Metrologia **49** (2012) S112–S117 doi:10.1088/0026-1394/49/2/S112

Extension of the NIST spectral power-responsivity calibration service to 2500 nm

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Received 1 September 2011, in final form 18 November 2011
Published 2 March 2012
Online at stacks.iop.org/Met/49/S112

Abstract

The National Institute of Standards and Technology (NIST) is working to extend the upper wavelength limit of the spectral power-responsivity calibration service from 1800 nm to 2500 nm. This extension is based on extended-InGaAs (EIGA) transfer- and working-standard radiometers and low-NEP pyroelectric transfer-standard detectors. The scale is traceable to the electrical-substitution cryogenic radiometer through the transfer-standard EIGA radiometers. The total uncertainty of the extended-responsivity reference scale (realized on four EIGA working-standard radiometers) is 1% ($k = 2$). The transfer of the reference scale from one of the four working standards to a test EIGA radiometer in direct-current (dc) measurement mode is described. The uncertainty of the transferred scale is 1.6% ($k = 2$) between 1200 nm and 2300 nm. The transfer was performed on the NIST Spectral Comparator Facility (SCF) without any modifications to the SCF. The EIGA radiometers have been characterized for spatial-response uniformity, temperature-dependent spectral responsivity, linearity, noise, long-term and short-term temporal stability. The preliminary results show that EIGA radiometers can be used over the spectral range between 900 nm and 2500 nm in dc mode and could eventually replace the regular InGaAs detectors in the SCF measurements. The total uncertainty budget for these measurements is discussed.

(Some figures may appear in colour only in the online journal)

1. Introduction

The effort to extend the spectral power-responsivity calibration service to longer wavelengths from 1800 nm to 2500 nm is motivated by the measurement needs of the remote sensing and the photovoltaic (PV) communities. The measurement needs arise primarily from the substantial solar spectral irradiance that is still present in the spectral region from 1800 nm to 2500 nm, and the need to calibrate PV cells which can be sensitive in this spectral region. In remote sensing, the calibration requirements at these wavelengths arise from the need to measure the reflected solar radiation in this spectral region.

Although spectral radiance and irradiance standard sources can be obtained with calibrations from 250 nm to 2500 nm, NIST currently offers calibration service for spectral power responsivity only to 1800 nm. This limitation in the calibration service is due to the absence of adequate detectors for use as working standards and transfer standards. The primary objective of this work is to establish a detector calibration service in this spectral region which is continuous with the silicon photodiode-based calibration service and also implemented in the same calibration facility.

We describe the steps towards establishing a spectral responsivity calibration service at NIST for the short-wave infrared (SW-IR) range. Following the reference spectral responsivity scale realization from 1800 nm to 2500 nm [1], this work is to describe the characterizations in the NIST Spectral Comparator Facility (SCF) [2] in direct-current (dc) measurement mode for routine calibrations and also the use of

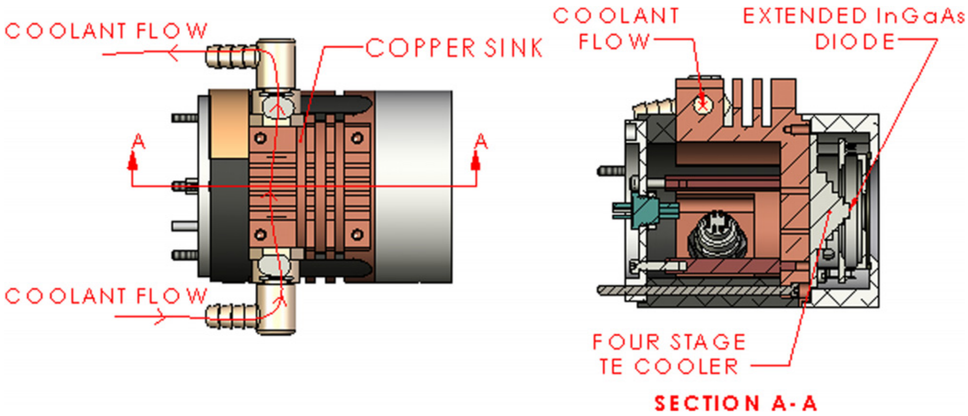

Figure 1. Side view and cross-section of an EIGA radiometer head built with a 5 mm diameter detector. The heat generated is removed with circulated water.

