Calibration of a High Dynamic Range, Low Light Level Visible Source

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ABSTRACT

Usage of image intensified (I^2) and other low light level devices have grown considerably over the past decade[1,2] As the systems have become more common place, the demand for production line test equipment has also grown. Accurate measurements of device response are a key part of determining acceptable system operation. However, differences in the spectral response of the unit under test (UUT) devices and the control detector; and the spectral distribution of the source, can lead to errors in test accuracy. These errors can be compounded by spectral variation in the source (or color temperature shifts) as a function of attenuation. These issues are often further confused by test system requirements that are not consistent with the desired parameter to be measured. For example, source requirements are often specified in illuminance while the UUT actually measures irradiance. We report on the calibration of a large dynamic range light source test system (> 7 orders), and discuss output compensation approaches for systems which control in a band different than the UUT being tested.

Keywords: LLTV, Low-light, EO Testing, Image Intensification, I2, Visible Testing

1. INTRODUCTION

Visible light imagers cover a tremendous dynamic range, from daylight to starlight conditions. A single test station for all visible sensors is desirable; however, engineering a source that can cover seven or more orders of magnitude and maintain the necessary accuracy and stability requirements is a challenge. Achieving low light levels without the use of attenuation filters requires an attenuator mechanism with a large dynamic range. Also, for fielded applications, there is a need for compact sources that can cover the required dynamic range for multiple sensors. SBIR has developed a family of Visible/Near Infrared (VIS/NIR) sources that cover the wide dynamic range demanded by today's sensors. The same detector and attenuator modules used in the sources form the basis for both fielded and laboratory test equipment. In order to cover the dynamic range with accuracy extensive calibration and validation is required to ensure proper operation.

The sources discussed below are based on a tungsten halogen lamp with an electro-mechanical attenuator to adjust the light level. This lamp and attenuator illuminate an integrating sphere which is viewed with and a silicon photodiode detector. The detector is used for feedback within a closed-loop control output. The source used approximates a blackbody output with an apparent temperature of 2856K (International Commission on Illumination or CIE illuminant A standard). Maintaining a consistent output spectrum throughout the dynamic range of a light source is critical to providing accurate output radiance with minimum of compensation on the part of the user. During calibration of any test system with a light source the spectral radiance of the source and the spectral response of the sensor must be considered. The sensor response will be the integral of the product of its spectral response and the source spectral radiance. If the source spectrum remains constant throughout the dynamic range of the system, a single integral will define system response and ease the calibration complexity of the system.

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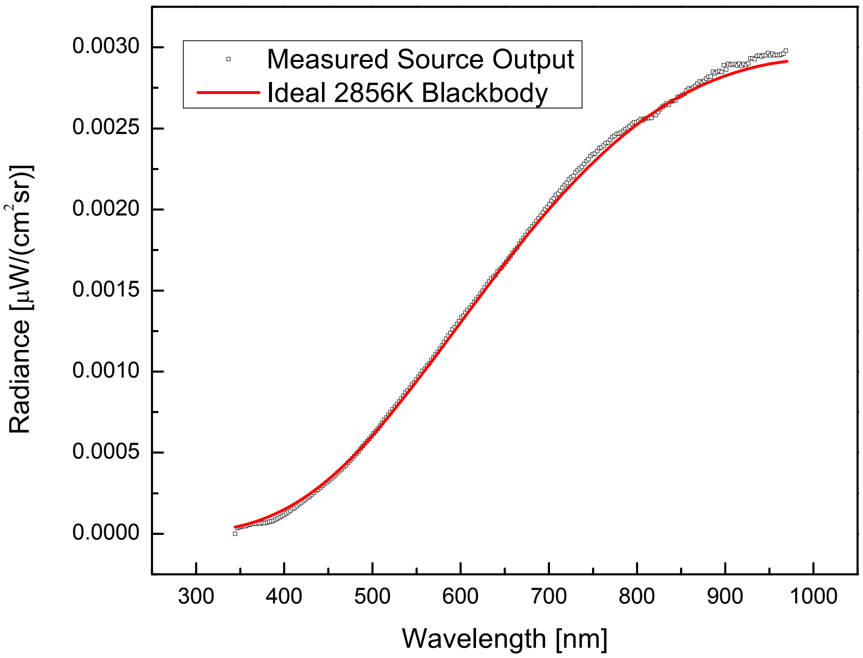

Figure 1. VSX spectrum compared to ideal blackbody source at 2856K.

