is the attenuation of the input signal due to the presence of the sphere. In spite of the large signal attenuation caused by the input sphere, the noise-equivalent power (NEP) of the ISIR is $5\,\mathrm{pW}\cdot\mathrm{Hz}^{-1/2}$. This low NEP makes it possible to perform our spectral calibrations at the output of a traditional monochromator.

3 Monochromator Used for Spectral Responsivity Calibrations

A 1 m single-grating monochromator, McPherson 2051[1] was used to calibrate the NIRT using the 18°-tilt ISIR. This monochromator is not part of the SCF where the ISIR was calibrated. (The ISIR at this time could not be calibrated at the SIRCUS facility.) The ISIR was calibrated against two reference responsivity scales (using similar SCF scale-derivation steps) with 0.42 % ($k = 2$) uncertainty. The first scale was the spectral power responsivity interpolated from the absolute tie points of a sphere-input extended-InGaAs transfer radiometer (sph-EIGA) [5] as shown (with full circles) in Fig. 2. The tie points were derived from the primary-standard cryogenic radiometer

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment are necessarily the best available for the purpose.

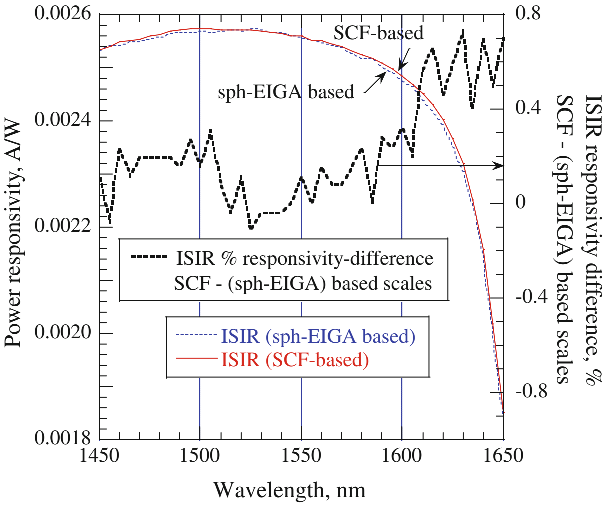

Fig. 3 SCF-determined and SIRCUS tie-points-corrected spectral responsivity of the ISIR

in the power measurement mode. The second reference scale was the (SCF-based) near-infrared responsivity scale which is the officially reported scale of the SCF. This scale was also derived from the cryogenic radiometer using different, but also temperature-controlled InGaAs detectors. The two spectral power responsivities of the ISIR (as determined from the two reference responsivity scales) are shown in Fig. 3. The responsivity difference of the two differently propagated scales is also shown in the graph. The differences between 1510 nm and 1580 nm (where the plateau of the NIRT is) are within +0.2 % and −0.1 %.

To convert the spectral power responsivity of the ISIR radiometer into spectral irradiance responsivity, an aperture with a measured area is attached to the entrance port of the radiometer. The area was determined using the knowledge of the area of a reference aperture by aperture substitution (in the same plane) in the front of a silicon trap detector. The irradiance source was an integrating sphere (source sphere) illuminated with a stabilized HeNe laser. The area determined for the ISIR aperture was 9.9806 mm^2. The expanded uncertainty of this aperture-area determination was 0.1 % ($k = 2$). The aperture area times the spectral power responsivity is the spectral irradiance responsivity of the ISIR.

The relative spectral radiance responsivity of the NIRT was calibrated from the spectral irradiance responsivity of the ISIR. Before the calibration, the uniformity of the irradiance in the aperture plane of the ISIR was evaluated. Figure 4 shows the normalized signals for both the X and Y ISIR-scans. The obtained curves are close to the theoretical (desired) $\cos^4\theta$ function. The angle θ is between the line connecting the ISIR aperture center to the source-sphere aperture center and the normal angle of the source-sphere aperture. The scans were made at the same spatial separation between the source sphere and the ISIR sphere. The exit-port radiance was determined from the irradiance calculated from the irradiance responsivity of the ISIR.

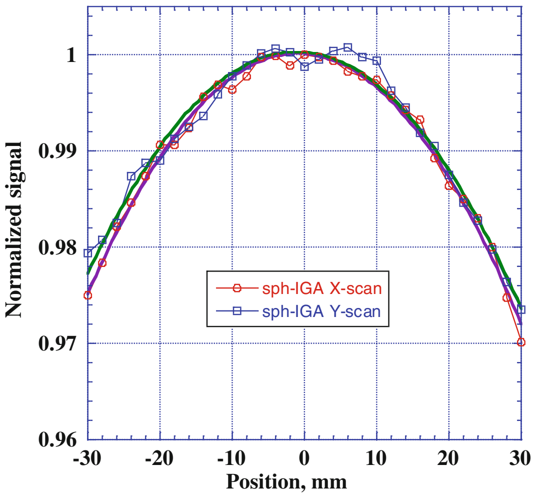

Fig. 4 Normalized signals for both the *X* and *Y* ISIR scans relative to the normal of the sphere-source aperture. The *curves* are close to the theoretical (desired) $\cos^4\theta$ function

