Methods

Measuring solar UV-B: why is it so difficult?

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The problem

I expect readers to be aware of the fact that measuring UV-B radiation is difficult. However, a short demonstration of some of the causes behind the difficulties will be of interest. I will discuss how the properties of the emission spectrum of a radiation source, the shape of the biological spectral weighting functions, and the spectral response of radiation detectors interact. I will demonstrate that spectra that when plotted on a linear scale can look completely noisy-free can suffer from very serious stray-light problems. Furthermore, I will demonstrate that this "unnoticeable" amount of stray is large enough to cause huge errors in estimates of effective UV exposures, and to a lesser extent in unweighted UV irradiances and exposures.

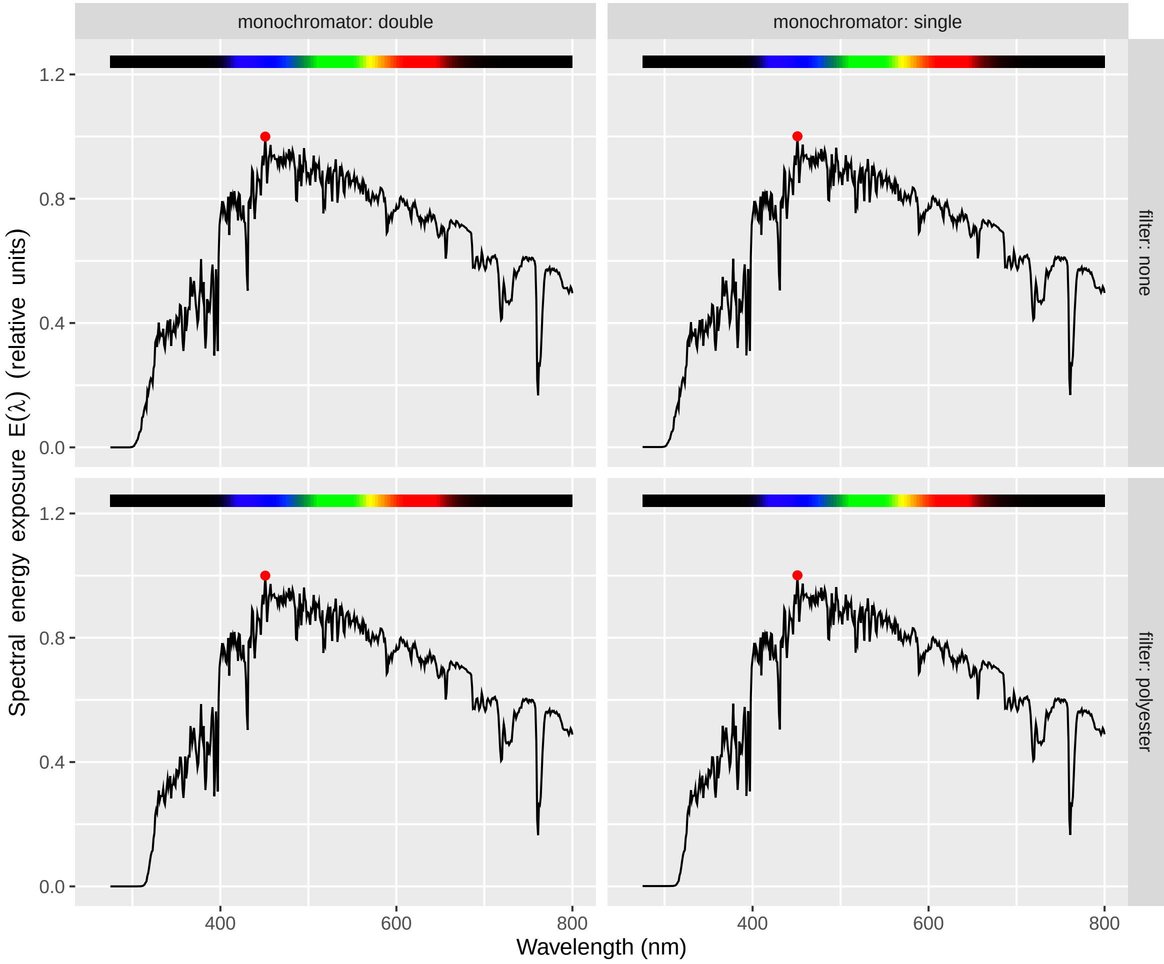
The difficulties of consistently measuring solar UV-B radiation at ground level has kept geophysicists and meteorologists occupied for many decades. In spite of this there is no easy or automated solution to the problem. Careful application of strict protocols both at the time of instrument calibration and at the time of measurement are needed to achieve acceptably good estimates (Seckmeyer et al. 2001, 2005, 2010).