A convenient way of discussing the spectral content of a tungsten filament visible/NIR source is to refer to its color temperature. Figure 1 shows the output of an SBIR VSX Series visible source compared to an ideal blackbody radiator at 2856K. The term color temperature has a precise definition based on the response of the human eye. For a source that is well described by a Planck curve, this temperature can be derived by calculating the ratio of radiance in a set of spectrally separate bands. Indeed, measuring through red and blue filters and then calculating the radiance ratio is a very common way of measuring color temperature for tungsten based sources. Just as the red and blue portions of the visible spectrum can be used to generate a band ratio which can then be used to extract an effective source temperature, other bands can be used as well. In fact, the bands need not be completely separate. As long as the source is reasonably well described by a blackbody curve, any two response curves that are spectrally sufficiently different can be used to extract a source temperature.

Consider the case of using a bare silicon (Si) detector compared to one with a flat spectral response. The measured signal of the flat detector will be proportional to the integral of the radiance in the response band of the detector, while that of the bare silicon detector will be modified by the silicon spectral response (Equations 1 and 2). Instead of using a discrete detector, a spectroradiometer and collect a continuous spectrum between 350 and 960 nm is used. This spectrum is integrated over the full band to represent the flat detector. The silicon detector is modeled by integrating the product of the source spectrum with the normalized silicon response. Figure 2 shows the calculated ratio of the two detectors for an ideal source over a range of temperatures. This change in ratio will lead to radiance errors if a non-flat detector is used. Figure 2 also shows the error introduced by source temperature change when using a bare silicon detector. It is important to note that although convenient, using a temperature to describe the spectral content of a real source can lead to confusion if that source does not follow a blackbody spectrum. Since the variable used for color temperature adjustment is lamp current; and is directly related to the filament temperature, it makes some sense to use source temperature as a figure of merit. However, to get accurate measurements from any real sensor, the entire source spectrum should be used.

$$Sig_{flat} = \int L(T,\lambda)d\lambda \qquad (1)$$

$$Sig_{Si} = \int \rho(\lambda) L(T,\lambda) d\lambda \qquad (2)$$

Where ρ(λ) is the spectral response of the detector, L(T,λ) is the spectral radiance described by the Plank function:

$$L(T,\lambda) = \frac{2hc}{\lambda^5} \frac{1}{e^{hc/kT} - 1} \qquad (3)^3$$

Where h is the Planck constant, c the speed of light in a vacuum, λ the wavelength, k the Stefan-Boltzmann constant and T the absolute temperature.

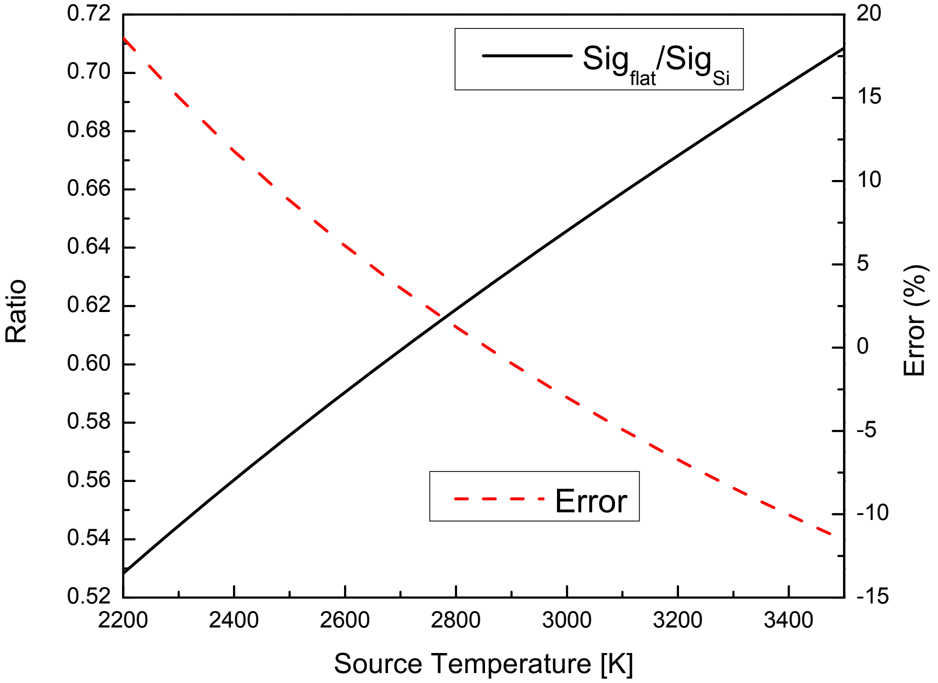

Figure 2 Ratio of flat response to bare silicon response as a function of source temperature. The dashed line and right axis show the radiance error as a function of source temperature when controlling with bare silicon detector

