ILLUMINANCE RESPONSIVITY CALIBRATION OF REFERENCE PHOTOMETERS AT THE NIST SIRCUS AND SCF FACILITIES

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ABSTRACT

The illuminance responsivities of two transfer standard photometers have been directly determined from their spectral responsivity calibrations at two different calibration facilities of NIST. The main characteristics of the two photometers, and their calibrations are described. The spectral and broad-band (illuminance) responsivities measured at the two different facilities are compared. The two different illuminance responsivity determinations on both photometers agreed within 0.1 % with an overall uncertainty of 0.2 % (k=2). A new photometric scale derivation scheme is also discussed.

Keywords: calibration, illuminance responsivity, photometry, spectral responsivity

1. INTRODUCTION

The illuminance responsivity scale of NIST, developed in 1991, has a relative expanded uncertainty of 0.39 % (k=2) [1]. With the development of the Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) facility [2], the spectral irradiance responsivity uncertainty could be lowered compared to the Spectral Comparator Facility (SCF) based 1991 scale [3]. This was the motivation to analyze how to improve the uncertainty of the 1991 scale. In order to satisfy this goal, high quality transfer standard photometers have been developed. These transfer standards can be calibrated not only at the SCF, but also at the SIRCUS. At SIRCUS, stabilized tunable-lasers are coupled into integrating sphere sources producing uniform irradiance for the irradiance measuring reference trap detectors and the illuminance measuring photometers. As a result of the SIRCUS used calibration geometry, the uncertainty of the SIRCUS made spectral irradiance responsivity calibrations can be dominated by the 0.06 % (k=2) uncertainty of the reference Si trap-detector [2]. However, the old photometer standards developed during the 1991 scale realization, cannot be calibrated at the SIRCUS because the remaining coherence at the sphere outputs can cause large interference fringes. Development of the new transfer standards was needed to fix this problem.

During a preliminary photometric scale comparison in 2007, the illuminance responsivities of the two reference photometers were compared. Both of them were calibrated at the two different NIST calibration facilities. The SCF-based calibration had a longer scale derivation chain than the SIRCUS calibration since the transfer standard photometers were calibrated against the old photometer standards with substitution when both photometers measured the same illuminance of a 2856 K lamp. The difference of the SIRCUS and SCF determined illuminance responsivity measurements was 0.4 % [4]. Though, this difference is within the reported uncertainties of the two different scale realizations of the two facilities, our goal is to decrease this difference and to obtain a better agreement between the two scales. In order to achieve this goal, the major uncertainty components of the two independent photometric scale realizations are analyzed and then improved. Characterizations and calibrations of the transfer standard photometers are discussed and the two independently realized illuminance responsivity scales are compared.

2. NIST REFERENCE PHOTOMETERS

First, as shown in Fig. 1, an irradiance measuring trap detector was developed [5]. Figure 2 shows how a temperature controlled filter-wheel was inserted and moved between the input aperture and the silicon tunnel-trap detector. Since the windowless photodiodes were exposed to the ambient air, the illuminance responsivity decreased with 0.2 % from 2003 to 2007 and with another 0.1 % - 0.15 % to 2009.

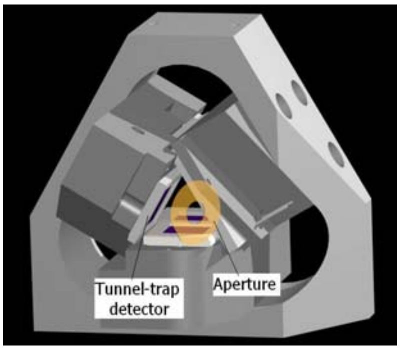

Figure 1. Trap detector with input aperture.

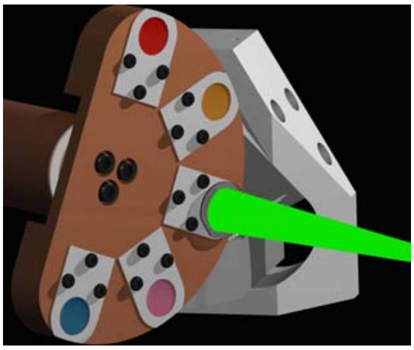

Figure 2. Temperature controlled filter wheel between the trap-detector and the aperture.

