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New Technologies to Reduce Stray Light for Measuring Solar UV with Array Spectroradiometers

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Abstract. Measurements of solar UV irradiance with array spectroradiometers (ASRM) are susceptible to errors in particular in the wavelength regions with low irradiance levels. This is due to the impact of stray light in the often compact single grating configuration of ASRMs. However, a significant advantage of ASRMs, in contrast to traditional scanning spectroradiometers, is their ability to detect one entire solar UV spectrum quasi instantaneously. This study aims to evaluate three different concepts and respective technologies to physically reduce the impact of stray light in conjunction with ASRM. 1. The concept of modulating the incoming solar radiation to reduce the dynamic range of the solar UV spectrum using the Digital Light Processing (DLP®) technology. 2. The concept of pre-selecting a range of wavelength before guiding the incoming radiation to an ASRM. The corresponding technologies for this pre-dispersing instrument are based on tunable MEMS gratings. 3. The high dynamic range of the solar UV light covering 6 orders of magnitude can be adjusted with static filters, either placed in front of the detector array or in the light path between the entrance optics and the ASRM. The evaluation of the concepts and technologies according to 6 different criteria reveals that the concept of level the dynamic range using the DLP® technology is the most promising approach to construct a prototype device of a novel ARSM.

Keywords: Digital Light Processing DLP®, Tunable MEMS grating, Tailored gradient band pass filter.

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INTRODUCTION

Measuring solar UV for climatology, human health and environmental research requires instrumentation that is sensitive to measure flux levels over the wavelength range from 290 nm to 440 nm, which typically increase 6 orders of magnitude from $\sim 10^{-3}$ to $\sim 10^3$ mW/m²/nm. Conventionally, high accuracy solar spectral measurements are made with rotating double grating scanning monochromator equipped with a single highly sensitive detector. Such systems have a substantial suppression of stray light.

An alternative approach would be to use a low cost array spectroradiometer (ASRM), which is, generally, a compact single grating monochromator system imaging the entrance slit onto an array detector. Such systems have the advantage of capturing simultaneously the solar irradiance spectrum. However, due to the impact of stray light radiation in the compact one-chamber setup, typical monochromator ASRM can cover only a dynamic range of about 3 orders of magnitude [1] over the UV solar spectrum entering in the instrument. This means that stray light radiation from longer wavelength regions with higher irradiances is present in the shorter wavelength regions with lower irradiances. In addition, UV measurements with ASRMs are also influenced by the lower sensitivity and higher noise of the array detector, compared with the PMT detectors conventionally used in scanning systems.

This study aims to evaluate techniques to reduce the stray light contribution in such systems. The study focuses on physically based methods to reduce stray light in the optical path of the systems. The concepts and technology

presented and evaluated here are reviewed according to different criteria for their potential to be applied in a conceptual prototype device.

METHOD

To evaluate the potential for stray light reduction by applying the different concepts, the generation of stray light based on the incoming radiation was simulated. An ASRM from the manufacturer “Avantes”, an AvaSpec ULS2048 equipped with a Hamamatsu back illuminated CCD (2048 pixels) and covering a wavelength range between 280 nm – 440 nm, was characterized with a tunable laser light source. The tunable laser was used to characterize the monochromator slit functions at a specific wavelength and the stray light contribution from that wavelength to the pixels corresponding to the other wavelengths in the spectrum.

Figure 1a) shows the normalized slit functions (black lines) and the stray light contribution at non irradiated regions. To simulate the stray light generation a spectrum was modeled using the radiation transfer model “libradtran” [2] for the wavelength range between 290 nm to 1080 nm, since also visible or infrared radiation induce stray light in the ASRM. The resulting spectrum was compared with a reference spectrum measured by a “Brewer” scanning double monochromator spectroradiometer [3]. Figure 1b) shows both the modeled spectrum (grey line) and the measured spectrum (dashed line).

The stray light contribution of the modeled spectrum for each wavelength was simulated by a simple matrix multiplication in the wavelength domain:

$$\text{Simulated Signal} = (\text{Slit Function Matrix} \times (\text{Modeled Input Spectrum} \times E(\lambda)))/E(\lambda) \quad (1)$$

where $E(\lambda)$ is the sensitivity of the detector. Since the variation of the detector sensitivity over the considered wavelength range is small and the stray light simulation is calculated on irradiance, $E(\lambda)$ was set to 1. For the simulations in section “Concepts and Technologies” $E(\lambda)$ denotes the function of modulating the input spectrum. Note that for each ASRM pixel the correspondent slit function matrix element was calculated using a linear interpolation of the measured and normalized tunable laser lines. Furthermore the contribution of stray light originating from radiation with wavelength between 440 nm – 1080 nm (out of range) were nominally set to parts in 10-5. Figure 1b) also shows the comparison of ASRM measured solar UV irradiance (black line) and the modeled stray light generation (black points), which is the component that leads to a significant overestimation of the solar UV radiation in the wavelength range below 305 nm.

