Stray light correction of array spectroradiometer data for solar UV measurements

Saulius Nevas[1], Julian Gröbner[2] and Luca Egli[1]

1. Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2. Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos, Switzerland

Introduction

Compact array spectroradiometers are used to monitor surface spectral solar ultraviolet radiation. In order to ensure measurements with acceptable uncertainties the instruments have to be carefully characterised and calibrated. One of the highest uncertainty components in the measurements by the array spectroradiometers is caused by a poor suppression of the spectral stray light, known also as the out-of-band response or spectral leakage. Their stray light properties are inferior to those of the scanning systems due to a compact design and the principle of operation of the instruments. Nevertheless, numerical correction methods exist enabling a correction of the stray light effects using a correction matrix determined with the help of spectrally tuneable monochromatic radiation [1, 2]. Provided that the stray light properties of an array spectroradiometer, i.e. the spectral response of the instrument to a monochromatic excitation, are known for any wavelength within the spectral range of the array spectroradiometer, a numerical improvement of the stray light suppression by one to two orders of magnitude is possible. The correction is, however, effective only as long as the spectral range of the instrument coincides with the spectral range of the array detector in use. Thus, a stray light correction matrix determined for an array spectroradiometer is limited to its spectral range to, e. g., 250 nm to 400 nm. Having a silicon CCD detector, that typically is able to detect optical radiation up to 1100 nm, the matrix would be little effective unless additional measures are taken in order to account for the stray light that is created outside of the spectral range of the spectroradiometer, i.e. within 400 nm to 1100 nm, which can still be detected by the Si-detector. The effect of the long-wavelength stray light is amplified due to the fact that thermal sources (e.g. halogen lamps) are used for the calibration of the instruments and the responsivity of the Si detectors is higher for the radiation at longer wavelengths than for shorter wavelengths. The simplest way of taking care of this stray light, let's call it out-of-range (OoR) in order to differentiate from the in-range (InR) stray light that is included in the correction matrix, would be by using bandpass filters or other spectral pre-selection techniques that block the OoR radiation at the entrance of the instrument [3]. It is also possible to characterise the effects of the OoR stray light using tuneable laser sources. In contrast to the normal stray light characterisation procedure, however, an additional calibrated instrument is needed as reference for the OoR radiation measurements during the characterisation. In this *UVNews* issue we present such a work started within the EMRP project "Traceability for surface spectral solar ultraviolet radiation" and show preliminary results obtained for a solar UV spectroradiometer operated by the PMOD/WRC in Davos.

Correction of out-of-range and in-range spectral stray light

We start with the equation (4) in the original stray light correction method by Zong. et al. [1]. Using a matrix notation, the spectral stray light signal vector $\mathbf{Y}_{\mathrm{s\_spec}}$ can be written as

$$\mathbf{Y}_{\mathrm{s\_spec}} = \mathbf{D} \cdot \mathbf{Y}_{\mathrm{IB}} + \mathbf{\Delta} \tag{1}$$

where $\mathbf{D}$ is the spectral stray light distribution matrix, $\mathbf{Y}_{\mathrm{IB}}$ is the in-band signal vector and $\mathbf{\Delta}$ is a vector with the OoR stray light contribution for every pixel of the detector. The OoR stray light vector $\mathbf{\Delta}$ can be found as

$$\mathbf{\Delta} = \mathbf{s}_{\mathrm{OoR}} \cdot \mathbf{E}_{\mathrm{OoR}} \cdot \delta\lambda\ , \tag{2}$$

provided that the responsivity of every detector pixel to the radiation at different wavelengths outside the spectral range of the instrument, put in a matrix $\mathbf{s}_{\mathrm{OoR}}$, and the spectral irradiance outside the spectral range of the spectroradiometer, contained in a vector $\mathbf{E}_{\mathrm{OoR}}$, are known. $\delta\lambda$ represents the OoR wavelength step with which the OoR stray light data are available. The dimension of the matrix $\mathbf{s}_{\mathrm{OoR}}$ is *N*x*M*, where *N* is the number of pixels in the array detector and *M* is the number of the OoR stray light data vectors distribute on a uniform wavelength grid throughout the OoR of the instrument, say every 1 nm. Then we can follow the matrix formalism of [1] and write down the measured signal vector as