Also, the baffling inside of the trap-photometer was not efficient enough. Figure 3 shows that in overfilled mode (at SIRCUS), because of the internal reflections of the photometer, the Si trap detector (that peaks at 970 nm), measured a small portion of the incident light which did not go through the filter. In underfilled mode (at SCF), the stray and reflected light attenuation was two orders of magnitude better.

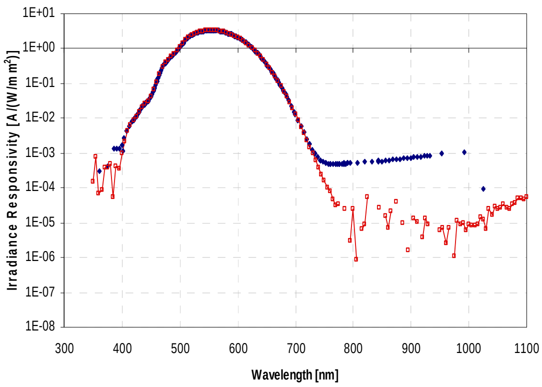

Figure 3. SIRCUS (full-diamonds) and SCF (open squares) measured trap-photometer irradiance-responsivities including the unfiltered internal stray and reflected light.

In order to improve the above problems, a second generation tristimulus colorimeter, Model F100, was developed. The picture of this device, where the Y-channel is used as the photometer, is shown in Fig. 4. The front cover where the aperture is mounted was removed. The preamplifier is attached to the side of the photo/colorimeter.

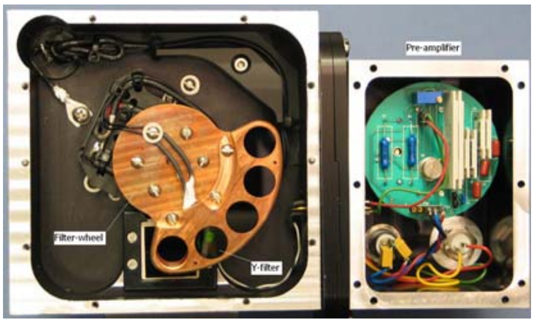

Figure 4. Picture of the single-element-Si photodiode based F100 colorimeter.

The detector is a large-area single-element silicon photodiode closed with a wedge window [4]. The 0.5 ^{o} wedge was needed to avoid interference fringes in the output signal of the photodiode. The spaces on the two sides of the temperature controlled filter-wheel are small resulting in five orders of magnitude blocking in the IR even in overfilled mode. Also, the thickness of the individually fabricated filter packages was at least 4.5 mm to minimize fringes. The less than 0.3 % peak-to-peak fringes of the Y-channel (as measured at the SIRCUS) before and after filtering the data are shown in Fig. 5. The filter combination was individually optimized to the CIE standard V(λ) function. No responsivity degradation could be measured on this improved photometer between 2007 and 2009.

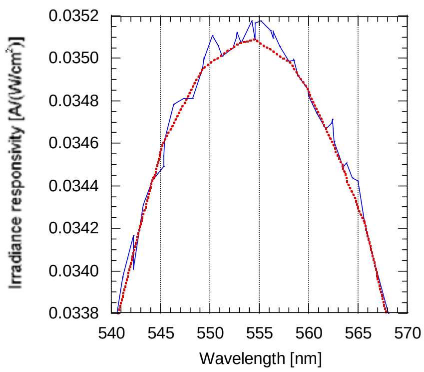

Figure 5. Filtered fringes of the SIRCUS measured trap-photometer.

3. NIST CALIBRATION FACILITIES

The reference photometers were calibrated at the SIRCUS and the SCF facilities. The uncertainty of illuminance responsivity calibrations at the SIRCUS is 0.1 % (k=2). At the SCF, spectral power responsivity calibrations can be performed routinely with an uncertainty of 0.2 % (k=2) between 525 nm and 950 nm. The uncertainty increases to 0.38 % (k=2) at 400 nm. The uncertainty of the SCF current-to-voltage converter calibrations is 0.08 % (k=2) which is comparable to the uncertainty of the working standard detector responsivity. The uncertainty of the SCF based illuminance responsivity calibrations, as reported in 1996, was 0.39 % (k=2) [1]. This uncertainty included a large component of 0.24 % (k=2) which was dominated by the internal reflections of the f/9 beam of the monochromator inside of the old photometer standards. Since the input geometry of the individual photometers, within the group of the old standards, was different, a variation (spread) was obtained in the illuminance responsivities. Also, the aperture areas obtained with the f/9 beam used raster-scan method, had a systematic error compared to the geometrically measured aperture areas. The converging beam had multiple reflections between the aperture and the detector because of the small separation between the two. Other uncertainty components, which cannot be found at the SIRCUS irradiance responsivity calibrations, originated from the small beam-spot focussed onto the spatially non-uniform filters and photodiodes and also the wavelength errors of the monochromator.