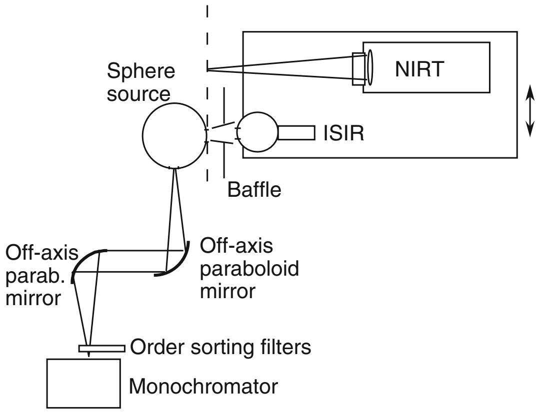

Fig. 5 Optical arrangement for the NIRT relative spectral responsivity measurement

The equation for the transfer of the relative spectral responsivity is

$$s(\lambda)_{\text{NIRT}} = \frac{I(\lambda)_{\text{NIRT}}}{I(\lambda)_{\text{SIGA}}} s(\lambda)_{\text{SIGA}} \tag{1}$$

where $s(\lambda)_{\text{NIRT}}$ is the relative spectral responsivity of the NIRT, $I(\lambda)_{\text{NIRT}}$ is the output current of the NIRT, $I(\lambda)_{\text{SIGA}}$ is the output current of the ISIR, and $s(\lambda)_{\text{SIGA}}$ is the relative spectral responsivity of the ISIR.

To avoid the significant spectral responsivity errors when the NIRT operates in the direct radiance measurement mode (imaging the exit slit of the monochromator), a sphere source-based calibration scheme, shown in Fig. 5, was used. These errors, resulting from the direct imaging of the monochromator exit slits, can be introduced from both the spectral, spatial and angular nonuniformities at the exit slits. These deviations can lead to a shift of the relative spectral responsivities as compared to that measured using a Lambertian source such as an integrating sphere. The radiation at

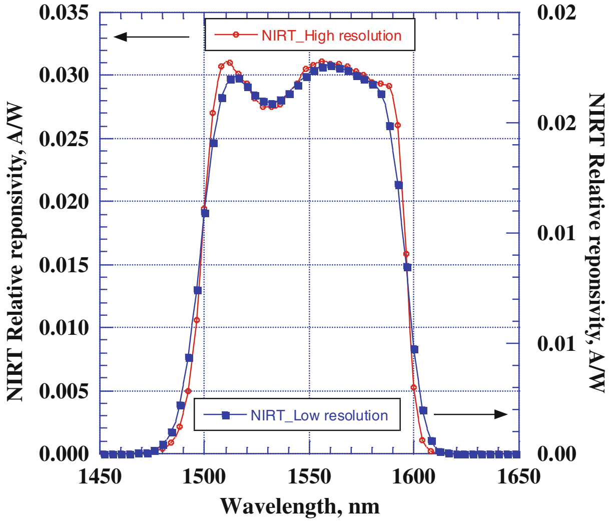

Fig. 6 Relative spectral responsivity of the NIRT measured with a small and a large slit-width using two different Y-scales for the two measurements

the exit slit of the monochromator, through order sorting filters, was introduced into an integrating sphere using off-axis paraboloid mirrors. Both the NIRT and the ISIR were mounted on an X–Y detector moving stage. With the remote-controlled moving stage, the NIRT was substituted for the ISIR. The target spot of the NIRT was positioned within the exit port of the sphere source. The ISIR was used to measure the irradiance from the exit port with a baffle in front of the ISIR aperture. The relative spectral responsivities were measured with two different slit-widths to illustrate the effect of the optical bandwidth for the curve shape. The width of the wider slit was 2.5 mm resulting in an optical bandwidth of 10 nm. The smaller slit-width was set at 0.4 mm leading to a bandwidth of 1.6 nm. During these relative responsivity measurements, the monochromator was scanned between 1450 nm and 1650 nm using 2 nm wavelength increments. The wavelength uncertainty ($k = 1$) was 0.05 nm. Figure 6 shows that the resolution of the relative spectral radiance responsivity is greater when the monochromator is used with a smaller slit-width. In this case, the structures/details of the NIRT responsivity curve are measured. Since the curve shapes are different with the two different slit-widths, care should be taken when selecting the wavelength for the absolute tie point to convert the relative curve into absolute radiance responsivity.