$$\mathbf{Y}_{\mathrm{meas}} = \mathbf{Y}_{\mathrm{IB}} + \mathbf{D} \cdot \mathbf{Y}_{\mathrm{IB}} + \mathbf{\Delta}\ , \tag{3}$$

and finally the spectroradiometer data vector corrected for both the InR and OoR spectral stray light as

$$\mathbf{Y}_{\mathrm{IB}} = [\mathbf{I} + \mathbf{D}]^{-1} \cdot [\mathbf{Y}_{\mathrm{meas}} - \mathbf{\Delta}] = \mathbf{A}^{-1} \cdot [\mathbf{Y}_{\mathrm{meas}} - \mathbf{\Delta}]\ . \tag{4}$$

Hence, the OoR stray light contribution $\mathbf{\Delta}$ first needs to be subtracted from the measured signal vector $\mathbf{Y}_{\mathrm{meas}}$, before applying the stray light correction matrix. It has also to be noted that the spectral irradiance $\mathbf{E}_{\mathrm{OoR}}$ outside of the spectral range of the array spectroradiometer, for the wavelengths up to 1100 nm, needs to be known for both the source used to calibrate the instrument and the source under test in order to be able to apply the correction of (4). For calibration sources such data is typically available. The OoR stray light estimation for a test source, i.e. the solar radiation, however, requires either measurements by an auxiliary spectroradiometer or some kind of prediction (e.g., with radiative transfer model calculations) for the spectral content in the OoR based on the InR measurement data by the instrument. An example of such a procedure is provided in the following section.

The stray light properties of array spectroradiometers, i.e. the Line Spread Functions (LSFs), can be determined by means of wavelength tunable lasers. At PTB, Pulsed Laser for Advanced Characterisation of Spectroradiometers (PLACOS) setup is routinely used for this purpose [4]. To determine the OoR stray light responsivity matrix $\mathbf{s}_{OoR}$ the setup was slightly modified. Figure 1 shows schematically the PLACOS setup adapted for the OoR stray light measurements. Here, a microlense array-based laser beam homogenizer was used to generate a uniform field irradiating subsequently the input optics of the solar UV array spectroradiometer and of a calibrated reference spectroradiometer with its spectral range extending from 200 nm to 1100 nm. The reference instrument enables to quantify the spectral irradiance to which the test instrument is exposed outside of his spectral range. The monitor instrument helps to compensate for the variation in the laser output power during the measurements.

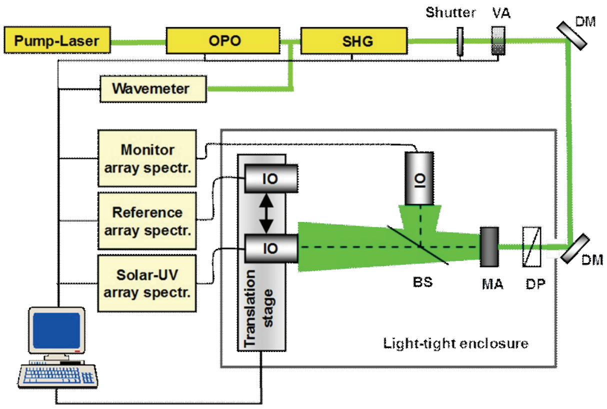

Figure 1. PLACOS setup adapted for the out-of-range stray light characterisation of array spectroradiometers. OPO: optical parametric osicilator; SHG: second harmonic generator; IO: input optics (diffuser head) connected via a fibre link to an array spectroradiometer; BS: beam splitter; MA: microlense array-based beam homogeniser; DP: depolariser; DM: dichroic mirror; VA: variable attenuator.