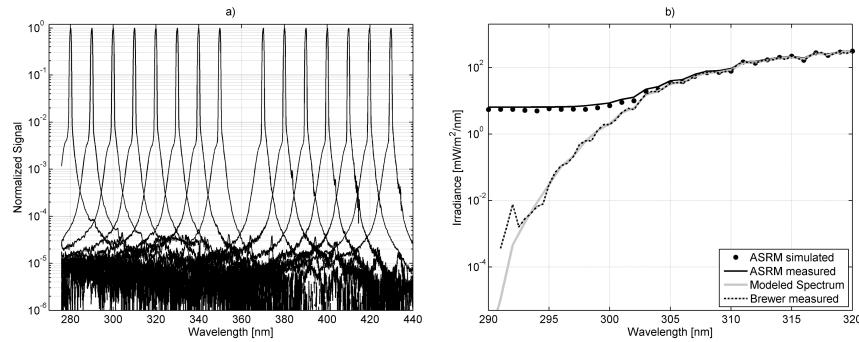


FIGURE 1. a) Normalized tunable laser signal (black lines) in the wavelength range between 280 nm to 440 nm measured with the “Avantes” array spectroradiometer. The stray light contribution is visible at the wings of the slit function at $\sim 10^{-5}$ b) Simulated stray light generation using the modeled input spectrum (grey line) with the *Slit Function Matrix* and equation 1. The simulated spectrum (points) is compared with a measured solar UV spectrum captured by the ASRM “Avantes” (black line).

CONCEPTS AND TECHNOLOGIES

Level the Dynamic Range

As mentioned above, in ASRMs stray light from UV radiation with higher irradiance at longer wavelengths can lead to significant error in the measurement at shorter wavelengths where the UV irradiance is lower. Therefore, the first concept is to modulate the incoming solar UV radiation in order to level the dynamic range of the incoming solar UV radiation to a constant value. Figure 2a) shows modulated solar radiation to a constant value of 10 mW/m²/nm, 1 mW/m²/nm and 0.1 mW/m²/nm, respectively. The result of the stray light simulation model shows that the impact of stray light can be significantly reduced displaying ~5 orders of magnitude of the solar UV Spectrum (Figure 2b). The feasibility of modulating radiation for each wavelength specifically was demonstrated by Rice et al. [4] (“spectral engine”), where a digital micro mirror array from Texas Instruments was used for digital light processing (DLP®, [5]). The high frequency (>23 kHz) of the DLP® allows to modulate the solar UV dynamic range down to 4 orders of magnitude. The main advantage of using this technology is that the entire spectrum can still be captured with the ASRM instantaneously. However, the efficiency of the DLP® in the UV range between 290 nm – 300 nm is only about 15% due to the transmission of the window on the currently available mirror arrays [6].

