Journal of Physics: Conference Series

PAPER • OPEN ACCESS

A simple method of UV stray light correction for field spectrometers in Ground Validation Sites

To cite this article: L Li *et al* 2022 *J. Phys.: Conf. Ser.* **2149** 012004

A simple method of UV stray light correction for field spectrometers in Ground Validation Sites

L Li [1], Z Wu[1], E R Woolliams[2], C Dai[1] and Y Wang[1]

[1] Division of Optics, National Institute of Metrology, Beijing, China
[2] Thermal and Radiometric Metrology Department, National Physical Laboratory, Teddington, UK

Correspondence: liling@nim.ac.cn

Abstract. Field spectrometers are widely applied in ground validation sites for remote sensing. However, the control of stray light is one of the most important factors to ensure accurate measurements, since the spectral distribution of target source differs significantly from the laboratory calibration source. Here, a simple UV stray light correction method for continuously distributed wide-spectrum light sources was established by using a set of bandpass filters. This analysis enabled a simple, low-cost method for correcting for the observed straylight.

1. Introduction

In order to increase the accuracy of current Earth Observation measurements, the methodologies used to perform the post-launch monitoring of Earth-observing sensors and onboard calibration systems have advanced to include in situ measurements at ground validation sites [1-3]. Such measurements may be part of a field campaign that is matched to a satellite overpass, or at permanently instrumented sites, such as the Radiometric Calibration Network, RadCalNet [4]. For both field campaigns and for permanently instrumented sites, array spectrometers can provide valuable information on the spectral reflectance of the ground, and in some cases the spectral properties of the downwelling solar and sky irradiance. However, stray light remains one of the biggest challenges, since CCD array spectrometers often have problems such as internal structural defects and unsatisfactory optical components, which seriously affect the accuracy of measurements. These effects can influence the determined ground reflectance, since the spectral distribution of solar radiance is different from that of the calibration light source (Fig. 1). Thus, the internal spectral stray light is one of the main uncertainty sources for laboratory calibrated spectrometers which are used in the ground-based validation sites.

The Baotou artificial (BTCN) and sandy (BSCN) sites of RadCalNet use spectrometers as the permanent instrumentation providing the RadCalNet service with spectral ground reflectance measurements every 30 minutes for satellite comparison. The uncertainty budget for these sites [5] showed that stray light was the dominant source of uncertainty for wavelengths below 500 nm.

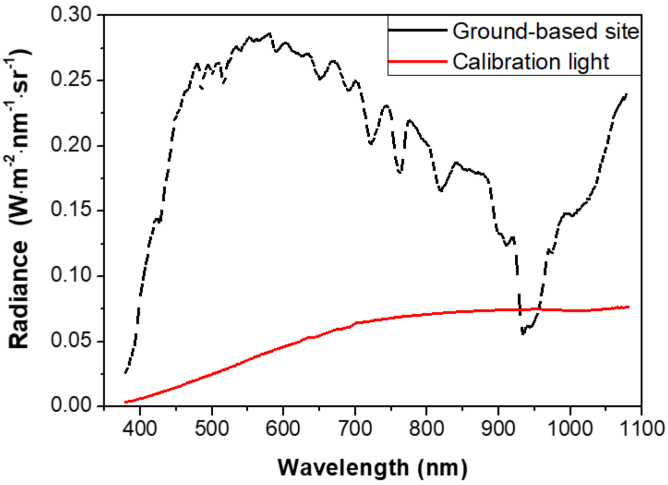

Figure 1. The radiance of a Spectralon panel illuminated by an FEL lamp and typical ground-based sites.

Several approaches for the correction of spectral stray light have been proposed [6-8]. In particular, the method proposed by Zong et al. [8] is widely used and has been studied by many researchers. It is an efficient and accurate correction method that obtains the spectral line spread functions for every pixel by using a set of monochromatic laser sources. This method is used to correct multichannel hyperspectral spectrographs of the Marine Optical Buoy (MOBY) and other optical instruments [9-11]. Building on the theoretical background of Zong et al., several researchers have developed practical approaches to stray light correction. Salim et al. presented an efficient and low-cost stray light correction approach based on a relatively simple system using a monochromator-based source [12]. Nevas et al. presented a method for the simultaneous correction of bandpass and stray light effects in array spectroradiometer data [13]. And then Nevas et al. presented an approach to characterize and correct stray light in spectra measured with array spectroradiometers and caused by out-of-spectral range radiation [14]. Talone et al. studied the stray light effects in above-water remote-sensing reflectance from hyperspectral radiometers [15]. Schinke et al. presented a guide to the implementation and uncertainty evaluation for spectral stray light corrections according to the widely used method as proposed by Zong et al. In their work, the significant uncertainty contributions result from drifts of the spectrometer's dark signal and the width of the in-band region selected for shaping stray light distribution functions were analyzed [16].