Preliminary results

As a first artifact selected for studies within the project, an AvaSpec-ULS array spectroradiometer owned by the PMOD/WRC, named AVOS, was characterized both for InR and OoR stray light properties at the PLACOS setup of PTB. The Instrument has a nominal spectral range of 280 nm to 440 nm, 0.7 nm bandpass and a Hamamatsu back-illuminated Si CCD with 2048 pixels. As a reference instrument for the OoR stray light characterization, another AvaSpec-ULS array spectroradiometer with its spectral range from 200 nm to 1100 nm was used. The determined InR stray light properties of the AVOS are shown in Figure 2. Figure 3 displays the responsivity of the spectroradiometer to the OoR stray light at several selected wavelengths. By examining Figure 3 one can notice that the response of the instrument to the OoR stray light is changing within the spectral range of the spectroradiometer mostly for the OoR wavelengths of up to about 600 nm. The response to the OoR radiation at wavelengths above 600 nm is relatively monotonous over the spectral range of the AVOS spectroradiometer meaning that the data can be safely interpolated based on the measurements at several OoR wavelengths.

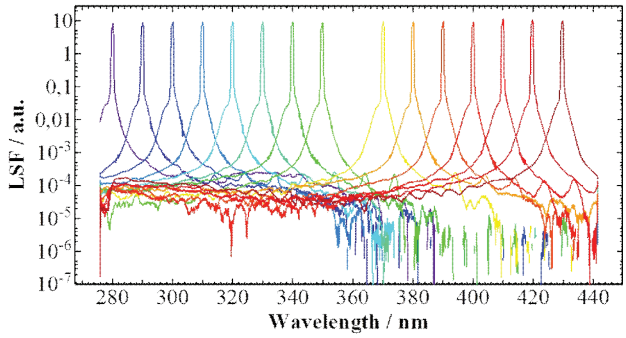

Figure 2. In-range stray light properties of the AVOS spectroradiometer.

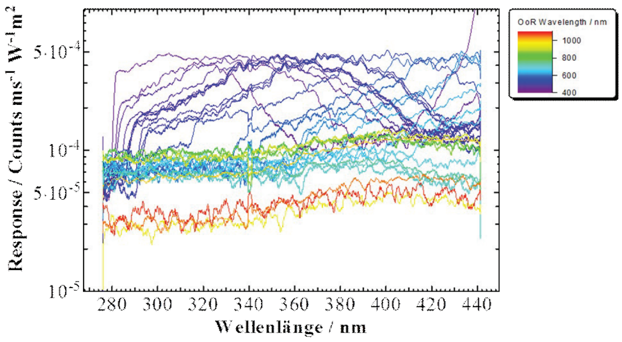

Figure 3. AVOS spectroradiometer response to the out-of-range stray light caused by the radiation at 440 nm to 1100 nm wavelengths.

The stray light characterisation data of the AVOS spectroradiometer was used to determine a correction matrix for the InR stray light. The OoR stray light contribution (2) during the spectral irradiance responsivity calibration of the instrument was estimated from the lamp spectral irradiance values. Thus, the responsivity of the spectroradiometer including the correction for the InR and OoR stray light could be determined with the help of (4). In the next step, solar UV irradiance data obtained by the AVOS spectroradiometer in a clear sky measurement campaign in Davos were treated. Here, the biggest challenge in applying the OoR stray light correction was to determine the solar OoR irradiance $\mathbf{E}_{OoR}$ during the measurements as no auxiliary instrument measuring the solar radiation up to 1100 nm was available during these measurements. For this purpose the OoR solar irradiance was estimated with the "Libradtran radiative transfer model" [5]. The model was initialized with measured input parameters (ozone, aerosols) and the radiative transfer was obtained under clear sky conditions. The modeled spectra showed accurate congruence to the InR UV measurements and it is, thus, assumed that the modeled OoR spectra reflect a realistic solar input from this wavelength range. Figure 4 shows results obtained with the OoR and OoR&InR stray light correction applied to AVOS measurement data compared with the double monochromator reference data and the solar irradiance determined by AVOS without any stray light correction.