Attaining a constant source spectrum over multiple orders of magnitude is difficult in any circumstance. Doing so with a compact source and mechanical attenuator adds to the challenge. Although spectral variations were minimized in the design of the attenuator used, some still develop, particularly in the lowest radiance portion of the range. The spectral features introduced as the attenuator closes are generally well behaved in that they are slowly varying, monotonic in wavelength and do not have any sharp features. In fact, the variations are reasonably well approximated by a change in the apparent temperature of the source. Because of this good behavior, it is possible to perform a first order correction by adjusting the current to the lamp. The system has closed-loop control, so any drift introduced by adjusting the lamp current can be accounted for and stable output at the desired set point can be achieved. The VIS/NIR source systems developed by SBIR and discussed in the context of this paper (VSX series, VEO-2, and Common EO) all use a custom programmable constant current lamp supply allowing automated correction of color temperature shifts as the attenuator closes.

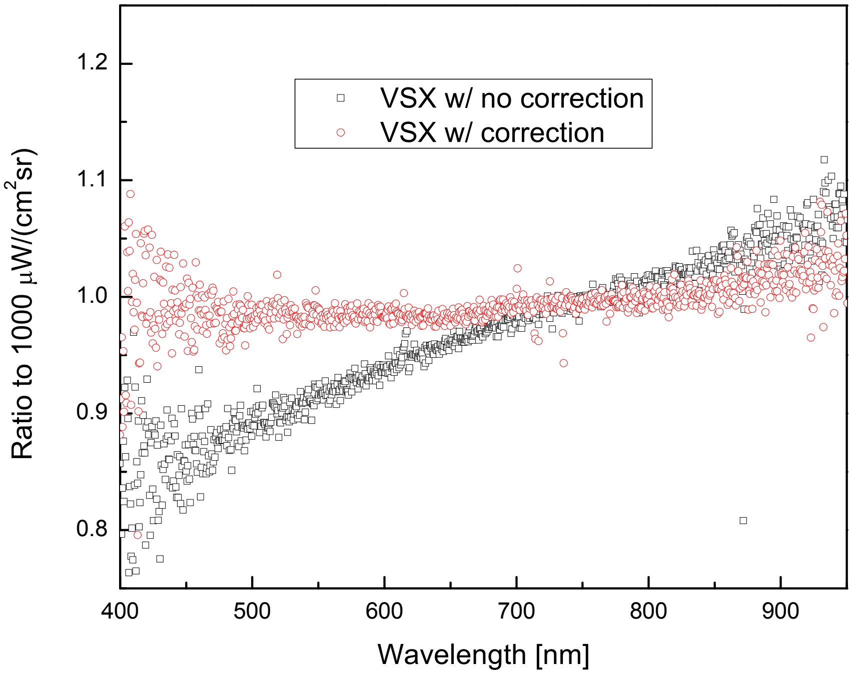

Figure 3 Ratio of the spectral radiance of a VSX source at 0.01 μW/(cm^{2}sr) to 1000 μW/(cm^{2}sr). The ratio has been normalized by the broadband radiance at the two set points.

Figure 3 shows the normalized ratio of a spectrum collected at 0.01 μW/(cm^{2}sr), to one collected at 1000 μW/(cm^{2}sr) without the spectral correction implemented along with a similar ratio after the lamp current has been adjusted to compensate for the spectral changes introduced by the attenuator. Although the spectral variation as a function of attenuation is approximated by a change in the temperature of the effective blackbody radiator, the fit is not perfect. In some cases, at very low radiance levels it is not possible to correct the spectrum at every wavelength. For the purposes of this paper, the correction has been weighted to give an acceptable response for both the CIE color temperature and for a bare silicon response. It is possible to adjust the lamp current to correct to other desired responses such as the photopic response or the response of a particular detector. It should be noted that although the correction cannot be perfect at every point on the spectrum, a broadband correction such as the bare silicon selected generally makes an improvement everywhere and provides acceptable accuracy for most applications.

