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Ralf Zuber et al.

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CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

COMBINED OUT OF RANGE AND IN BAND STRAY LIGHT CORRECTION FOR ARRAY SPECTRORADIOMETERS

Zuber, R.[1], Ribnitzky, M.[1]
[1] Gigahertz-Optik GmbH, Türkenfeld, GERMANY

r.zuber@gigahertz-optik.de

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Abstract

Insufficient stray light rejection of array spectroradiometers, in especially the UV spectral range, limits the application of these devices. One important example would be UV hazard measurements. This study shows that a combination of different stray light corrections methods can improve the stray light reduction performance of UV array spectroradiometers significantly, to meet these requirements. The ACGIH E_{eff} (identical ICNIRP) values measured with an uncorrected array spectroradiometer showed expected large deviations of 73% for a sunbed tanning lamp and 105% for a halogen lamp, relative to a double monochromator reference.
With the applied combined Out-of-Range and In-Band stray light correction method, these measurements were within 3% of the reference double monochromator based system.
Furthermore, the measurements showed a detection limit of 2E-5 W/m²/nm for the double monochromator and comparable 3E-5 W/m²/nm for the stray light corrected array spectroradiometer. This was in contrast to 5E-4 W/m²/nm for the uncorrected array spectroradiometer. The results suggest that photobiological safety measurements according to IEC / DIN EN 62471 are possible with the applied combined stray light correction method for the used spectroradiometer.

Keywords: Spectroradiometer, Stray light reduction, UV hazard

1 Introduction

Typically, insufficient stray light rejection of array spectroradiometers in the blue and especially in the UV spectral range limits the application of these devices in this spectral region (Egli et al., 2016). One such important example would be UV hazard measurements. The measurements required to determine the American Conference of Governmental Industrial Hygienists (ACGIH) corneal hazard of broadband ultraviolet (UV) sources make particularly high demands on the suppression of stray light. The same applies to photobiological safety within IEC/DIN EN 62471 or ICNIRP (International Commission on Non-Ionizing Radiation Protection) UV measurements (ICNIRP, 1995). Hence, the accepted and recommended technology/devices are double monochromator based systems (IEC/DIN EN 62471).
This study shows that a combination of stray light suppression by different correction methods can improve the stray light reduction performance of UV array spectroradiometers significantly to meet these requirements.

2 Methods

In an array spectroradiometer two different types of internal stray light can be distinguished by its origin. The so called Out-of-Range (OoR) stray light is generated by a signal outside the spectral range of the spectroradiometer; stray light originating from within the spectral range of the spectroradiometer is referred as In-Band (IB) stray light (ISO/CIE, 1984, CIE, 2018). The OoR stray light can be measured and corrected by using edge filters for instance (Shaw and Goodman, 2008, Nevas, 2015). However, these methods are not able to correct for IB stray light. The IB stray light can be corrected by using established stray light matrix correction (SLMC) methods (Zong et al., 2006, Nevas et al., 2012). The presented study uses a combination of both methods in order to achieve significantly improved performance; especially for dedicated UV array spectroradiometers which are silicon detector based and therefore, depending on the light source, may have significant OoR and IB stray light.

An intercomparison of a corrected and an uncorrected array spectroradiometer and a double monochromator reference has been performed by measuring different light sources (tungsten, xenon, sunbed tanning lamp, light emitting diode (LED)).

3 Instrument design and characterisation

The BTS2048-UV-S series array spectroradiometers developed and manufactured by Gigahertz-Optik are based on the well-known Czerny-Turner (Shafer et al., 1964) spectrometer design. The spectrometer uses a temperature controlled back-thinned CCD detector with 2048 pixels and an electronic shutter integrated in a compact optical bench with 16 bit analogue digital converter (ADC) resolution. To enable stray light corrected measurements, a miniaturised filter wheel with up to six different optical filters is integrated in the optical path between the entrance optic and spectrometer unit. Integration times from 2 µs up to 60 s provide a high dynamic range in the spectral range from 200 nm to 430 nm (Zuber et al., 2018b). Various device versions with different spectral range and input optics exist. The BTS2048-UV-S with OoR stray light correction already applied, is introduced and characterized for instance with respect to linearity, optical bandwidth, cosine response and wavelength accuracy in Zuber et al. (2018b) and Zuber et al. (2018a). A measurement uncertainty evaluation of this device is presented for direct irradiance measurements, calibrated with a low standard uncertainty calibration source of PTB, in Vaskuri et al. (2018). In the following Figure 1, a schematic diagram is shown. In Table 1 the uncertainty budget from Vaskuri et al. (2018) is presented.