The main problem is that UV-B irradiance is only a small fraction of the global solar irradiance at ground level. In winter at medium and high latitudes the UVB:PAR ratio is at its minimum, and very close to zero, and when the sun is at its highest elevation at Midsummer in Helsinki, the UVB:PAR photon ratio is at its maximum, but still only $\approx 0.002 : 1$. Being this the maximum, and global radiation approximately twice as much as PAR, we will normally want to resolve changes in the UVB:PAR irradiance ratio as small as 0.0001. In other words, we want to resolve a change in the flux of UV-B photons that is nearly 10 000 times smaller than the flux of photons in the band from 400 to 700 nm, and do this reliably and without recalibration of the instruments even when the shape of the spectrum changes with solar elevation.

Broad-band sensors are easier to use and cheaper than spectrometers. However, as their spectral response curve is broad and with a shape that depends on both the characteristics of the detector and of the additional filters used, they need always to be separately calibrated for each type of light source to be measured (see Aphalo et al. 2012). If only one light source is to be measured, for example sunlight, it is possible to use broadband sensors with a good protocol that takes into account sources of bias like sensor temperature and solar elevation. When measuring the UV-B output from different sources it becomes cumbersome and error-prone to have to switch among calibrations and regularly repeat all the calibrations. In the case of measurements of mixed radiation from sources of different types, broadband sensors should be avoided in most cases. In the current article, I will only discuss spectral measurements.

The main cause of difficulties is stray light within spectrometers. Stray light is light that has gone *astray from its expected optical path* and may, for example, reach a pixel in an array detector it is not expected to imping on, such as one corresponding to a different wavelength. Stray light originates in reflections and scattering at mirror and grating surfaces and to some extent can be attenuated by blackening the interior of the spectrometer case and adding baffles. However, the most effective solution is to separate the light beam into different wavelengths twice by means of two monochromators po-

Figure 7.1: Simulated effect of spectrometer stray light. In this figure the effect of a small amount of stray light is simulated based on the characteristics of two types of spectroradiometers. The two spectra for each light source are visually indistinguishable although the simulated amounts of stray light differ. Stray light was simulated by adding a baseline of 1:1 000 of the spectral irradiance at the peak of the spectrum (marked with red dot) for the single monochromator, and a baseline of 1:1 000 000 of the spectral irradiance at the peak for the double monochromator instrument.



sitioned 'in series' in the optical path.

There is only one type of instrument in common use that has a good-enough stray light performance for reliably and consistently quantifying UVB irradiance in sunlight: a highly-specified double-monochromator scanning-spectroradiometer with a cooled detector. These instruments vary from big to very big in size, and are usually difficult to transport and expensive. On the other hand the stray light level can be as good as 1:1 000 000. In single monochromator scanning spectrometers stray light is about 1/1000 as good or about 1:1 000. With a suitable grating, array spectrometers can provide good spectral resolution. Spectrometers with array detectors, cannot be built with two monochromators operating in tandem and consequently can achieve "physical" stray light specifications of from 1:500 to 1:1 000 in the UV-region.