The Photometer Bench, as a third facility, is used to calibrate test photometers against reference photometers using the photometer substitution method. In previous photometric calibrations, the old photometer standards were the reference photometers and either test photometers or luminous intensity lamps were calibrated against them. In future calibrations, the old photometers will be used as working standards and they will be calibrated against the (fringe-free) reference photometers. As part of our analysis, it was tested how the stray-light-changes for the different photometers can contribute to the uncertainty budget. The stray-light at the Photometer Bench is much higher than at the spectral responsivity calibration facilities because of the broad-band radiation of the luminous intensity lamp. The stray-light caused uncertainty component can be kept small if the light-shutter is sized and positioned such that the stray-light seen by the photometers is comparable in the shutter open and closed positions. Also, double or multiple baffling is needed to keep the stray light (seen by photometers of different acceptance angles) low. Care should be taken when photometers with diffusers are used because they can measure the stray-light from a large solid angle. Poor stray-light design and baffling could cause uncertainty contributions up to 1 % (k=2) or higher.

4. CALIBRATIONS

The spectral responsivities of both reference photometers were measured at the two different responsivity calibration facilities to determine their irradiance responsivities and then to calculate their illuminance responsivities.

4.1. Spectral irradiance responsivities

Since the basic operational mode of the SCF facility is radiant power measurement, it was necessary to determine the aperture areas for both reference photometers. The aperture areas were determined from a raster-scan method at the SCF when the photopic filter was removed from the photodiode. The f/9 scanning beam did not cause multiple reflections between the aperture and the detector because of the 14 mm separation between them in the new reference photometers. The aperture areas were also determined from an irradiance-to-power responsivity ratio measurement at the SIRCUS. In this case, the irradiance responsivity was performed with a “point source” geometry and the area determination was made against the known aperture area of the reference trap detector of the SIRCUS (at one laser wavelength). The trap-detector aperture was calibrated at the NIST aperture-area calibration facility with 0.02 % (k=2) uncertainty [6]. The obtained aperture areas are shown in Table 1.

Table 1. Measured aperture areas of the F100 transfer standard photometer.

	SIRCUS	SCF
Area [mm^2]	19.730	19.708

The difference between the SIRCUS and the SCF measured areas was 0.11 %. The relative expanded uncertainties of both methods were less than 0.08 % (*k*=2).

The 5 mm diameter aperture of the transfer standard colorimeters caused a beam clipping during the spectral power responsivity calibrations at the SCF. The 1.1 mm diameter monochromatic beam imaged to the aperture plane had some spatially scattered light (halo) around the aperture-hole which was clipped by the aperture itself. The halo was caused by imaging problems. Because of the clipping, less flux was measured by the photometers than with the reference Si detector of the SCF. The loss caused by the beam clipping was measured using a 10 mm diameter silicon photodiode and a 5 mm diameter aperture (from the same batch as the photometer aperture). The aperture was in front of the detector during one spectral scan and then removed for the second measurement. Figure 6 shows the percent response difference obtained from the two measurements. The difference was wavelength dependent. To decrease this dominating uncertainty component of the spectral power responsivity calibration, a wavelength dependent correction was applied to the photometer spectral responsivity. As a result of this correction, the 0.3 % to 0.6 % systematic errors decreased to 0.05 % for the overall visible range.

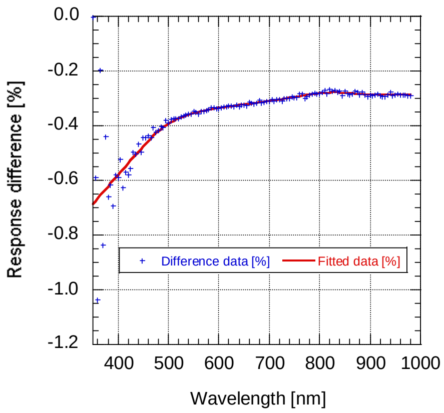

Figure 6. Response difference of two SCF responsivity measurements made with and without a 5 mm aperture in front of a large Si photodiode.