However, the tunable lasers are relatively expensive and hard to maintain for most laboratories. In a previous study at NPL, Salim et al. evaluated the stray light performance of spectrometers by cut-on filters. Shaw presented the stray light errors in array spectrometer of goniospectroradiometric measurement system by using a filter wheel containing several band-pass filters [17].

In this paper, the stray light performances of various typical field spectrometers were characterized. A simple and low-cost correction method was established for continuously distributed wide-spectrum light sources by using a set of bandpass filters. The mathematical correction result was also validated.

2. Stray light characterization

To assess the stray light performance of different spectrometers, a cut-on (long pass) filter was used. Cut-on filters have extremely low transmittance at wavelengths shorter than the cut-on wavelength. For an ideal system, the ratio of the measured signals for the lamp with filter to those for the unfiltered lamp will give a result equal to the transmittance of the cut-on filter. In the fact, any significant measured signal at these wavelengths therefore indicates the presence of stray light. Four field spectrometers, FieldSpec4 (ASD), HR-1024i (SVC), PSR+3500 (Spectral Evolution), and CR280 (Colorimetry Research), were calibrated by reflectance panel and FEL lamp. Then a 450 nm cut-on filter was placed in front of each spectrometer, with the same measurement settings as for the unfiltered measurements.

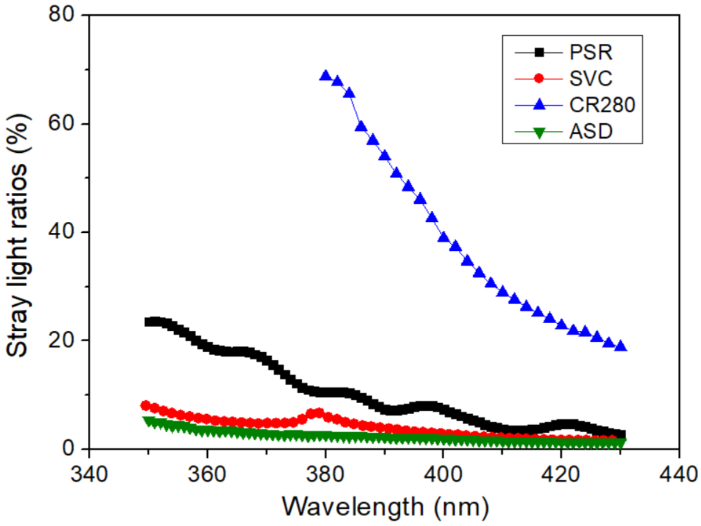

Figure 2. The stray light ratios of four field spectrometers.

The stray light ratios (σ) for the UV wavelengths were calculated by dividing the measured signal with the cut-on filter, by the measured signal during the original calibration, using the formula $\sigma = L_{\mathrm{f}}/L_{\mathrm{c}} \times 100\%$. As is shown in Figure 2, The stray light ratios are more than 5% for wavelengths around 350 nm, even for the best spectrometers. This is because the spectral radiance of lamp-panel source is several orders of magnitude higher at longer visible to near-infrared wavelengths than at shorter visible or ultraviolet wavelengths and the silicon-based detector arrays have a significantly higher spectral responsivity at longer visible and near-infrared wavelengths than at shorter wavelengths. Thus, if even a small fraction of the longer wavelength radiation is scattered onto the short wavelength sensing part of the detector array, it can dominate the signal measured at these shorter wavelengths. For the more compact spectrometers, such as the CR 280 (used for the Baotou measurements), the σ value is much higher.

In order to evaluate the UV stray light performance of CR 280 caused by light of different wavelengths, a set of cut-on filters were used, the transmittance of filters (Fig. 3) was measured by the standard setup in NIM. The cut-on filters have extremely low transmittance around 1E-6~1E-7. As shown in Figure 4, the percentage of stray light in UV range can be obtained which caused by different wavelength ranges. The stray light at 390 nm originating from 550 nm to infrared wavelengths is notated by $L_{\mathrm{stray\ a,390}}$, and that originating from 650 nm to infrared range notated by $L_{\mathrm{stray\ b,390}}$. The stray light at 390 nm caused by the wavelength range from 550 nm to 650 nm can be obtained by subtracting $L_{\mathrm{stray\ b,390}}$ from $L_{\mathrm{stray\ a,390}}$. Similarly, the UV stray light caused by 650 nm – 780 nm and 780 nm – 900 nm can be obtained.