2. EXPERIMENTAL SETUP

Two systems were calibrated using the methods described above. The first was SBIR's VSX-02 VIS/NIR source. The second was a VEO-2 integrated field test system. The VSX is a laboratory instrument designed primarily as an illumination source for target projection systems. Its broadband radiance range goes from 10000 μW/(cm^{2}sr) to 0.0001 μW/(cm^{2}sr). The lamp module (including the lamp and attenuator) and the detector module are the same design as those used in the fieldable systems such as Common EO (CEO) and VEO-2. The resolution and stability of a visible source using similar hardware have been presented in previous proceedings[4]. Although the sources provide broadband illumination, it is common to specify them in terms of their photopic characteristics. To ensure the best accuracy where a truly photopic source is required, a photopic filter is typically used in front of the control detector to limit its response to the desired band. Although this improves accuracy in the photopic region, the addition of the photopic filter significantly reduces the radiance falling on the control detector. The signal to noise ratio of the control detector sets the lower limit of the system control. One of the benefits of the spectral correction described above is that by removing the need for the filter it allows improved control at lower light levels without sacrificing accuracy in the photopic region.

The VEO-2 system is a compact, portable high performance test system that is used for test and evaluation of IR, visible/TV, DVO, and laser rangefinder/designator UUTs. It is designed to be operated in conjunction with the VIPER-T test station and is used by the Marine Corps for testing in both depot and field settings.

Spectroradiometric measurements were made using a Gamma Scientific GS-1290-1EX. The unit was equipped with a 200mm lens and all measurements were made using the largest aperture of 5 degrees. For the VEO-2 target projector, the spectroradiometer was focused at infinity. For the VSX source, it was focused at the plane of the output port.

The initial calibration of the system requires some calibration of the control sensor. This can be accomplished without using the spectral correction algorithm. Although there may be a slight broadband error introduced it will be corrected later during the final radiometric calibration using the correction algorithm. The detector/amplifier has four gain stages, each of which uses a two point (gain and offset) calibration. Once the detector is calibrated, the spectroradiometer is used to measure several points throughout the dynamic range of the system. For the first three gain stages, used at the all but the lowest light levels, the color temperature is derived using the standard CIE color temperature calculation. Starting at the collected point nearest the cross-over to the final gain stage the general method using the ratio between the silicon response and a spectrally flat detector is used. The later ratio is scaled so that the two are in agreement at the cross-over point. This removes systematic errors that may be introduced by any spectral content of the rest of the system, such as absorption bands in mirror coatings. The effective source temperature table is loaded into the system and a slope relating lamp current to color temperature is determined by measuring the temperature change of the source at a moderate light level after a minimal change in lamp current.

Custom software was developed to collect uncorrected measurements over the entire dynamic range. In addition to the CIE standard color temperature measurements, effective source temperatures based on the ratio of the silicon response to that of a flat detector are calculated. For low radiance levels, the silicon detector derived temperatures are averaged with the CIE color temperature measurements to generate a broadband correction. The correction table is loaded into the source controller and the four gain stages of the system are calibrated with the source temperature corrected. Following the calibration, measurements covering the entire dynamic range of the system are repeated to confirm the color temperature and radiance meets the specification of the system.

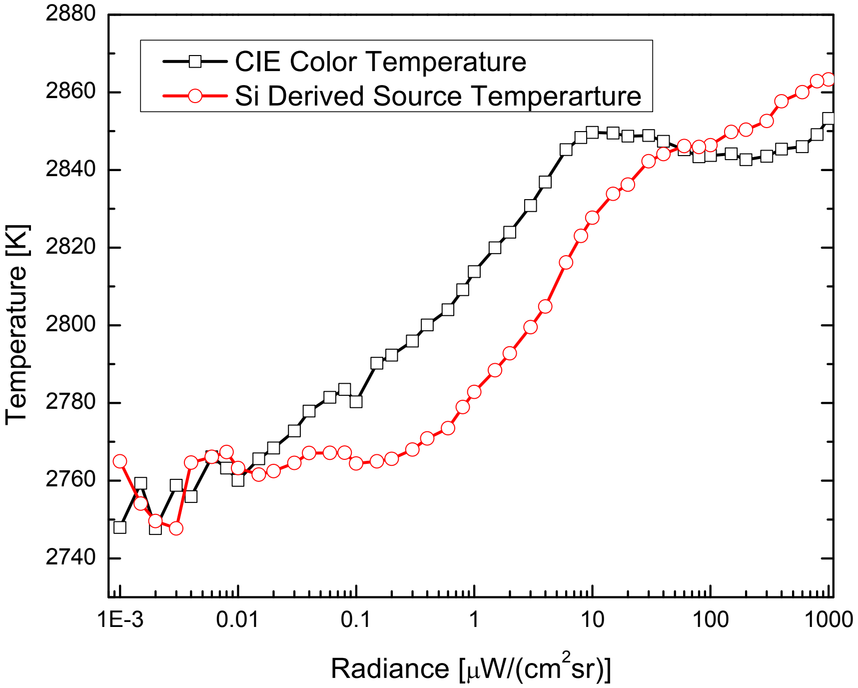

Figure 4 Source temperatures for VSX prior to correction.