If we plot the measured solar spectrum using a linear scale, stray light of 1:1000 is almost impossible to notice by sight, even in direct comparison with a figure showing data with no stray light (Figure 7.1). Consequently, at first sight, one would conclude that such an small amount of stray light is harmless. However, if we calculate biologically effective irradiance and look in detail at the UV-B region of the spectrum, we can see that the error introduced by the stray light is really of large magnitude (Figure 7.2). Especially under a polyester filter, it would appear that there is a significant amount of UV-B radiation present, when in reality it is absent. This example is a simplified simulation, but based on actual data measured by Lasse Ylianttila on our Maya2000 Pro spectrometer.

A partial solution: estimate stray light from UV-C region

Can we estimate stray light to correct the readings? Yes, we can estimate it if the stray light affects adjacent regions of the array similarly (stray light is truly scattered). As very few photons emitted by the sun at wavelengths shorter than 293 nm reach ground level, we can assume solar spectral irradiance in this region to be zero. From this it follows that non-zero readings at these short wavelengths are a measurement of stray light—after subtracting the pixel readings in full darkness measured very close in time. The dark measurement should be paired to the actual measurement and obtained at most within a minute or so of each other. This approach seems to sometimes work well enough with spectrometers based on Sony's ILX511B linear silicon CCD array when measuring artificial UV sources in the absence of strong visible light. This is an approximation because the stray light is unlikely to be 100% scattered. In practice there is another constraint to consider: that array detectors usually have different regions coated with different filters, which affect the sensitivity of their pixels to stray light. Consequently, which of these pixels can be used to assess stray light will depend on the instrument. As with any correction, it needs to be validated and applied in exactly the same way during measurements and instrument calibration.

A partial solution: measure and subtract the stray light

Can we measure stray light to correct the readings? Yes, but only if variation of irradiance in time is negligible. If comparable paired measurements can be made we can measure the stray light by blocking the UV radiation with a filter for one of these measurements. In this case we can correct for stray light using stray light measured at the wavelengths of interest. This approach seems to be needed, at least for some instruments based on detectors such as Hamamatsu's back-thinned 2D FFT-CCD 'array' used in Ocean Optics high end spectrometers like the Maya2000 Pro. The reason why this instrument behaves different is that stray light is not fully scattered—different pixels in the detector will receive stray photons from different spectral regions of the radiation being measured. In our own Maya2000 Pro mostly from the near infra-red (NIR) region.

This type of stray light measurement is just a rough quantification because the filter used to measure stray may also absorb some of the photons being reflected and scattered inside the instrument to produce the stray light itself. Consequently the filter used should be chosen taking this into account, for example high NIR transmittance may be needed. How effective this correction will be in practice cannot be easily simulated and will also be instrument specific. As with the correction described in the previous section, this correction is not good enough for measuring effective UV-B radiation in sunlight, but may work well enough when measuring lamps.

More complex approaches

More complex approaches use one of the two methods described above to estimate stray light but in addition correct for the slit function of the instrument. This improves the wavelength resolution by correcting for the light that 'bleeds' to adjacent pixels. Furthermore, measuring low signal and high signal areas of the spectrum with different integration times and merging the resulting spectra significantly increases the dynamic range of the instrument. In many cases, this allows a signal to noise ratio as good as 1:10 000 to be attained in sunlight. Such complex sets of corrections need to be carefully validated against a reference instrument such as a well calibrated double-monochromator scanning spectroradiometer under a range of daylight conditions and other sources to be

Figure 7.2: Simulated effect of spectrometer stray light. In this second figure we plot the same data but limiting the range of wavelengths and instead of plotting the raw spectral irradiance we plot the spectral irradiance weighted with Green's formulation of M. M. Caldwell's Generalized Plant Damage Spectrum (GEN_G). The effect of the minute amount of stray light on the estimated UV-B irradiance is large in the case of single monochromator instruments resulting in an overestimation by more than 50% of the effective irradiance for unfiltered lamps (the best case) and in an overestimation by 85 *times* for the polyester-filtered lamps! Now the effect of instrument stray light is clearly visible as the red area!