The measured aperture area was multiplied by the SCF measured spectral power responsivity of the photometer to obtain the SCF-based spectral irradiance responsivity. During the SCF calibrations, the wavelength shift of the monochromator was minimized to less than 0.1 nm before the spectral responsivity scans.

The SIRCUS and SCF measured spectral irradiance responsivities of the F100 photometer are shown in Fig. 7. The logarithmic scale shows that equal blocking was measured in both power and irradiance modes.

The SCF-based spectral irradiance responsivity of both transfer standard photometers was compared to the SIRCUS measured spectral irradiance responsivity. The absolute difference for the trap-detector based photometer is shown in Fig. 8. The graph also shows the SCF determined spectral irradiance responsivity around the peak responsivity of the trap-photometer. The structures in the difference curve are caused by the filtered fringes of the SIRCUS data.

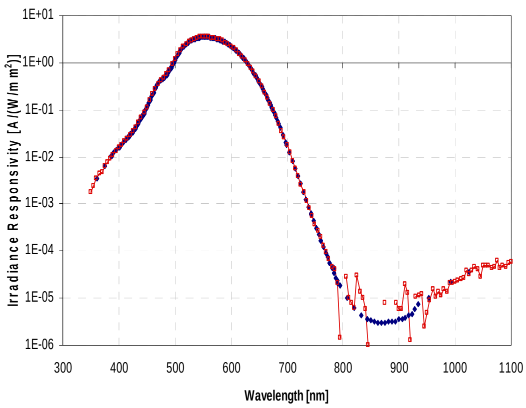

Figure 7. SIRCUS (full diamond) and SCF (open square) measured spectral irradiance responsivities of the F100 photometer.

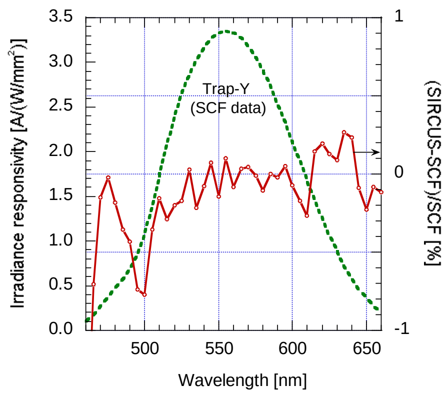

Figure 8. Difference of the SIRCUS and SCF measured spectral irradiance responsivities of the trap-photometer.

The spatial uniformity of responsivity of the F100 photometer is shown in Fig. 9. The spatial scan was made at 555 nm with 0.5 mm increments. The diameter of the scanning spot was 1.1 mm. The 0.1 % contours illustrate the combined spatial non-uniformity of the illuminance measuring photometer including the transmittance changes of the photopic filter combination and the responsivity changes of the Si photodiode.

The current-to-voltage converters of the reference photometers were calibrated against the new NIST reference current-to-voltage converter which has an uncertainty of 0.013 % (k=2) for all gain selections up to 10^{10} V/A [7]. This uncertainty is about six times smaller than the present amplifier-gain calibration uncertainty at the SCF.

4.2. Illuminance responsivities

After the spectral irradiance responsivity comparisons, the illuminance responsivities of the reference photometers were calculated. The illuminance responsivity is a ratio

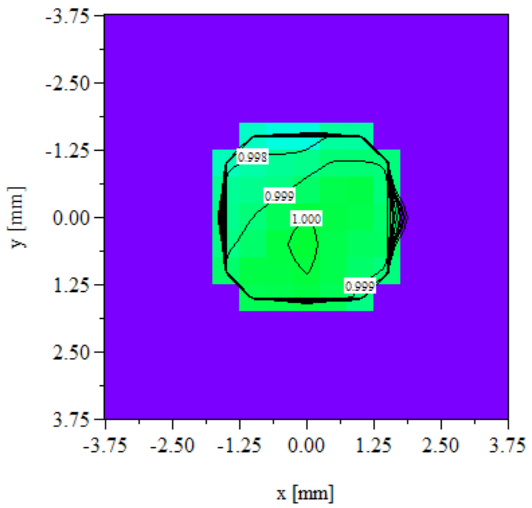

Figure 9. Spatial non-uniformity of responsivity of the F100 photometer.

where the spectral product of the measured responsivity and the source irradiance is divided by the CIE standard value [4]. The integral of both the numerator and the denominator was made from 350 nm to 1300 nm to minimize errors from filter leakage and fluorescence. The illuminance responsivity comparison (directly calculated from the SCF and SIRCUS spectral irradiance responsivities) for the Trap and F100 reference photometers is shown in Table 2.