3. PERFORMANCE DATA

3.1 VSX

A VSX-02 visible source was calibrated according using the method described above from 1000 μW/(cm^{2}sr) to 0.001 μW/(cm^{2}sr). Overall the correction method uf adjusting the lamp current was successful. Post correction spectra at all radiance levels were very close to the 1000 μW/(cm^{2}sr) nominal spectrum. All ratios were flat, similar to that shown in Figure 3. The color temperature shift and radiance error as a function of radiance set point, both before and after correction are shown in Figures 4 and 5. Figure 4 shows the color temperature of the system as measured during the initial measurement without use of the correction algorithm. It shows a variation from a start of 2856K at 1000 μW/(cm^{2}sr) to a low of 2745K at 0.001 μW/(cm^{2}sr). Figure 5 shows the color temperature with the use of the color temperature correction algorithm. The color temperature variation is considerably reduced. Whereas the initial range was over 100K, the system now has a maximum deviation of 27K from the 2856K nominal value. It is also worth noting that the color temperature measurements at the low end have increased error due to the low signal in the spectroradiometer measurements there.

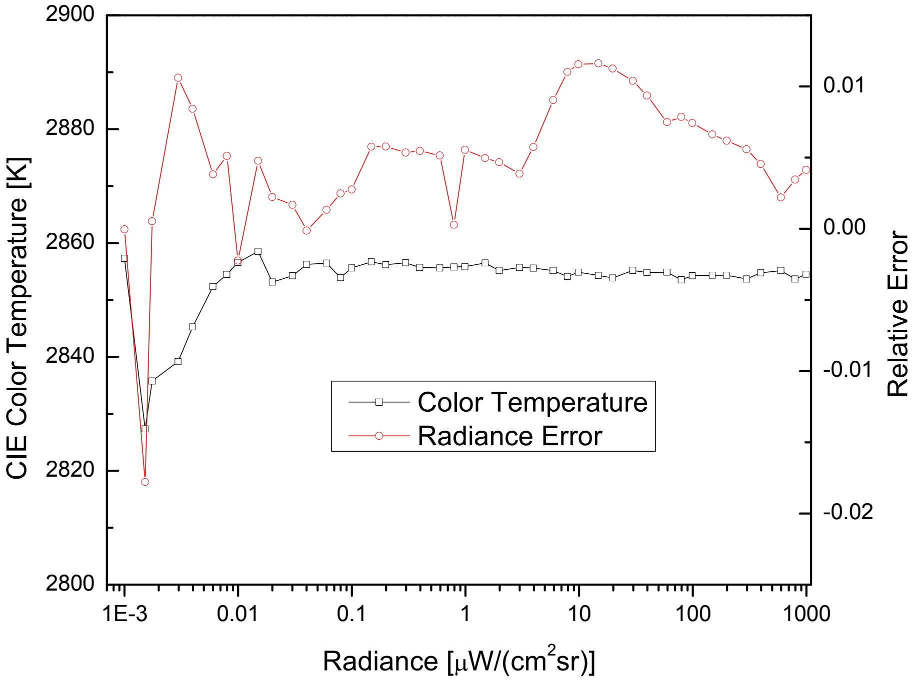

Figure 5 CT shift and radiance error in the VSX system after correction.

3.2 VEO-2

The VEO-2 system calibration follows a similar path to that of the VSX. One significant difference is that the system is calibrated through the collimator. In the case of VEO-2, the collimator consists of an off-axis parabola mirror as well as a secondary flat mirror. Both mirrors use aluminum with a dielectric coating for protection. The two mirrors introduce a significant absorption in the source spectrum as shown in Figure 6. Although the visible portion of the spectrum matches the blackbody spectrum reasonably well, the NIR portion of the VEO-2 spectrum shows a 20% dip near 800nm. A similar procedure was used on the VEO-2 starting with an initial detector calibration, followed by a color temperature measurement. The color temperature is then corrected after which a final detector calibration is performed. The spectral dip in the VEO-2 output has a significant effect on the in the Si/flat ratio leading to a source temperature of 2983K at 1000 μW/(cm^{2}sr) as opposed to 2856K in a CIE measurement. Correcting this systematic error is necessary to get any meaningful results from the Si detector derived temperature. Not only does the collimator transmission cause the ratio to change in magnitude, it also affects the relationship between the silicon control detector and the flat detector used for calibration. The collimator dip affects the spectrum near the detector peak proportionally more than the rest of the detector response. The result is a reduced slope of the ratio between the bare silicon detector and flat detector as a function of temperature. In order to properly deal with the collimator response, it must be incorporated in the modeled blackbody response. This leads to an approximate 40% decrease in the relative slope of the ratio between the silicon and flat detectors.