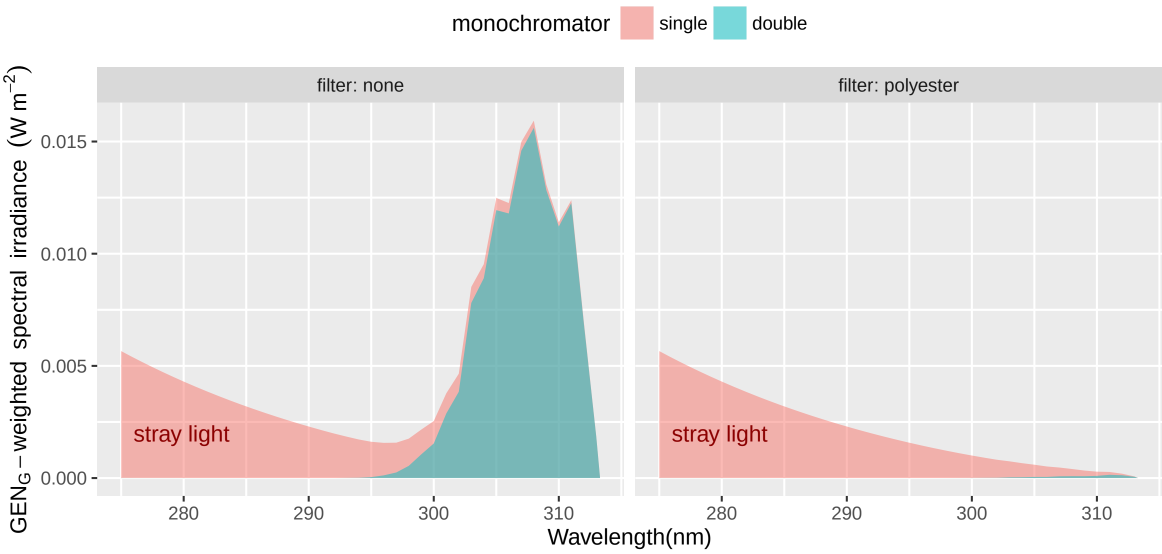


Figure 7.3: Simulated effect of spectrometer stray light. In this third set of figures, we plot the new data simulating measurements with a single monochromator spectrometer *corrected for stray-light, slit-function, and obtained using 'bracketing' of integration time*, as in Figure 7.2 the range of wavelengths is limited and instead of plotting the raw spectral irradiance, the spectral irradiance weighted with Green's formulation of M. M. Caldwell's Generalized Plant Damage Spectrum (GEN_G) is plotteed. Now the improvement achieved by the simulated use of the special measurement and data processing protocols is visible as a reduction of the red area compared to that in Figure 7.2.

measured.

Different algorithms and approaches for applying corrections and characterising array spectrometers have been published in the optics, meteorology and geophysics literature (Ansko et al. 2008; Coleman et al. 2008; Kreuter and Blumthaler 2009; Seckmeyer et al. 2010; Ylianttila et al. 2005; Zong et al. 2006). Even with all such corrections, array spectrometers are not comparable to double-monochromator scanning spectroradiometers in their performance and usually considered unsuitable for long-term monitoring, but may be good enough for short-term or spot measurements when errors as large as $\pm 15\%$ are tolerable (Figure 7.3).

A hardware-based solution: VIS-blind detectors

Can we make the instrument blind to stray light? Yes. There is a new type of array detector under development. These arrays are made of silicon carbide (SiC) instead of silicon and are intrinsically blind to visible radiation. Sensitivity at 320 nm is 20 *orders of magnitude* higher than at 500 nm. At the moment there is only one commercial instrument available (Fig. 7.4). Spectral resolution is about 3 nm and quantum efficiency lower than that of more traditional arrays. Of course, this instrument can be used to measure only UV radiation.