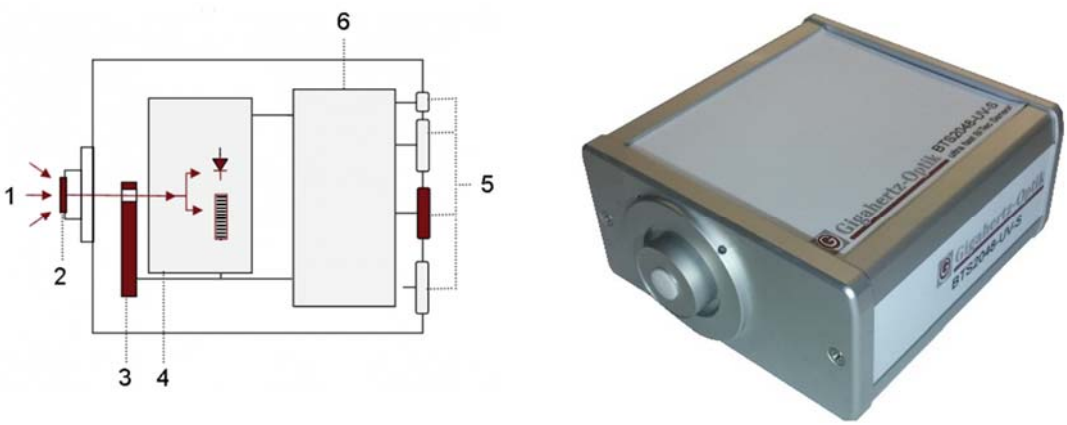

Figure 1 – Schematic setup of the BTS2048-UV-S and photo of the instrument. 1) Incoming optical radiation 2) Direct entrance port with cosine diffuser 3) Filter wheel 4) BiTec sensor system 5) Electrical connectors 6) Microprocessor for data processing and communication.

Table 1 – Measurement uncertainties for direct spectral irradiance measurement

Uncertainty component	Standard uncertainty / %
Radiometric calibration	0.8
Lamp stability	0.2
Non-linearity and stray light	0.4
Stability	0.8
Temperature dependency	0.1
Measurement noise	0.2
Wavelength shift	0.1
Combined uncertainty (k=1)	1.24
Expanded measurement uncertainty (k=2.5)	2.5

In this study based on this device the stray light reduction was improved further. Therefore, as stated in chapter 2, a combination of the OoR stray light correction with an edge filter and an IR stray light correction according to Zong et al. (2006) was applied.

4 Measurement data / intercomparison

In the following sub-chapters measurements of tungsten, xenon, sunbed tanning lamp and light emitting diode (LED) sources are compared to a double monochromator measurement system, which fulfils the IEC/DIN EN 62471 specifications. In order to illustrate the performance of the combined stray light correction, the uncorrected data (no OoR and IB correction applied) is also presented.

4.1 Halogen lamp

In Figure 2 a 250 W halogen lamp measurement at 500 mm distance is illustrated with logarithmic scale to show the differences in stray light performance.