The VEO-2 unit showed a larger source temperature variation compared to the VSX. This is attributed to differences in the two source designs including baffling and the attenuator to sphere interface. As in the VSX, the two temperatures deviate as the attenuator closes. However, as opposed to the VSX, the two temperatures deviate more significantly as the radiance drops below 10 µW/(cm^{2}sr) (Figure 7). Figure 9 shows a ratio of the pre and post correction radiance at 0.01 µW/(cm^{2}sr) to that at 1000 µW/(cm^{2}sr). Both show a feature near 680 nm where the output at longer wavelengths is higher than that at shorter wavelengths. This feature, while small, is enough to limit the effectiveness of the source temperature correction. Corrections based on the CIE color temperature lead to a flat spectrum from 650 nm down, but the output above 700nm is relatively higher and leads to a slight radiometric error when controlling with a bare silicon detector. Correcting to the silicon derived source temperature would lead to a significantly higher CIE color temperature. In the case shown the correction is based on the CIE color temperature. The resulting color temperature variation and radiance error are shown in Figure 8. The pre-correction radiance error at 0.001 µW/(cm^{2}sr) was greater than 10%. Although increasing the lamp current further could improve the radiance accuracy, the color temperature would increase significantly. There is also a practical limit to how much increased current can be applied to the lamp before causing damage.

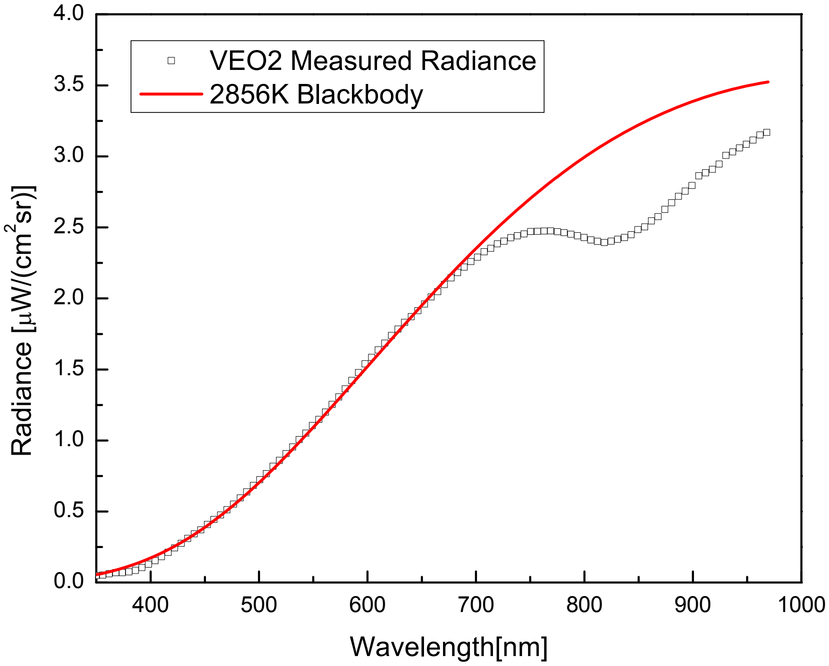

Figure 6 VEO-2 Spectrum compared to a 2856K blackbody. The dip near 850 nm is due to absorption of the collimator mirror coatings.