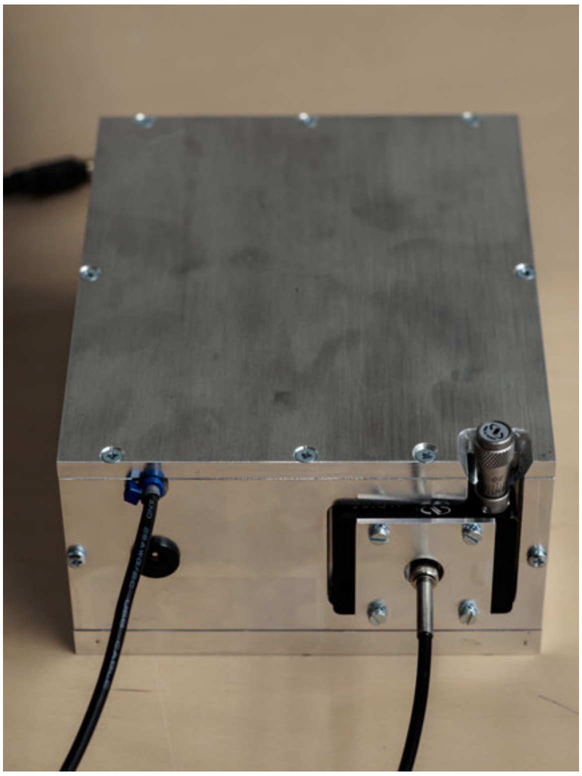


Figure 7.4: Photograph of a sglux LIN128 spectrometer. The array detector used in this instrument is blind to visible radiation and consequently immune to visible and infra-red stray light. In addition it is equipped with a convex grating that focuses the radiation directly onto the detector. Not having additional mirrors in the optical path also contributes to improved stray-light characteristics.

A model-based solution: radiative transfer models

For the estimation of daily, and in some cases hourly, spectral UV exposure radiative transfer models (RTMs) are accurate especially for clear sky conditions (e.g. García et al. 2016). The effect of clouds can be estimated in different ways, but a reliable and easy to implement method is to use measured global radiation to estimate the cloud depth (Lindfors et al. 2009, 2007). Instantaneous estimates are also possible but these require global radiation to be measured on site. The model ‘libRadtran’ is widely used for this purpose, and in its latest version can simulate the whole solar spectrum at ground level (Emde et al. 2015). The spectral irradiance under large sized filters can be approximated by convolving the spectral transmittance of filters by the simulated solar spectrum. The accuracy of the estimated spectral irradiance under a filter will be subject to errors at low solar elevations because of stray light, and because the total transmittance of filters at narrow angles of incidence may decrease due to increased reflection.

The model ‘libRadtran’ is currently popular and actively maintained, and has its main focus in atmospheric radiation transfer and spectral simulation. There another model that can be also used for spectral simulations: Tropospheric Ultraviolet and Visible (TUV) radiation model (Madronich 1992). This model is actively maintained, however much of it is related to the modeling of atmospheric chemistry. There is an on-line version, or Quick-TUV (http://cprm.acom.ucar.edu/Models/TUV/Interactive_TUV/) which can be used to simulate the UV region of the solar spectrum, and simpler to use than the full-blow version or 'libRadtran'. The much older and simpler model developed by Green and Björn, is considered to been superseded by the more complex models described above.

Conclusions

Array spectrometers have advantages compared to scanning spectrometers. Most importantly the whole spectrum is measured simultaneously and almost instantaneously while with scanning spectrometers the acquisition of a single spectrum can take even minutes and each data point is acquired at a different instant in time. Array spectrometers are also smaller, use less power, and are less sensitive to vibration than scanning spectrometers, making them suitable for field measurements at remote locations.

Although it is possible to use array spectrometers for measuring solar UV radiation, even after applying corrections, UV-B estimates are only of good quality under a limited range of conditions (Egli et al. 2016; Seckmeyer et al. 2010). In the case of UV-B lamps and UV-B LEDs if their output is measured in the absence of other comparatively stronger sources of visible radiation, good estimates are obtainable as long as a good protocol is used.

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