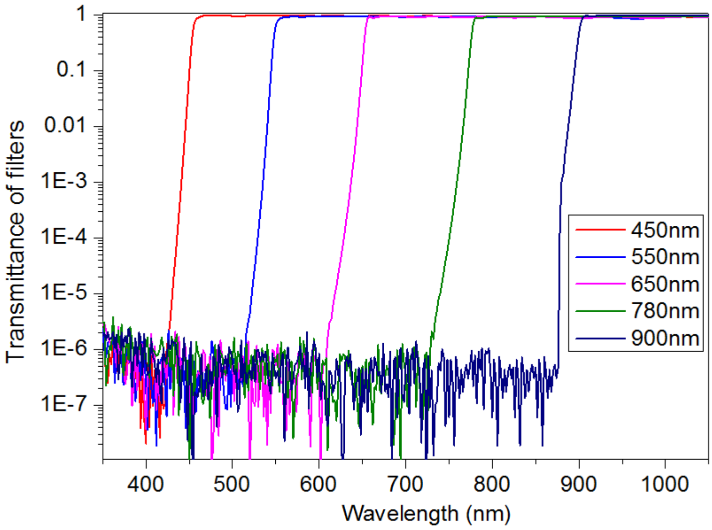

Figure 3. The transmittance of different cut-on filters.

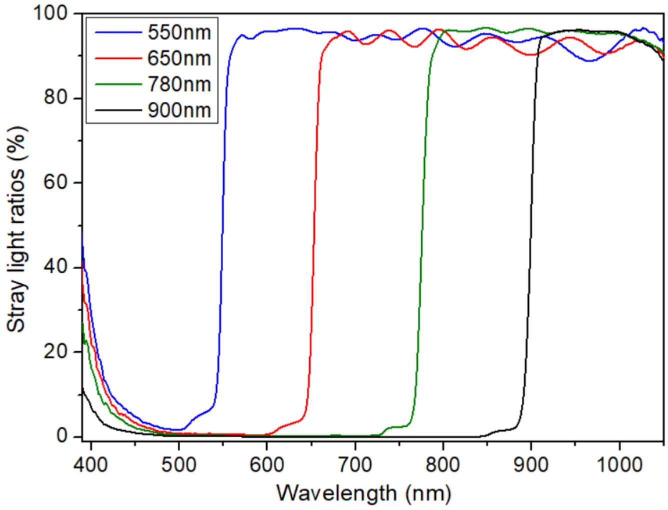

Figure 4. Stray light ratios (ratio of signal with and without the filter) of CR280 with different cut-on filters.

3. Results

The stray light of UV wavelength ranges can be evaluated since it is mainly from long wavelengths to short wavelengths. According to the correction method of Ma et al. [5], the corrected signal in the field can be calculated from the measured signal at longer wavelengths and the signal, $s(l)$ determined in the laboratory during calibration as:

$$s(l) = \frac{L_{\text{f, cal}}(l)}{\int_{\lambda_{\min}}^{1080\text{nm}} \tau_{\text{f}}(\lambda)\, L_{\text{true, cal}}(\lambda) d\lambda}$$

$$L_{\text{true, field}}(l) = L_{\text{nf, field}}(l) - s(l) \int_{\lambda_{\min}}^{1080\text{nm}} L_{\text{true, field}}(\lambda) d\lambda$$

$L_{\text{nf, source}}(\lambda)$ is the signal with no filter of the source, $L_{\text{f, source}}(\lambda)$ is the signal with a filter and the source, $L_{\text{true, source}}(\lambda)$ is the signal that would be measured if the instrument had no stray light response, $\tau_{\text{f}}(\lambda)$ is the transmittance of filter, l is the wavelength (of a short wavelength pixel that is sensitive to the stray light), $\lambda_{\min}$ is the shortest wavelength that is considered "long wavelength", $s(l)$ is the fraction of the long wavelength light that makes it to pixel l.

Here, the 550 nm cut-on filter results were used to evaluate $s(l)$ for wavelengths up to 500 nm and the 650 nm cut-on filter for wavelengths from 502 nm to 590 nm. A 780 nm cut-on filter was used from 592 nm to 710 nm and a 900 nm cut-on filter for wavelengths from 712 nm to 870 nm. As is shown in Figure 5, the stray light is less significant in the field than in the laboratory because in the field the radiance at long wavelengths is a similar magnitude to that at short wavelengths, while in the laboratory the source is considerably brighter at longer wavelengths.