the already developed extended-InGaAs (EIGA) radiometers for this work [3]. We show here that, in the future, regular InGaAs detectors/radiometers will not be needed for responsivity scale realization in the near-infrared wavelength ranges, and that Si and EIGA detectors can be used as standards (reference radiometers) to cover the entire wavelength region from 250 nm to 2500 nm.

2. EIGA transfer- and working-standard radiometers

The EIGA transfer-standard radiometers were constructed using 3 mm diameter EIGA detectors attached directly to 50 mm diameter sintered polytetrafluoroethylene (PTFE) integrating spheres [3] to have spatially uniform input responsivity for radiant-power measurements. These transfer radiometers were directly calibrated using the cryogenic electrical-substitution radiometer.

The EIGA working-standard radiometers were built using 5 mm diameter detectors. In order to avoid condensation or frost, the detectors are packaged in a hermetically sealed container with an anti-reflection coated sapphire window which is also back-filled with an inert gas. All detectors were cooled to about −70 °C ± 0.05 °C with a four-stage thermoelectric (TE) cooler. The heat generated from this cooling was dissipated with the use of heat sinks mounted to the detector heads. Each heat sink was cooled using either forced air (using a small fan) or water (using a fan-cooled radiator). Although the water cooling is more efficient at removing the heat generated by the TE coolers, both designs were equally capable of maintaining stable temperatures at the detector. The drawings of a 5 mm EIGA detector head showing the heat sink and the circulated-water cooling are shown in figure 1.

3. EIGA radiometer characterizations

The electronic and radiometric characteristics have been evaluated to minimize measurement uncertainties for both radiant-power and irradiance responsivities in both alternating-current (ac) and dc measurement modes. Although the EIGA radiometers should optimally be operated in ac mode to avoid the changes due to the background thermal radiation, most of the characterizations were performed in dc mode to minimize the changes to the present SCF operations.

3.1. Output drift and noise of EIGA radiometers

The output noise and drift of the detector preamplifier of the 3 mm diameter EIGA radiometers were previously measured [3]. The measured noise-equivalent current (NEC) was 4 pA in dc mode and 20 fA in ac mode. Since the SCF operates in dc mode, the dc mode measurements for the 5 mm EIGA detectors, which have about 30 times lower (∼70 kΩ) shunt resistances compared with the 1 MΩ to 3 MΩ shunt resistances of the 3 mm EIGA detectors, were repeated. The difference in the shunt resistances means a 30 times higher voltage amplification for the input noise and drift in the radiometers using the 5 mm detectors. According to our recent noise and drift tests on the 5 mm EIGA detectors, the drift-equivalent current, after about 1 h warm-up time, was close to 200 pA, which is an order of magnitude larger than the NEC when the dc mode measurements are a few minutes apart. The drift and noise tests were evaluated from 20 consecutive data points, each taken with an integration time for the duration of 100 power line cycles.

3.2. Spatial response of EIGA detectors

The spatial uniformity of the EIGA detectors must be known if the total radiant power in the incident beam is to be measured with low uncertainties. The spatial uniformity of the responsivity was measured at a large number of wavelengths. Shown in figure 2, the spatial uniformity of the responsivity was 0.5% (max-to-min) at 2100 nm. The measured uniformity was similar between 1200 nm and 2300 nm. However, it increased to a total variation of 1.5% at 2400 nm and to a much larger variation of 25% at 2500 nm. This last result is shown in figure 3. The variation in the uniformity was 0.8% at 1100 nm, 1% at 1000 nm and 2.5% at 900 nm. The diameter of the scanning spot size was 1.1 mm and the step increments of the movement were 0.5 mm. The results indicate that the spatial uniformity of the tested EIGA photodiode is wavelength dependent. The spatial uniformity is suitable