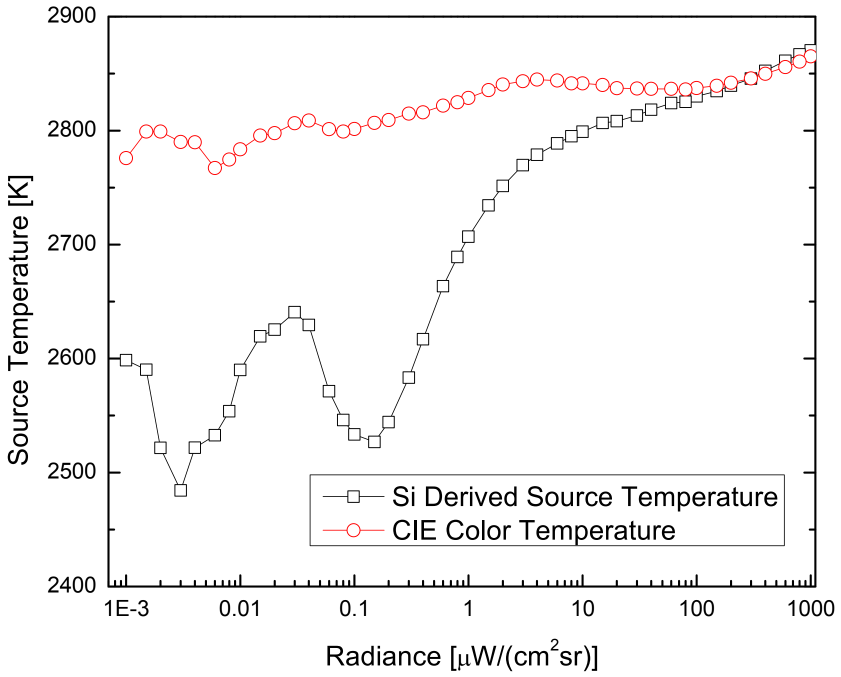

Figure 7 Source temperature variation in VEO-2. The silicon derived temperature has been corrected to match the CIE temperature at 1000 μW/(cm^{2}sr). The correction used for this system follows the CIE color temperature.

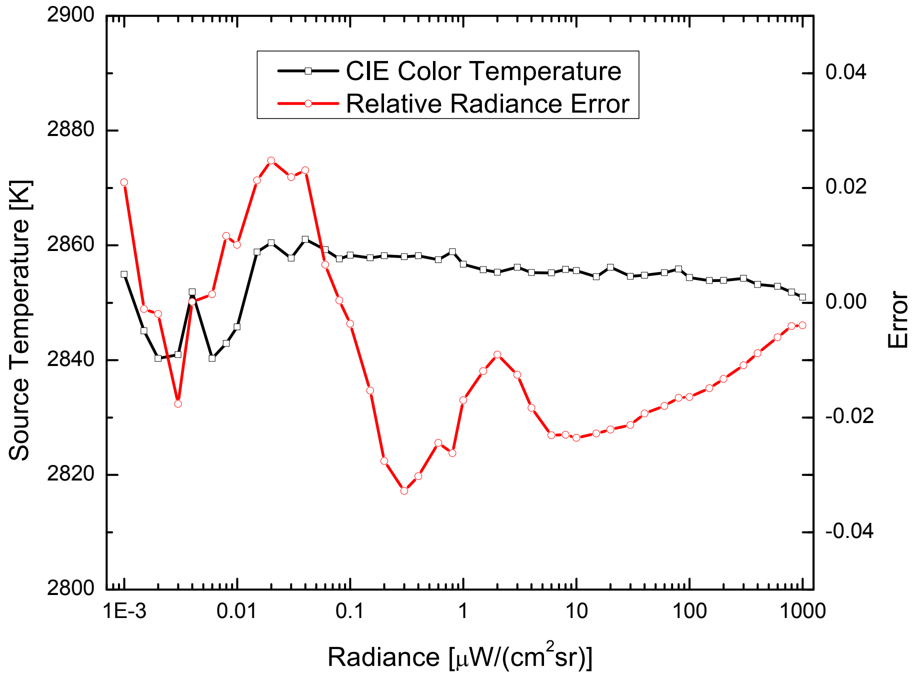

Figure 8 VEO-2 radiance error and color temperature after correction. Achieving similar results to the VSX is not possible due to the slight spectral variation shown in Figure 9.