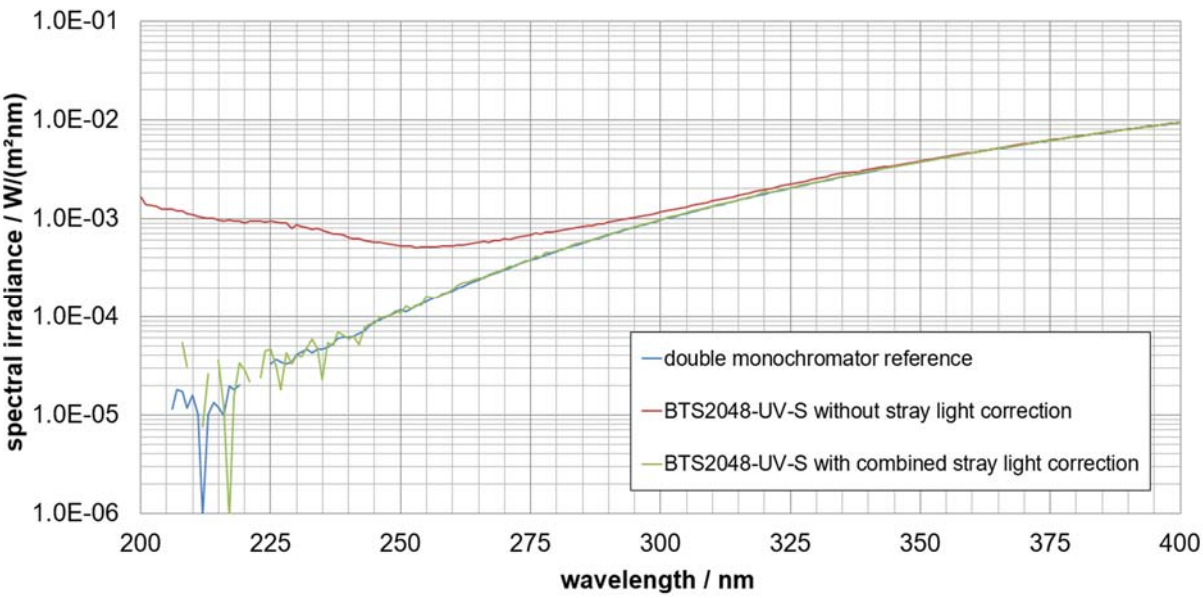

Figure 2 – Logarithmic plot of an intercomparison measurement of a 250 W halogen lamp at 500 mm distance from a double monochromator reference and the BTS2048-UV-S with and without correction.

4.2 Sunbed tanning lamp

In Figure 3 a 4x 15 W sunbed tanning lamp measurement at 150 mm distance is illustrated with logarithmic scale to show the differences in stray light performance.