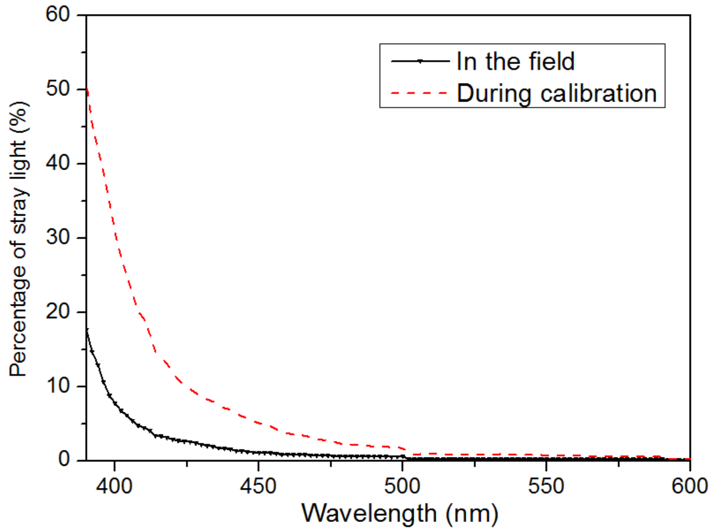

Figure 5. Stray light signal as a percentage of the measured signal for both calibration and for a typical in field radiance

The equations above allow the field radiance to be corrected based on the laboratory measurements alone. It is also possible to test the stray light levels in the field using the same cut-on filters, however this is not practical during automated, routine operations. To check whether the stray light correction that was calculated for the field measurements based on the laboratory calibration and the equations above is valid, a comparison was made between the calculated an in-field measured stray light results. For this analysis, the compact spectrometer CR 280 was installed in the field and the radiance of solar diffuser panel was measured. Then a 550 nm cut-on filter was placed in front of CR 280, with the same measurement settings as for the unfiltered measurements in a very short time interval. As shown in Figure 6, the stray light of CR 280 measured in field is almost the same with that evaluated results based on the laboratory FEL lamp test. The deviation of measured result and calculated one is below 1.5%, compared to a deviation of 14% before correction.

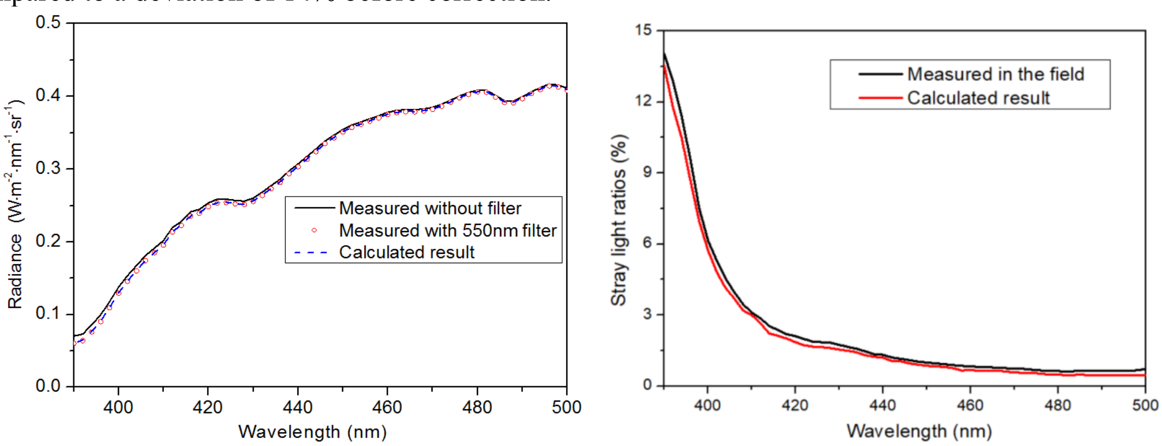

Figure 6. Validation of the stray light correction method

4. Conclusion

In this paper, a simple and low-cost stray light correction method was described. Measurements in the laboratory with a simple set of bandpass filters could be used to calculate an in-field correction that was close to that measured by bandpass filters in the field. This means that the automated measurements do not need to be adjusted to include in-field filter measurements. This method can be easily used for most commercial array spectrometers, which is applied to measure continuously distributed wide-spectrum light sources. It is important to note, however, that this method makes several assumptions, including that the cut-on filters have perfect rectangular cut-on spectral shapes and, more significantly, that the spectrometer itself only has spectral stray light that is longer wavelength light reaching the shortest wavelengths. In practice we would expect a more complex stray light response and therefore work is ongoing to set up methods for more complete stray light characterization based on the method of Zong et al. Such an analysis on the same spectrometer would also provide information on the uncertainty associated with this simpler method. However, the stray light correction method described here has provided an immediate and noticeable improvement to the RadCalNet data provided by the Baotou sites.