4 Absolute Responsivity Tie Point

The absolute conversion from the relative spectral radiance responsivity of the NIRT into absolute responsivity can be made in two different ways. One way to convert the relative spectral radiance responsivity of the NIRT into absolute responsivity is to apply an absolute responsivity tie point at a single wavelength. The tie point(s) can be made using single-mode stabilized laser(s) introduced into a source sphere. The lasers can be tuned to 1520 nm or 1545 nm where the NIRT relative responsivity does not change with the monochromator slit-width. The exit-port radiance of the sphere source can be derived from the irradiance responsivity of the ISIR if the geometry of this flux transfer is accurately known. This work with lasers will be performed at the SIRCUS facility at a later time.

At present, a second method has been applied. The determination of the absolute calibration factor(s) that give the tie point(s) to convert the NIRT relative spectral responsivity into absolute responsivity was derived from a Zn fixed point blackbody measurement. The spectral radiance responsivity of the NIRT is

$$R(\lambda)_{\mathrm{NIRT}} = \frac{I_{\mathrm{Total}}}{\int s(\lambda)_{\mathrm{NIRT}}\, L(\lambda, T_{\mathrm{Zn}})\mathrm{d}\lambda} s(\lambda)_{\mathrm{NIRT}} \tag{2}$$

where I_{Total} is the total current of the NIRT and $L(\lambda, T_{\mathrm{Zn}})$ is the radiance of the Zn fixed point blackbody. The absolute calibration factor derived from the Zn fixed point is 1.4865 for the relative curve measured with the higher resolution and 2.6170 for the relative curve measured with the lower resolution. Since the higher resolution spectral radiance responsivity curve of the NIRT (converted into absolute) describes the actual spectral responsivity better than the lower resolution curve, it will be used to extend this calibration method for the measurement of blackbody temperatures between the In point (429.7485 K) and the Ag point (1234.93 K). Figure 7 shows the measured signal (photocurrent) versus blackbody temperature on a logarithmic scale. The graph also shows that the NIRT signals, calculated for the other four fixed point blackbody temperatures from the absolute spectral radiance responsivity, agree with the five signals

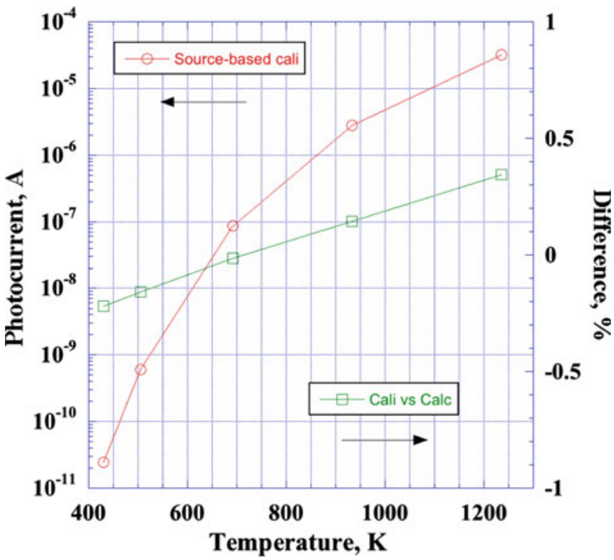

Fig. 7 NIRT-measured signals versus temperature; agreement of the calculated NIRT signals (from the absolute spectral radiance responsivity) to the measured NIRT signals of five fixed point blackbodies

measured earlier by the NIRT on the same five fixed point blackbodies. The obtained signal difference between the calculated and measured values at the five blackbody temperatures is slightly temperature dependent. The temperature dependence of the difference depends on the uncertainty of the NIRT relative spectral radiance responsivity determination which is slightly larger than the 0.42 % ($k = 2$) responsivity uncertainty of the ISIR. The plan is to improve this uncertainty at the following SIRCUS calibrations to the 0.05 % ($k = 2$) level to obtain the required 10 mK ($k = 2$) uncertainty at 157 °C. Using the discussed simple and fast monochromator-based spectral responsivity calibrations, the SIRCUS-based unique and time-consuming absolute responsivity calibrations may not be needed for the overall wavelength range of the NIRT. Although our calibrations were performed with higher measurement uncertainties, the signal differences shown in Fig. 7 verify a reasonable agreement (<0.5 % in current over this wide temperature range) within the combined uncertainties between the method discussed here and the ITS-90-based calibration methods.

5 Conclusions

A monochromator-based calibration method was described to determine the relative spectral radiance responsivity of a NIRT against a sphere-input InGaAs (ISIR) reference detector. The relative spectral responsivity of the NIRT is then converted into an absolute spectral responsivity by measuring the radiation from a Zn fixed point blackbody. Using the absolute spectral radiance responsivity of the NIRT, the temperature calibrations were extended to blackbody temperatures between the In fixed point and the Ag fixed point. The NIRT signal differences obtained between the calibration method described here and the ITS-90-based calibrations are in agreement with <0.5 % in current over this wide temperature range.

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