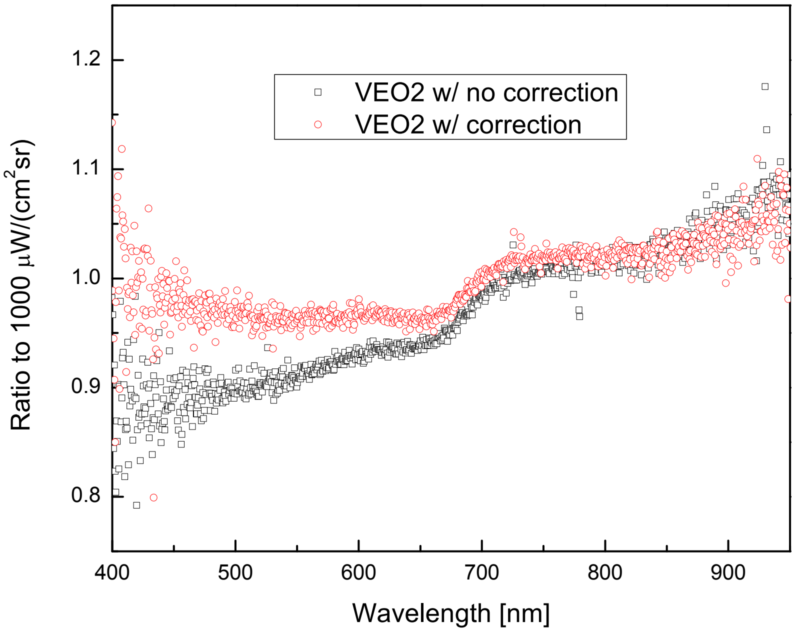

Figure 9. VEO-2 Comparison at 0.01 μW/(cm^{2}sr) . The above plots show the ratio of VEO-2 spectra between 1000 and 0.01 μW/(cm^{2}sr) both before and after correction. The VSX data in Figure 3 is quite well behaved compared to the VEO-2 above. The VEO-2 data shows a spectral feature near 675nm which limits the effectiveness of the lamp current correction.

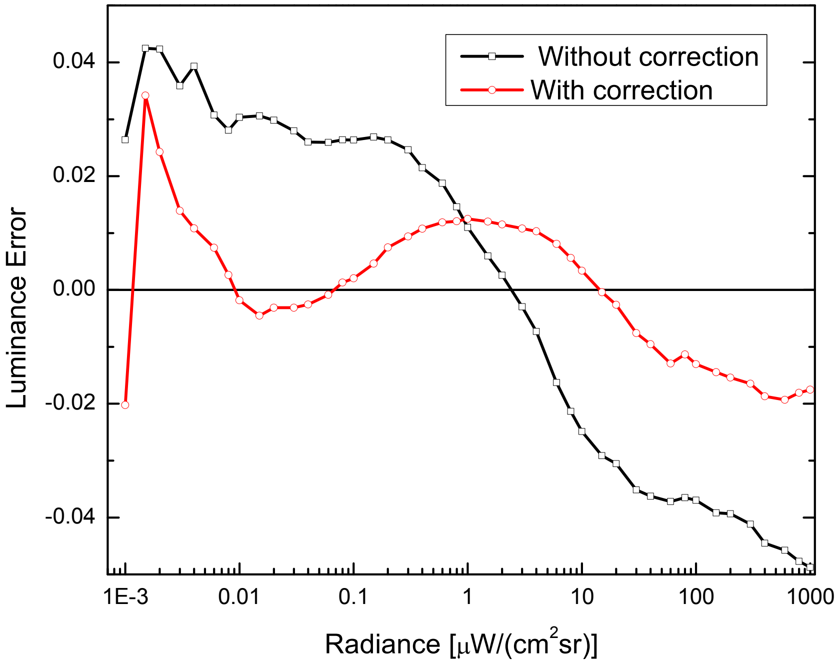

Figure 10. Luminance to radiance ratio.

Historically many source requirements are specified in terms of luminance. While proper for instances involving the response of the human eye, luminance is not a good measure when testing the response of many sensors available today. It can be a proper measure when discussing the visible output of many image intensification devices. In the case of the luminance requirement the correction of the source temperature allows accurate control at low light levels. Figure 10 shows the ratio of luminance to radiance for the VSX system before and after source temperature correction. Without the source temperature correction afforded by the lamp current control the luminance to radiance ratio decreases by almost 9%. After the correction, the ratio is more stable over the dynamic range of the source though it does reach a maximum deviation of 5% near the low end of the range.

4. SUMMARY

Having a constant spectrum over the entire dynamic range of a visible/NIR light source is critical accurate and repeatable testing. Without color temperature correction variations exist in the source spectrum as a function of attenuation. Adjustment of the lamp current can correct these spectral errors and lead to a more consistent spectrum. Color temperature and a similar effective source temperature derived from other band ratios were shown to give calibration data and lead to optimized spectral correction with an automated data collection routine. For the VSX system, spectral errors were kept to less than 4% over the measurable range of the source. Broadband radiometric error was kept to <2% over the range. In the case of the VEO-2 system, comparable results were achieved down to 0.1 $\mu W/(cm^2 sr)$. Below that level, spectral variations prevent an optimal correction in both CIE color temperature and radiance accuracy. Selecting an average between the two corrections leads to acceptable system performance for the fielded system.

There is very little discussion of spectral effects in the literature for low light level visible test systems. Some of this may be due to a lack of spectral test capabilities at low light levels. There also seems to be a trend in continuing to use luminance or even illuminance to specify a source output. The latter is especially troubling as it refers to the intensity of light falling on a surface and does not have an angular component. It would benefit the community if a proper requirement standard were developed to replace the ones that frequent current requirements documents. The standard should consider the source spectrum and be specified in terms of radiance. There would be an effort to convert from existing requirements but the improved accuracy and consistency would be worth the effort.

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