Acknowledgments
This work was supported by the National Key R&D Program of China, 2018YFB0504800 (2018YFB0504804).

References

[1] Chander G, Hewison T J, Fox N, Wu X, Xiong X and Blackwell W J Overview of Intercalibration of Satellite Instruments 2013 *IEEE Trans. Geosci. Remote Sens.* **51** 1056–80.
[2] Bouvet M Radiometric comparison of multispectral imagers over a pseudo-invariant calibration site using a reference radiometric model 2014 *Remote Sens. Environ.* **140** 141–154.
[3] Czapla-Myers J, McCorkel J, Anderson N and Biggar S Earth-observing satellite intercomparison using the Radiometric Calibration Test Site at Railroad Valley 2017 *J. Appl. Remote Sens.* **12** 012004.
[4] Bouvet M, Thome K, Berthelot B, Bialek A, Czapla-Myers J, Fox P N, Goryl P, Henry P, Ma L, Marcq S, Meygret A, Wenny B N and Woolliams E R RadCalNet: A Radiometric Calibration Network for Earth Observing Imagers Operating in the Visible to Shortwave Infrared Spectral Range 2019 *Remote Sens.* **11** 2401.
[5] Ma L, Zhao Y, Woolliams E R, Dai C, Wang N, Liu Y, Li L, Wang X, Gao C, Li C and Tang L Uncertainty Analysis for RadCalNet Instrumented Test Sites Using the Baotou Sites BTCN and BSCN as Examples 2020 *Remote Sens.* **12** 1696.
[6] Brown S W, Johnson B C, Feinholz M E, Yarbrough M A, Flora S J, Lykke K R, Clark D K, Stray-light correction algorithm for spectrographs 2003 *Metrologia* **40** 81–4.
[7] Ylianttila L, Visuri R, Huurto L and Jokela K Evaluation of a single-monochromator diode array spectroradiometer for sunbed UV-radiation measurements 2005 *Photochem. Photobiol.* **81** 333–41.
[8] Zong Y, Brown S W, Johnson B C, Lykke K R and Ohno Y Simple spectral stray light correction method for array Spectroradiometers 2006 *Appl. Opt.* **45** 1111–9.
[9] Feinholz M E, Flora S J, Brown S W, Zong Y, Lykke K R, Yarbrough M A, Johnson B C and Clark D K Stray light correction algorithm for multichannel hyperspectral spectrographs 2012 *Appl. Opt.* **51** 3631–41.
[10] Shen H, Pan J, Feng H and Liu M Stray light errors in spectral colour measurement and two rejection methods 2009 *Metrologia* **46** 129–35.
[11] Park S, Lee D H, Kim Y W and Park S N Uncertainty evaluation for the spectroradiometric measurement of the averaged light-emitting diode intensity 2007 *Appl. Opt.* **46** 2851–8.
[12] Salim S G R, Fox N P, Hartree W S, Woolliams E R, Sun T and Grattan K T V Stray light correction for diode-array-based spectrometers using a monochromator 2011 *Appl. Opt.* **50**

5130–8.
[13] Nevas S, Wübbeler G, Sperling A, Elster C and Teuber A Simultaneous correction of bandpass and stray light effects in array spectroradiometer data 2012 *Metrologia* **49** 43–7.
[14] Nevas S, Gröbner J, Egli L and Blumthale M Stray light correction of array spectroradiometers for solar UV measurements 2014 *Appl. Opt.* **53** 4313–9.
[15] Talone M, Zibordi G, Ansko I, Banks A C and Kuusk J Stray light effects in above-water remote-sensing reflectance from hyperspectral radiometers 2016 *Appl. Opt.* **55** 3966–77.
[16] Schinke C, Franke M, Bothe K and Nevas S Implementation and uncertainty evaluation of spectral stray light correction by Zong's method 2019 *Appl. Opt.* **58** 9998–10009.
[17] Shaw M and Goodman T Array-based goniospectroradiometer for measurement of spectral radiant intensity and spectral total flux of light sources 2008 *Appl. Opt.* **47** 2637–47.