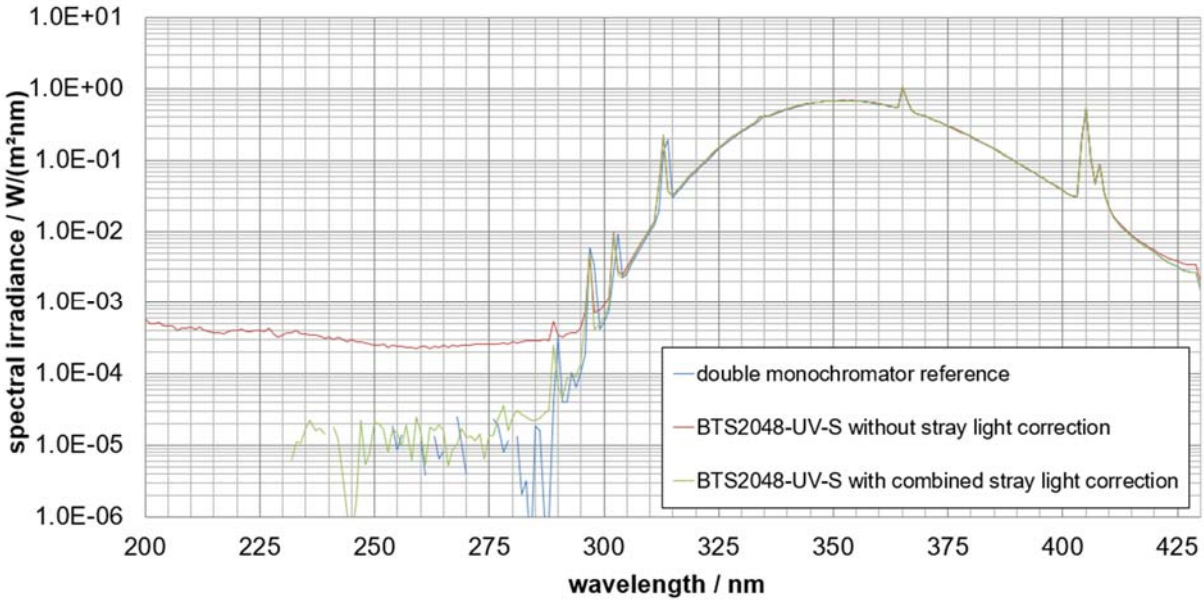

Figure 3 – Logarithmic plot of an intercomparison measurement of a 4x 15 W sunbed tanning lamp at 150 mm distance from a double monochromator reference and the BTS2048-UV-S with and without correction.

4.3 Xenon lamp

In Figure 4 a 450 W xenon lamp measurement at 180 mm distance is illustrated with logarithmic scale to show the differences in stray light performance.

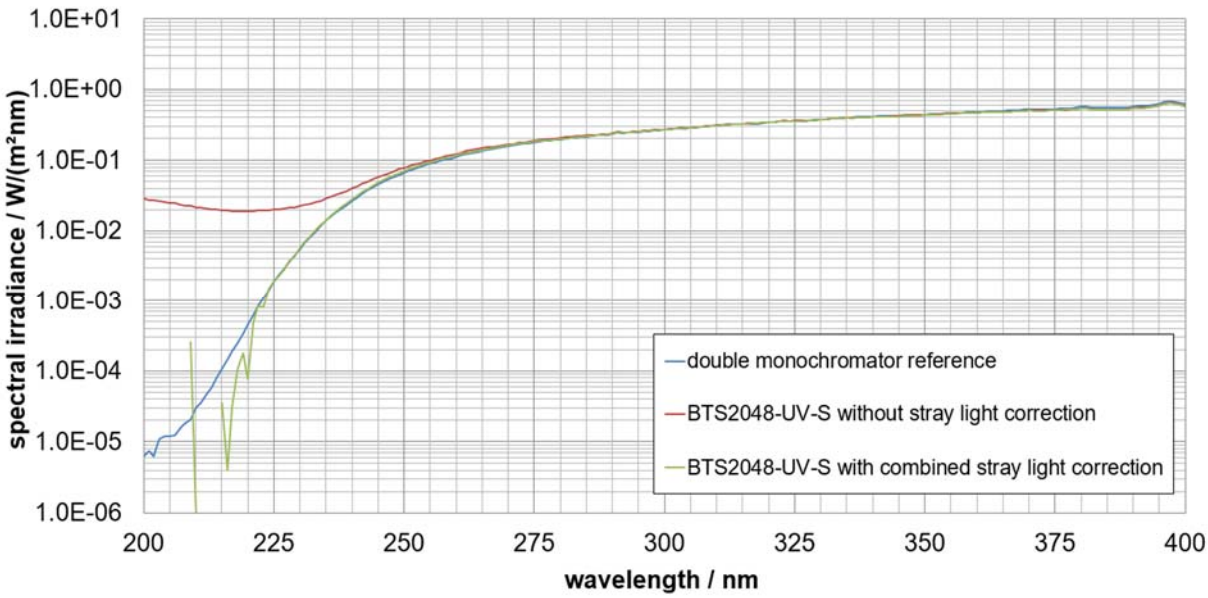

Figure 4 – Logarithmic plot of an intercomparison measurement of a 450 W halogen lamp at 180 mm distance from a double monochromator reference and the BTS2048-UV-S with and without correction.

4.4 Light emitting diode (LED)

In Figure 5 a 365nm LED measurement at 500 mm distance is illustrated with logarithmic scale to show the differences in stray light performance.

