Realization of a spectral radiance responsivity scale with a laser-based source and Si radiance meters

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Abstract. A spectral radiance responsivity (SRR) scale derived from the spectral irradiance responsivity scale has been realized on the newly developed NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS). The scales were directly derived from the primary standard cryogenic radiometer using transfer standard irradiance trap detectors and laser-based uniform sources. Silicon radiance meters of standards quality have been developed to hold the SRR scale. The radiance meters were characterized and optimized for size-of-source effects. The optimized meters were calibrated for SRR against the monochromatic uniform source. In addition to the SIRCUS calibrations, preliminary tests were also made on the Spectral Comparator Facility (SCF) of the NIST. These relative SRR tests were made in both imaging and non-imaging measurement modes. The results of the different SRR calibrations are compared and evaluated.

1. Introduction

The high accuracy of primary standard cryogenic radiometers [1] can be utilized only if radiometers of improved quality are developed and calibrated directly against a primary standard. To achieve this goal, we are developing a reference (high-accuracy) calibration facility for measuring spectral irradiance and radiance responsivity [2]. This facility utilizes uniform sources with integrating spheres and lasers [3-5] in order to obtain uncertainties on a lower scale than those of traditional monochromators [6]. This paper describes how the irradiance responsivity scale is propagated to the radiance responsivity scale on the SIRCUS facility. The design and basic radiometric characterization of a broadband working standard Si radiance meter are discussed. This high-performance radiance meter will hold the high-accuracy SRR scale. Arrangements and considerations are discussed for accurate relative and absolute SRR measurements.

2. Derivation of radiance responsivity scale

Figure 1 shows the scale propagation from the NIST High Accuracy Cryogenic Radiometer (HACR) to the SRR scale. Si trap detectors are calibrated against the HACR at several laser lines. The response interpolation is made between 406 nm and 920 nm based on the physical model of the Hamamatsu 1337 Si photodiodes [7]. The aperture area in front of the trap detector is measured to a high accuracy using point source geometry [8]. The irradiance responsivity of the transfer standard Si trap detector is equal to the product of its power responsivity and the aperture area.

The SRR scale is derived from the spectral irradiance responsivity scale. First, the radiant intensity of the uniform source is determined from the irradiance responsivity of the detector and the distance between detector and source apertures. In this case, the distance is large (about 1 m), therefore the source is used as a point source. The radiance within the source aperture (at a laser wavelength) is the ratio of the radiant intensity to the area of the source aperture. When calibrating the radiance meter against the Lambertian (uniform) source, its target area (the measured spot) has to be within the source aperture (of 5 cm diameter). The radiance responsivity of the meter is the ratio of its electrical output signal to the measured source radiance.

3. Design of Si radiance meter

Figure 2 shows the design of the transfer standard Si radiance meter. The input optics are attached to the radiometer base unit. A bevelled aperture in the mirror serves as a field stop and it is positioned at the focus of the camera lens. The surroundings of the target area of the source can be viewed through the eyepiece. The target radiation is imaged on to the centre of the Si photodiode through a second set of

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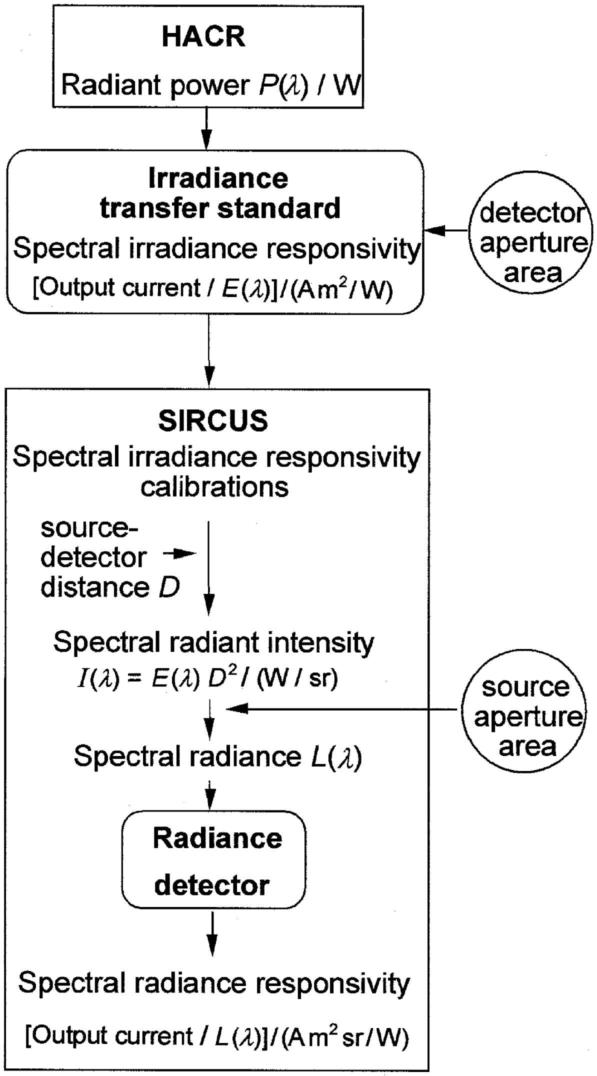