Table 2. The illuminance responsivities of the two reference photometers determined at two responsivity calibration facilities.

	SIRCUS		SCF		SIRCUS/ SCF
	nA/lx	Year	nA/lx	Year	Ratio
Trap Ph.	4.901	2007	4.885	2007	1.0033
	4.885	2009	4.887	2009	0.9996
F-100	5.187	2007	5.166	2007	1.0041
	5.177	2009	5.178	2009	0.9998

The 2007 (first) lines for both photometers show an indirect comparison of the illuminance responsivities. In the indirect comparison, the SCF-based illuminance responsivity was not directly derived from the SCF measured spectral responsivity. Instead it was transferred from the old photometers to the reference photometers (that are test devices in this case) using the detector substitution method at the Photometer Bench. During the substitution, both the old and the new reference photometers measured the same 2856 K luminous intensity lamp. The obtained SCF-based illuminance responsivity of the reference photometer was then compared to the SIRCUS-based (directly derived) illuminance responsivity. The 2009 (second) lines show direct comparisons where not only the SIRCUS but also the SCF based illuminance responsivities were obtained directly from the spectral irradiance responsivity data. In the F100 data, the 0.41 % deviation between the SIRCUS and the SCF results in 2007 decreased to 0.02 % because the uncertainty of the 2009 direct comparison is lower than that of the indirect comparison (using the long SCF plus Photometer Bench derived chain) in 2007. On the F100, the SIRCUS-based responsivity decreased by 0.2 % and the SCF-based responsivity increased by 0.19 % between 2007 and 2009. These changes, measured on the stable F100, are within the 0.2 % (k=2) combined uncertainty of the SIRCUS and SCF based illuminance responsivity calibrations. This 0.2 % (k=2) uncertainty of the two independent scale realizations is about a factor of two improvement over the old SCF-based illuminance responsivity scale [1].

The decrease obtained in the SIRCUS-based illuminance responsivity of the Trap photometer was 0.33 % between 2007 and 2009. This change includes a 0.1 % - 0.15 % degradation in the illuminance responsivity of the Trap-photometer (which decreased another 0.2 % from 2003 to 2007). A 0.04 % illuminance responsivity difference was measured at the SCF for the Trap-photometer between 2007 and 2009. This difference also includes the 0.1 % - 0.15 % permanent responsivity degradation of the Trap-photometer. The 2009 (second) lines in the last column of Table 2 show that the directly determined SIRCUS and SCF illuminance responsivities agree within 0.04 % for both reference photometers.

5. CONCLUSIONS

The first and second generation illuminance measuring transfer standard photometers were characterized and calibrated at two different NIST facilities. After improving the discussed problems in the photometer design and also in a few calibration steps, the SIRCUS and SCF based illuminance responsivity scales were compared using the two transfer standard photometers. The illuminance responsivities of both transfer standards agreed within 0.04 % from the SIRCUS and SCF calibrations during the recent 2009 comparison. The combined relative expanded uncertainty of the SIRCUS and SCF based illuminance responsivity calibrations was 0.2 % (k=2), about a factor of two lower than the uncertainty of the irradiance responsivity scale of NIST published in 1996. The results verify that no adjustments are needed in the present NIST illuminance responsivity scale. It was shown that the SCF can produce illuminance responsivity results equal to the SIRCUS results and the expanded uncertainty can be 0.2 % (k=2). All photometer spectral responsivity calibrations can be made at the SCF which is much faster and less expensive than the SIRCUS. It is suggested to utilize the here discussed improvements in both the SCF and the Photometer Bench calibration procedures to decrease the 1996 scale uncertainty by about a factor of two. The uncertainty of the old photometric scale can be improved if the photometer standards used in the 1996 scale and also reference photometers of customers are calibrated against the transfer standard photometers.

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