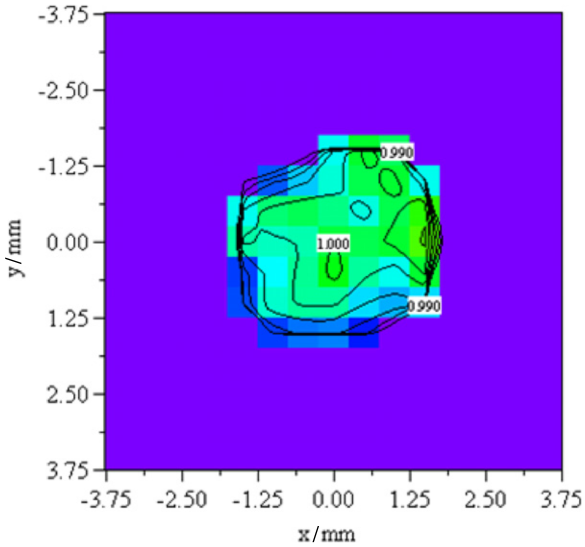

Figure 2. The spatial responsivity non-uniformity of a 5 mm EIGA detector at 2100 nm is illustrated with 0.2% contours.

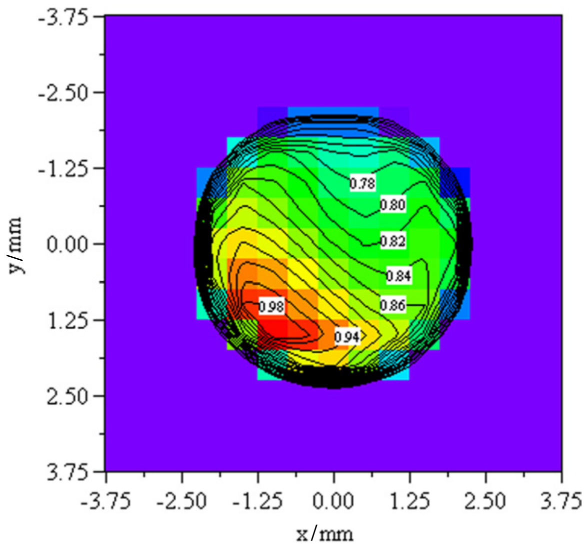

Figure 3. The spatial responsivity non-uniformity of a 5 mm EIGA detector at 2500 nm is illustrated with 2% contours.

for low-uncertainty spectral power-responsivity scale transfers between 1200 nm and 2300 nm. If the spatial alignment is reproducible using motorized stages, then the component of uncertainty due to spatial uniformity would be low even at the wavelength range from 900 nm to 1050 nm where spectral overlaps with silicon diodes exist. However, the detector should be positioned with care at the long wavelength region to obtain low repeatability and reproducibility errors (in power mode) in spite of the large spatial variations in the power responsivity.

3.3. Temperature-dependent spectral responsivity of EIGA detector

The temperature-dependent spectral power responsivity of a representative 5 mm EIGA detector was measured to determine the temperature sensitivity of the detector responsivity.