Figure 1. Derivation of a scale of spectral radiance responsivity.

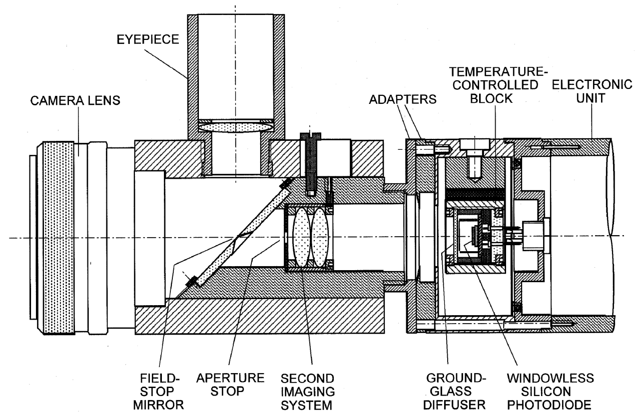

Figure 2. Working standard Si radiance meter.

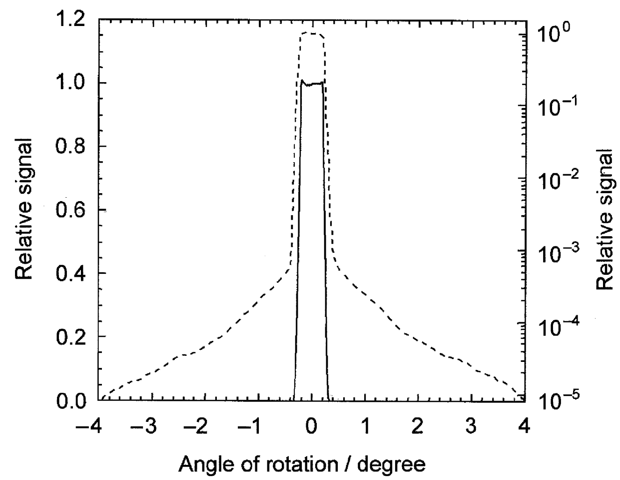

Figure 3. Angular responsivity of the Si radiance meter. Horizontal response (dashed line, logarithmic scale) and vertical response (solid line, linear scale).

imaging optics, producing a well-defined field-of-view and very efficient out-of-target blocking. The aperture stop in front of the second imaging system keeps the flux response of the optics constant for different target distance (lens focus) adjustments. In order to eliminate interference, we replaced the original plane-parallel window of the Si photodiode with a ground-glass diffuser of high transmittance.

4. Characterization of Si radiance meter

Figure 3 shows the angular responsivity of the Si radiance meter. The measured source was a 1000 W tungsten-halogen lamp equipped with a 5 mm aperture, at a distance of 4 cm from the lamp. The distance between the radiometer and the source aperture was about 2.5 m. The radiometer was rotated in the horizontal plane around a pivot point in the centre of its camera lens. This scan was repeated after a 90° rotation of the radiometer around its axis in order to also obtain the angular responsivity in the perpendicular (vertical) plane. The radiance measurement angle is 0.6° (full-width-at-half-maximum) and the out-of-target blocking (the ratio of the signal at zero rotation angle to that at a different rotation angle) is 2×10^3 at 0.5°, 10^4 at 1.5° and over 10^5 at 4°. The vertical and horizontal scans gave similar results.