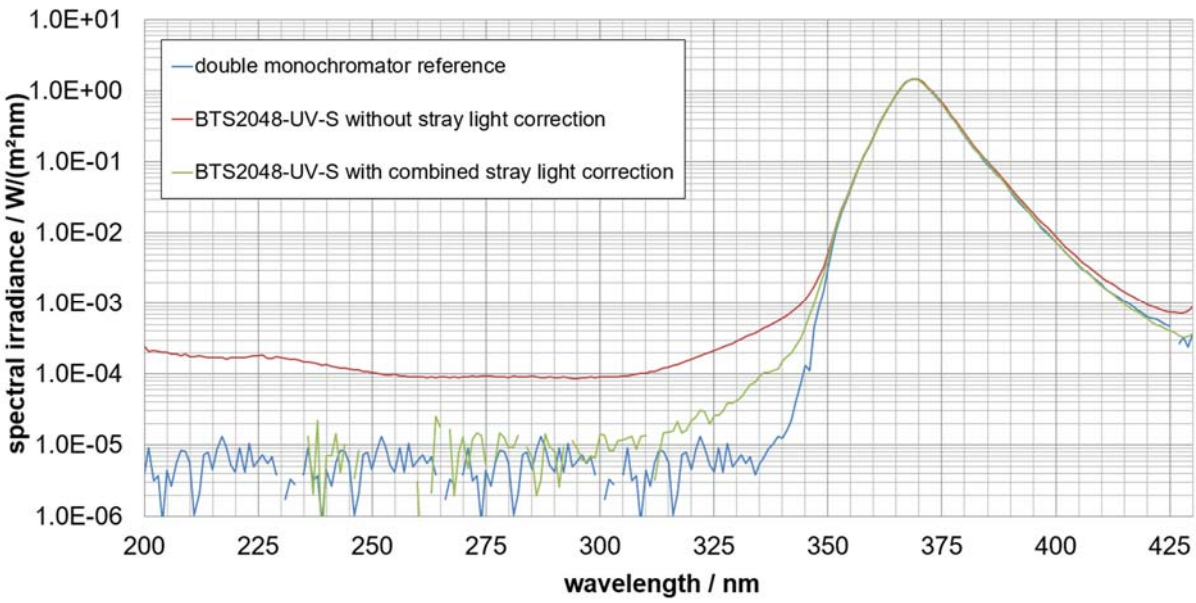

Figure 5 – Logarithmic plot of an intercomparison measurement of a 365 nm LED at 500 mm distance from a double monochromator reference and the BTS2048-UV-S with and without correction.

In Table 2 the deviation of ACGIH E_{eff} and the detection limit of the different array spectroradiometer measurements are presented.

Table 2 – Intercomparison

		Halogen lamp	Sunbed tanning lamp	Xenon lamp	365 nm LED
Deviation E_{eff}	without SLC	105%	74%	6.7%	7.6%
	combined SLC	1.5%	-2.5%	2.1%	0.4%
Detection limit	without SLC	1E-3	2E-4	2E-2	1E-4
	combined SLC	2E-5	1E-5	3E-5	1E-5

Note: For the evaluation of the 365 nm LED values, only the spectral range from 300 nm to 430 nm was used.

5 Discussion and conclusion

The ACGIH E_{eff} (E_{eff} = effective irradiance; weighted; identical ICNIRP weighted or IEC/DIN EN 62471) values measured with the uncorrected array spectroradiometer showed expected large deviations of 73% for the sunbed tanning lamp and 105% for the halogen lamp relative to the double monochromator. For a xenon lamp and a 365 nm LED the deviation is below 10%. These results show why double monochromators are the recommended devices for this kind of measurement.

However, with the use of the introduced combined stray light correction methods, all E_{eff} values measured with the array spectroradiometer (independent of the light source measured) were within 3% of the double monochromator reference. These comparable results suggest that for the used device with the introduced combined stray light correction method, UV hazard evaluations according to ACGIH/ICNIRP or IEC/DIN EN 62471 (2006) are possible.

The results showed that the most critical light source tested in terms of stray light was the xenon lamp with a detection limit of 3E-5. The uncorrected measurement reached only a level of 2E-2. For this specific light source, an improvement of three orders of magnitude was achieved. The least critical light source was the LED with a detection limit of 1E-5 for the corrected measurement and 1E-4 for the uncorrected measurement. These different stray light levels can be explained by the different relative spectral distributions of the light sources. The xenon lamp produces more IB and OoR stray light compared to the 365 nm LED.

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