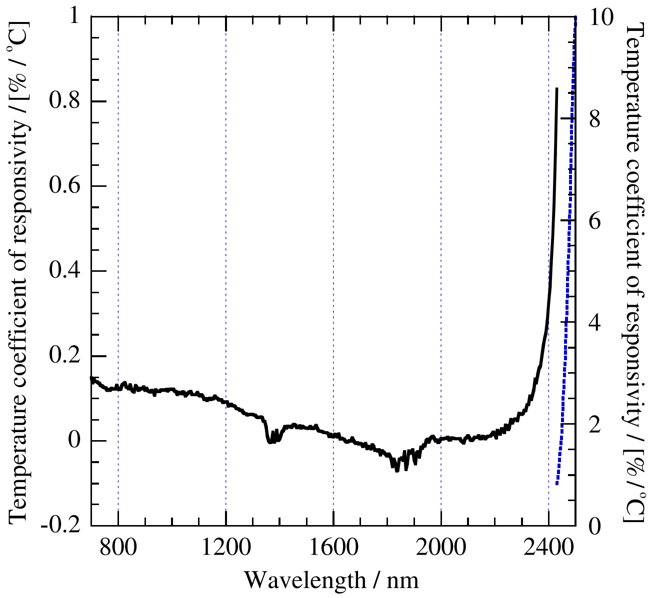

Figure 4. Temperature coefficient of power responsivity versus wavelength of a 5 mm EIGA detector. The solid curve is scaled on the left-Y and the dashed curve is scaled on the right-Y (ten times less sensitive than the left-Y).

The spectral power responsivity of the EIGA detector was measured at detector temperatures set to $-63\,^\circ$C, $-53\,^\circ$C, $-43\,^\circ$C, and the measurements repeated at $-63\,^\circ$C for examination of any hysteresis in the responsivities. The changes in the responsivities were found to scale with temperature. Figure 4 shows the measured temperature coefficients of responsivity versus wavelength. The solid curve is scaled on the left-Y axis. The temperature coefficients are less than $0.15\%\,^\circ\mathrm{C}^{-1}$ between 700 nm and 2350 nm. The $10\%\,^\circ\mathrm{C}^{-1}$ coefficient at 2500 nm, shown with the dashed curve (scaled on the right-Y), indicates that the temperature instability at this wavelength cannot be larger than $0.05\,^\circ$C if a responsivity change of less than 0.5% is needed.

3.4. Linearity of EIGA radiometers

Since the detectors can be used at different incident power levels, the linearity of the EIGA photodiodes was also measured. The linearity of EIGA detectors was tested on the Beam Conjoiner [4]. The linearity testing was performed using a quartz-halogen tungsten (QTH) lamp which was modulated at 13 Hz using a chopper wheel. The QTH lamp was not spectrally filtered. Care was taken to underfill the detector with the incident radiation since overfilling of the detector with the incident radiation could result in non-linear response of the detector [5]. The detector was directly attached to a trans-impedance amplifier which was set at a gain of $10^6\ \mathrm{V\,A^{-1}}$. The signals were measured using a lock-in amplifier to avoid thermal drift issues during the measurements. The ac linearity of the lock-in amplifier was in turn tested using a silicon photodiode which was determined to be linear in dc mode and then operated in ac mode. The signal-to-flux ratio of one linearity test for a $2\frac{1}{2}$ decade signal change is shown in figure 5. The non-linearity is less than 0.1%. The spread of the data

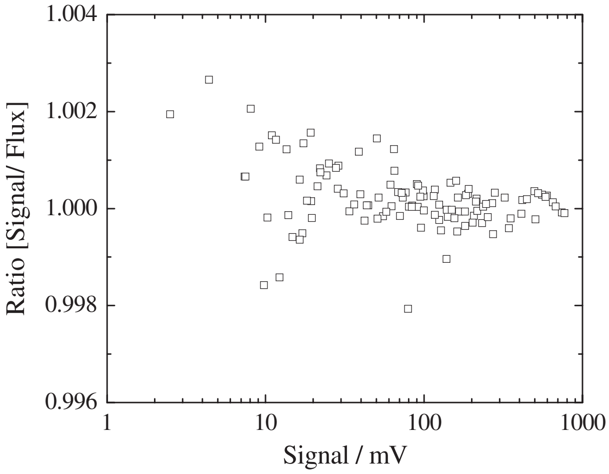

Figure 5. One run of a linearity test of an EIGA detector.

points at the low-power end is caused by the poor signal-to-noise ratio.