5. Absolute spectral radiance responsivity

The absolute SRR was measured on the SIRCUS facility using a 20 cm diameter Spectralon-coated integrating sphere. The sphere was irradiated by 98 laser lines of different wavelengths between 400 nm and 920 nm. The measurement steps followed the scale-derivation chart in Figure 1. The solid line in Figure 5 shows the absolute SRR of the working standard radiance meter.

6. Uncertainties

Table 1 summarizes the uncertainty budget of the SIRCUS radiance responsivity. Type A and Type B uncertainties [9] are shown for both

Table 1. Relative Type A, Type B and combined standard uncertainties $(k = 1)$ of the SIRCUS present radiance responsivity calibrations (future calibration uncertainties are shown in italics).

Origin of uncertainty	Present measurements		Planned (future) measurements	
	$100 \times u_A(x_j)/x_j$	$100 \times u_B(x_j)/x_j$	$100 \times u_A(x_j)/x_j$	$100 \times u_B(x_j)/x_j$
Source radiance				
Spectral power responsivity of trap		0.03		0.02
Aperture area of trap		0.01		0.01
Source-to-trap distance squared	0.05		0.02	
Repeatability of trap	0.05		0.02	
Aperture area of source		0.04		0.02
Amplifier gain		0.04		0.02
Radiance transfer to test detector				
Spatial radiance non-uniformity of source				
Uncorrected		0.1		
Corrected		*0.02*		*0.01*
Repeatability of test detector	0.05		0.01	
Size-of-source effect of test detector				
Uncorrected		0.15		
Corrected		*0.02*		*0.01*
Amplifier gain		0.04		0.02
100 × Relative combined standard uncertainty				
Uncorrected	0.21			
Corrected	*0.12*		*0.054*	

present (preliminary) and future calibrations. The source radiance uncertainties are separated from the uncertainties of the radiance transfer to test radiance meters. We plan to decrease the present (uncorrected) relative combined standard uncertainty $(k = 1)$ of 2.1 parts in 10^3 to about 5 parts in 10^4 after improving the uncertainties as indicated in the table.

7. Measurements of spectral radiance responsivity using the SCF

Independent relative SRR measurements were made on the SCF. We made two preliminary tests with two different beam geometries. The first was a simple, non-imaging method that can be used for high-quality radiance meters where a second imaging optics always projects the beam on to the same position on the detector. In this case, the target spot of the radiance meter was not defined. Figure 5 shows these test results (non-imaged SCF curves). With normalization at 705 nm, the curve for relative radiance responsivity agrees with the results of the absolute (SIRCUS) radiance responsivity measurements within 1 part in 10^2 between 475 nm and 920 nm. The repeatability uncertainty was equal to or less than 2.5 parts in 10^3, estimated from three scans of relative spectral responsivity made with different (repeated) alignments. The relative standard uncertainties $(k = 1)$ of the SCF measurements are 7.8 parts in 10^3 at 400 nm and 1.1 parts in 10^3 from 450 nm to 900 nm in power responsivity mode [6], and 9.4 parts in 10^3 at 400 nm and almost constant at 5.4 parts in 10^3 in the visible up to 925 nm in irradiance responsivity mode [10].

Because the non-imaging method is incorrect for radiance responsivity measurements, we suggest here an imaging-type test method. We made a preliminary test using this second method where the standard arrangement of the SCF was modified to measure simple radiance meters in which the detector may have spatially non-uniform responsivity and no second imaging optics are used. Figure 4 shows the modification. The $f/9$ converging beam from the monochromator, in front of the two lenses, produces a spot 1.1 mm in diameter (on the surface of the power-measuring detector in the standard SCF arrangement). In the modification, a camera lens of 35 mm focal length is used as a relay lens to magnify this spot into a 15 mm diameter image, inside an achromatic collector lens of 350 mm focal length. The collector lens collects the radiation exiting from the relay lens and projects it into the centre of the camera lens of the radiance meter. The distance of the radiance meter from the collector lens has to be adjusted until the diameter of the target spot of the radiance meter is equal to the diameter of the reference detector, which is positioned directly after the collector lens. The reference detector must be circular (e.g. a 1 cm^2 silicon detector). In the eyepiece of the radiance meter, the black (measured) spot must be in the centre of the 15 mm diameter image inside the collector lens. The relative radiance responsivity of the meter will be the power responsivity of the reference detector multiplied by the ratio of the output signal of the radiance meter to that of the reference detector.