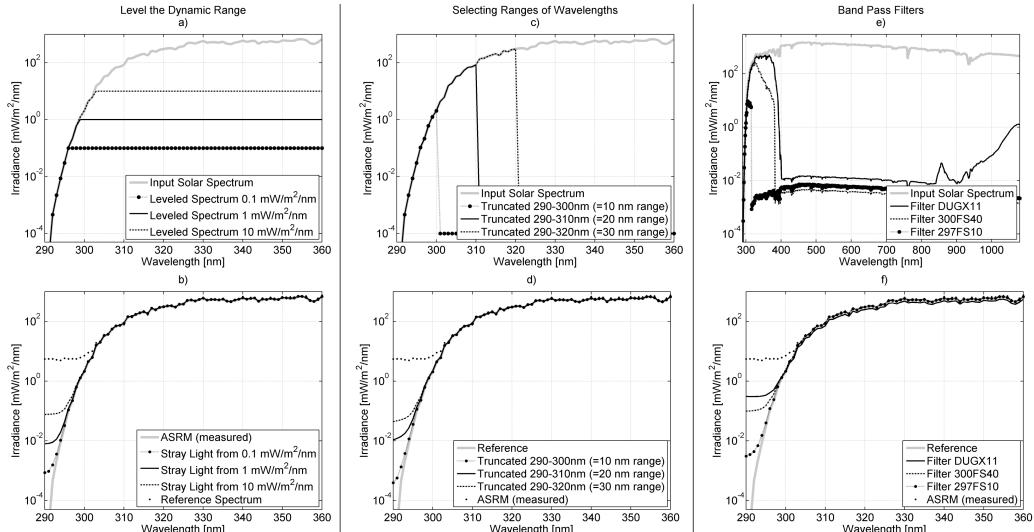


FIGURE 2. Expected stray light generation applying 3 different concepts of modulation the incoming solar UV radiation: a) & b) level the dynamic range of the input solar UV, c) & d) pre-selecting ranges of wavelength of the incoming light and e) & f) modulation the solar UV spectrum with different band pass filters.

Selecting Ranges of Wavelength

The impact of stray light radiation from wavelength regions with high solar UV intensities can also be reduced by pre-selecting ranges of wavelength prior to guide the incoming radiation to the ASRM. This impact of this approach is shown in Figure 2c) and 2d), where a pre-selection of a wavelength range of 10 nm leads to accurate detection of solar UV down to about 5 orders of magnitude. A technology to apply this concept of pre-dispersing the incoming radiation can be found in [7] using tunable Microelectromechanical systems (MEMS) gratings, with which the location of the peak wavelength can be quickly and conveniently adjusted. The instrument is designed to be a pre-dispersing device operating either in free space or with a fiber input and a fiber output. The latter option would allow a direct coupling into a commercially available ASRM. The optical function of the MEMS grating is periodic: thus in order to isolate a single wavelength region, a cascade of two MEMS gratings would be required to cancel out not required wavelength regions.

Static Band Pass Filters

An alternate but more conventional approach to modulate incoming radiation or pre-selecting wavelength ranges is use of band pass filters. Two concepts apply to band pass filters: a) Tailored gradient band pass filter placed in front of detector array, which transmits only radiation of wavelength dedicated for corresponding pixels at the ASRM, & b) Different band pass filters in the light path before guiding light into ASRM. Fig. 2e) and 2f) show expected improvement of solar UV measurement with commercially available filters. A band pass filter with a full half width max. of ~10 nm allows to detect ~5 orders of magnitude of solar UV dynamic range. An advantage of using band pass filters is simple setup, in particular for tailored gradient filters placed in front of detector. However, filter material may degenerate during exposure to UV radiation [8], altering spectral properties. Furthermore filters in the light path between the entrance optics & ASRM have to be changed mechanically to measure an entire UV spectrum sequentially, which may also contribute to substantial uncertainties of measurements.

EVALUATION AND SUMMARY

To evaluate the 3 different concepts and technologies to their potential to construct a prototype device, we choose 6 different criteria: (1) *Potential for stray light reduction*, according to the results in section "Concepts and Technologies"; (2) *Efficiency* of the light throughput to ensure an accurate detectability in the ASRM; (3) *Stability / Reproducibility* for long-term absolute calibration; (4) *Operational reliability / Simplicity* for application in potential UV monitoring networks; (5) *Applicability*, according to the requirements mentioned in the Introduction; and (6) *Cost efficiency*. The different concepts and related technologies are rated with a ranking point system: The best concept according to a specific criterion & based on available information is rated subjectively by the authors with 4 points and a low expected performance is rated with only 1 point (Table 1). Due to the subjective evaluation a weighting of a specific criterion was disregarded and a qualitatively rating is provided based on the ranking points.

TABLE (1). Ranking point system to evaluate the most promising concept and corresponding technology according to different criteria.

Technology	Criterion						Rating
DLP	Stray Light 4	Efficiency 1	Stability 4	Reliability 3	Applicability 4	Cost 2	High
MEMS Grating	2	4	3	1	1	3	Medium
Gradient Filter	3	3	1	4	3	1	Medium
Band Pass Filter	1	2	2	2	2	4	Low

Evaluation with the ranking point system shows that the modulation of incoming solar UV radiation with DLP® is the most promising technology, due to its large potential for stray light reduction, good reproducibility and wide applicability of the precisely adjustable device. Since the efficiency of the DLP® technology is a major concern, the potential prototype device should exhibit an efficiency as high as possible. Therefore it is proposed that a novel ASRM based on the DLP® technology should be designed and constructed for further evaluation of this concept.

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