3.5. Signal-to-noise and drift ratios at the SCF

One of the critical tests is checking the ability of the EIGA working standards to measure the dc spectral power output of the NIST SCF with low uncertainties. Typically, the SCF operates in two-beam ratio mode for the Si and near-IR wavelength ranges. In the two-beam ratio mode, a monitor diode is always used so that the ratios of the signals between the working-standard detector and the monitor diode detector and the corresponding ratio with the diode under test are used for the calibrations. Any common signal changes in the two channels (such as the lamp intensity changes) can be compensated by the simultaneous (signal/monitor) ratio made by the computer. The initial tests described here were performed using a single detector or the one-beam mode so that the noise and drift components are not measured under optimal conditions.

The effect of the long-term drift for the spectral scans in the one-beam mode was tested. The dc output signal of the reference 5 mm EIGA radiometer (used in the present EIGA radiometer calibrations at the SCF) was measured in two consecutive spectral scans. The measured signals of the two spectral scans are shown in figure 6. The signal differences from the two scans are also plotted. The signal difference fluctuated between 0.2% and 0.5% of the signal nominal values. The scan-to-scan signal-change (drift) was 0.3% with drift and noise fluctuations of about ±30%. The signal differences obtained with another 5 mm EIGA radiometer during four spectral scans were within ±0.5%. These signal changes indicate that the one-beam mode at the SCF is suitable for dc mode calibrations with acceptable measurement uncertainties. It is expected that the long-term signal-drift can be decreased using the two-beam ratio mode where a monitor EIGA radiometer is used in addition to the test and reference EIGA radiometers. In addition, the water vapour absorption features can be seen near 1400 nm and at 1850 nm. The reduction in the signals observed at 2200 nm is due to the OH absorption in the fused-silica prism in the monochromator. These fluctuations due to the atmospheric absorption can be reduced by purging the path in the monochromator and the detector compartments with dry air.

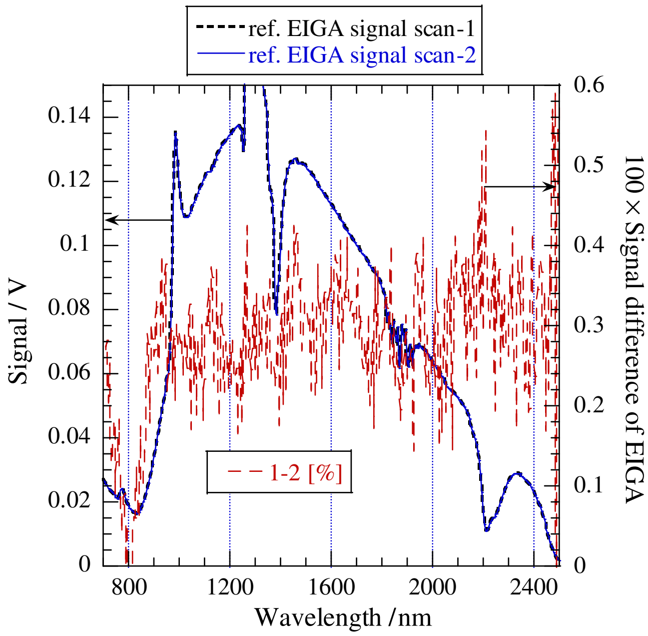

Figure 6. Measured signals from two consecutive spectral scans (left-Y axis) and the percentage signal difference from the two scans (right-Y axis).