In our preliminary test, an $18\ \text{mm} \times 18\ \text{mm}$ reference Si detector was used and the desired match between the target spot and the detector diameter was not achieved. Because of chromatic aberrations in the lenses, the size of the magnified spot inside the collector lens was wavelength-dependent. The lenses were optimized for the visible range. The irradiance

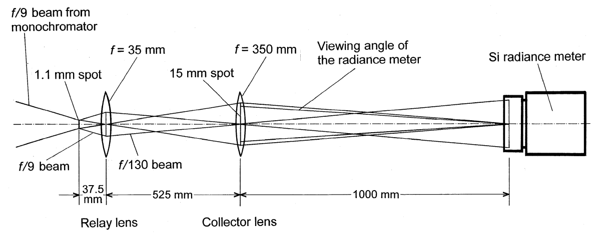

Figure 4. Optical arrangement for measuring the relative responsivity of a radiance meter.

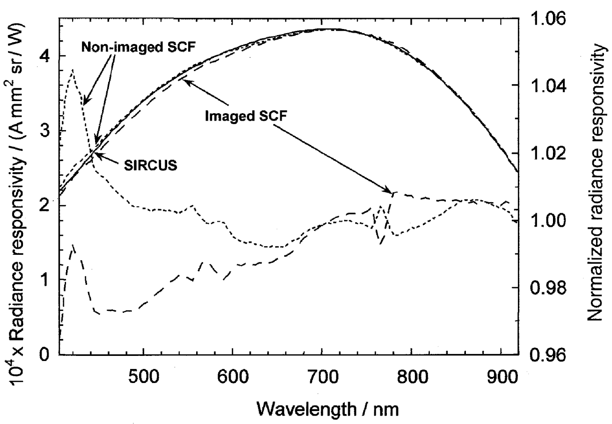

Figure 5. SRR of the NIST radiance meter #303. The curves of relative radiance responsivity were measured on the SCF in both imaging and non-imaging modes and normalized to the absolute responsivity as measured on the SIRCUS facility. The normalization was made at 705 nm. The responsivity ratios are shown relative to the SIRCUS results.

distribution within the monochromator output spot also depends on the wavelength. These problems caused relatively large uncertainties for wavelengths shorter than 420 nm. In Figure 5, which summarizes the radiance responsivity measurements, the normalization was made at 705 nm, the peak responsivity of the photodiode, resulting in a discrepancy of about 2.5 % (relative to the absolute radiance responsivity) at 450 nm (imaged SCF curves).

The two relative radiance responsivity curves are different not only because of the non-optimized arrangement of the imaged SCF measurements (as mentioned above), but also because the transmittance of the antireflection coating can be different for the different incident angles of the two cases. A systematic uncertainty in the relative radiance responsivity was measured at 420 nm. This problem, which requires further examination, significantly increased the responsivity deviation of the non-imaged SCF measurements relative to the SIRCUS results for wavelengths shorter than 475 nm.

8. Conclusions

SRR calibrations were performed on the preliminary SIRCUS facility. The first radiance responsivity measurements had a relative combined standard uncertainty of 2.1 parts in 10^3, which is three to four times better than the SCF irradiance responsivity uncertainty in the same wavelength range. The dominating uncertainty components were revealed. We could also estimate the achievable uncertainties and the improvements required to finalize the facility. Comparison of the SIRCUS responsivity measurements with the traditional monochromator-based SCF measurements showed that systematic errors in the SCF SRR measurements can be verified. The SIRCUS, with its final control and measurement system, including a variety of transfer and working standard radiometers and improved correction and calibration procedures, will serve as a high-accuracy reference calibration facility for radiometry, photometry, and colorimetry.

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Note. Identification of commercial equipment to adequately specify an experimental set-up does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose.

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