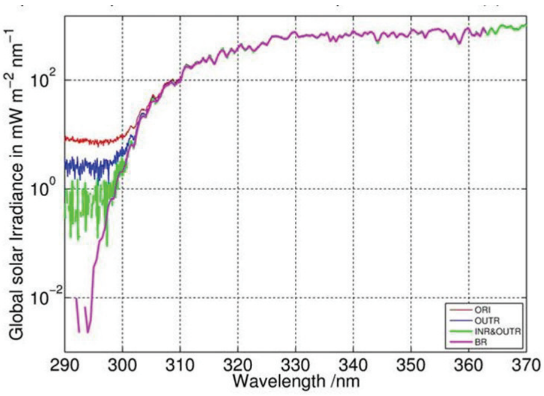

Figure 4. Stray light correction of AVOS spectroradiometer. Magenta Curve is the solar spectrum measured with a scanning double monochromator. The red curve is the calibrated solar spectrum from AVOS without any stray light correction applied. The blue and green curves are the solar spectra corrected for the OoR and the OoR&InR stray light, respectively.

Conclusion and outlook

Stray light characterisation of array spectroradiometers using wavelength tuneable lasers provides fundametal information on the instrument performance under any spectral distribution of a source being measured and enables to correct the data numerically in terms of a correction matrix. The determined correction matrix, however, is efficient as long as the spectral range of the instrument covers the spectral range of the built in detector. In the case of Si array detectors, the longest wavelength that the detector is able to register extends up to 1100 nm. Thus, solar UV spectroradiometers designed for a narrow spectral range need additional efforts to account for the out-of-range stray light. Within the EMRP project Traceability for surface spectral solar ultraviolet radiation laser-based characterisation method was considered in order to enable a numerical correction not only of the InR but also of the OoR stray light. The preliminary data obtained with the array spectroradiometer of PMOD/WRC show that this approach works. The biggest challenge in applying the OoR stray light correction is quantifying the spectral irradiance that is not measured directly by the instrument itself but still causes a stray light contribution to the measured signal. We showed also a way of estimating it based on an extrapolation of the solar UV measurement data by the instrument. A suitable filtering technique blocking the radiation outside the spectral range of the spectroradiometer, though, may be simpler in application.

It is planned to characterise a number of array spectroradiometers of stakeholders and participants in the project for the stray light properties. The efficiency of the stray light rejection methods will be tested in an intercomparison campaign with adjoined workshop in June 2014 at PMOD/WRC. A full article is also planned to be published on the stray light correction methodology for taking into account both the OoR and InR stray light.

Acknowledgement. This report was compiled within the EMRP ENV03 Project "Traceability for surface spectral solar ultraviolet radiation." The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

References

[1] Y. Zong, S. W. Brown, B.C. Johnson, K. R. Lykke and Y. Ohno, "Simple spectral stray light correction method for array spectroradiometers," *Appl. Opt.* **45**, 1111–1119 (2006).

[2] S. Nevas, G.Wübbeler, A. Sperling, C. Elster and A. Teuber, "Simultaneous correction of bandpass and stray light effects in array spectroradiometer data," *Metrologia* **49**, S43–S47 (2012).

[3] L. Egli, J. Gröbner, M. Smid, G. Porrovecchio, T. Burnitt, K. Nield, S. Gibson, J. Dubard, S. Nevas and M. Tormen, "New Technologies to Reduce Stray Light for Measuring Solar UV with Array Spectroradiometers," IRS (in press).

[4] S. Nevas, M. Lindemann, A. Sperling, A. Teuber and R. Maass, "Colorimetry of LEDs with Array Spectroradiometers," *MAPAN—J. Metrol. Soc. India* **24**.

[5] B. Mayer and A. Kylling, "Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use," *Atmos. Chem. Phys.* **5**, 1855-1877, doi:10.5194/acp-5-1855-2005 (2005).