4. Calibrations

The basis of the extended spectral responsivity scale is from the calibration of the spectral power responsivities at discrete wavelengths using a sphere-input EIGA radiometer which is, in turn, calibrated using the electrical-substitution cryogenic radiometer at the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) facility [1, 3]. The calibrations at these discrete wavelengths were interpolated to other wavelengths using the SCF [2] spectral power-responsivity scale to 1600 nm, and the spectral responsivity of the low-NEP pyroelectric transfer-standard radiometer [6]. Four working-standard EIGA radiometers (with 5 mm diameter detectors) were calibrated against the sphere-input EIGA transfer standard. One of the four radiometers was used here as a reference detector. A 3 mm diameter test EIGA radiometer was calibrated against one of the 5 mm working-standard EIGA detectors using the detector substitution method. The calibration was performed in the one-beam measurement mode of the SCF and the output dc voltages of both the test and the reference radiometers were measured, in sequence, during three consecutive spectral scans. The SCF was not modified for this calibration. The radiometers were moved into the output of the monochromator by a motorized detector stage at the end of one wavelength scan (from 700 nm to 2500 nm). The average of the three spectral power responsivities is plotted in figure 7. The percentage standard deviations calculated from the three spectral power responsivities are also shown. The standard deviations are

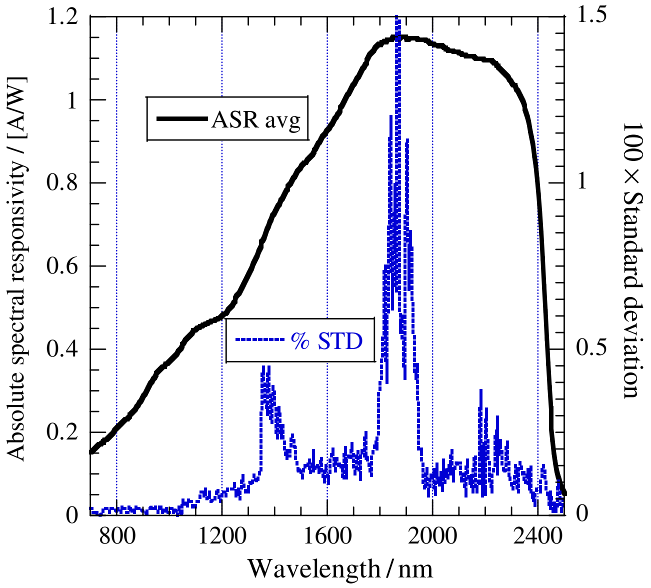

Figure 7. Average absolute spectral power responsivity (ASR) of the test EIGA radiometer from three spectral scans. The standard deviations (on the right-Y axis) are increased because of the absorption bands and the prism contamination (at 2200 nm) of the monochromator.

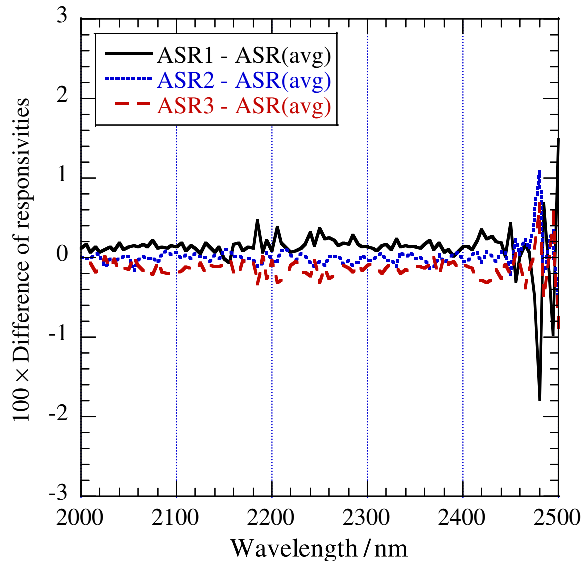

Figure 8. Difference of the absolute spectral power responsivities (ASR) measured in three scans for the test EIGA radiometer within the 2000 nm to 2500 nm atmospheric window.

less than 0.2% ($k = 2$) between 700 nm and 2500 nm except at three spectral regions. At these three spectral regions, the standard deviations increased due to the presence of water vapour absorption features near 1400 nm and at 1850 nm and also because of the OH absorption in the prism at 2200 nm.

The repeatability of the three spectral power responsivities (from the three scans) compared with their average within the 2 µm to 2.5 µm atmospheric window is shown in figure 8. The responsivity differences are within ±0.4% to about 2470 nm. The differences are doubled at the high wavelength end of the spectral scan because of the decreased signal-to-noise (and drift) ratios.

5. Uncertainty budget

The uncertainty budget for these measurements is estimated in table 1. The dominant uncertainty components of the above EIGA (3 mm) radiometer calibration are the uncertainty of the reference spectral power-responsivity scale and the spectral responsivity changes (repeatability) from the three consecutive spectral scans performed in the one-beam measurement mode. The spectral responsivity changes are caused by the temperature- and noise-dependent responsivity variations during the spectral scans when the positions of the reference and test detectors were not changed. The uncertainty components caused by monochromator wavelength errors and EIGA-detector non-linearity are negligibly small compared with the discussed dominating components.

The relative expanded uncertainty between 900 nm and 1200 nm and also from 2300 nm to 2400 nm is 2.0% ($k = 2$) and it increases to 3.0% ($k = 2$) between 2475 nm and 2500 nm.

Table 1. Uncertainty budget for the spectral power-responsivity calibration of an EIGA (3 mm) radiometer for the wavelength interval between 1200 nm and 2300 nm.

Dominant uncertainty components	Type A	Type B	Total
Reference radiant-power responsivity scale	0.5%		
Reference-detector position		0.3%	
Test-detector position		0.3%	
Spectral responsivity differences from three scans	0.4%		
Relative combined standard uncertainty			**0.8%**
Relative expanded uncertainty with $k = 2$			**1.6%**

6. Conclusions

This work describes the scale transfer from the reference spectral responsivity scale which has a 1% ($k = 2$) responsivity uncertainty. The scale transfer has been performed in the SCF using the detector substitution method. The spectral power responsivity was transferred to a test EIGA radiometer from one of the four working-standard EIGA radiometers that hold the reference scale. The transfer was performed in a one-beam dc measurement mode which requires, for three consecutive scans, the substitution of the reference and test radiometers after each spectral scan. The uncertainty of the scale transfer was dominated by the uncertainty of the reference scale, the spatial non-uniformity of the EIGA detectors, and the spectral responsivity differences from the three consecutive scans. The obtained 1.6% ($k = 2$) uncertainty between 1200 nm and 2300 nm and the less than 3% ($k = 2$) uncertainties between 900 nm and 2500 nm verified that the SCF can be used in this spectral range in dc measurement mode. Work is being continued to reduce the uncertainty using the two-beam (ratio) dc mode. Transfers with lower uncertainties will be possible with the two-beam ratio method where the long-term drift effects (including lamp-changes) will be decreased.

References

[1] Eppeldauer G P *et al* 2010 Extension of the NIST spectral power and irradiance responsivity calibrations to 2.5 micrometers *Proc. CIE Expert Symp. on Spectral and Imaging Methods for Photometry and Radiometry* CIE x036:2010 (Vienna: CIE) pp 66–71

[2] Larason T C and Houston J M 2008 *Spectroradiometric Detector Measurements* NIST Special Publication 250-41 (Gaithersburg, MD: NIST)

[3] Eppeldauer G P and Yoon H W 2007 Short-wave infrared radiometers design and characterizations *Proc. SPIE* **6542** 65420O

[4] Yoon H W, Butler J J, Larason T C and Eppeldauer G P 2003 Linearity of InGaAs photodiodes *Metrologia* **40** S154–8

[5] Corredera P *et al* 2003 Anomalous non-linear behaviour of InGaAs photodiodes with overfilled illumination *Metrologia* **40** S150–3

[6] Eppeldauer G P *et al* 2009 Extension of the NIST spectral responsivity scale to the infrared using improved-NEP pyroelectric detectors *Metrologia* **46** S155–9