Stray-light correction of in-water array spectroradiometers. Effects on underwater optical measurements

Elena Torrecilla, Sergi Pons, Meritxell Vilaseca, Jaume Piera, Jaume Pujol

***Abstract*—Two miniature hyperspectral sensors are being considered to become part of a marine observatory system. The effect of stray-light radiation on its response is discussed in this article. A new method to correct the unwanted spectral stray-light radiation has been developed and applied to both hyperspectral sensors. The correction method has been proved as effective for both considered miniature spectrographs using different calibration light sources. Furthermore, preliminary results of spectral stray-light corrections applied to underwater light field measurements point out that spectral stray-light correction plays an important role in accurate underwater optical hyperspectral measurements and its later spectral analysis.**

***Index Terms*—Array detector, spectrograph, stray-light, calibration, ocean optics, spectral analysis**

I. INTRODUCTION

HYPERSPECTRAL technology has been used for various studies in optical oceanography within the last years. High spectral resolution measurements can yield more information than traditional measurements obtained in discrete spectral bands, and in combination with techniques of spectral analysis may provide the potential to classify complex oceanic environments, finer-scale features and depth-dependent optical properties. Some processing techniques based on the shape analysis of hyperspectral data can contribute to the characterization of water dynamics and marine ecosystems including the identification of different constituents in the water column. Miniaturization and power supply reduction of hyperspectral instrumentation has allowed to overcome this challenge, giving rise to a great number of sensor configurations, suitable to be incorporated to autonomous sampling platforms of oceanographic observing systems. Particularly, two miniature hyperspectral systems, described in [1] and [2], are being considered to become part of a marine observatory based on a sensor network. Both miniature instruments are based on spectrographs, spectroradiometers with multi-element array detectors that acquire an entire spectrum over some finite spectral region simultaneously. These kinds of devices have been widely used as a tool for rapid measurements of spectral distributions in a variety of underwater radiometric applications where acquisition speed is an important issue.

In spectrographs with multielement array detectors, the dispersive element, i.e. a single grating, is fixed [3]. This fact makes the spectral selection to be determined by the image of the entrance slit onto a reference plane where the multi-element array detector is placed, as well as by the size of the individual elements in the detector array. Ideally, an image element on a pixel of the detector array for a particular wavelength is composed only of the spectral components of the source element within the instrument's bandpass at the particular wavelength. In practice, the image is modified by the presence of stray or scattered light. The spectral stray-light is described as the background radiation that has been scattered due to imperfections in the dispersive element and other optical elements of the instrument (surfaces, internal buffles, higher-order diffraction, etc.).

In ocean optics research, this unwanted radiation called stray-light can cause potentially significant errors in the measured radiances given that light conditions can be extremely low. These errors can be specially large when measuring spectral regions (e.g. blue or UV regions) where the spectrograph's response and the signal-to-noise ratio are small. In order to reduce measurement uncertainties when using the proposed spectrographs, correction of the instrument's response for measurement errors arising from the instrument's spectral stray-light must be considered. A key aspect to consider to correct spectral stray-light is the spectral shape of the lamp-based calibration source used. For underwater light field measurements, instruments have been typically calibrated against incandescent sources with a peak radiance in the short-wave infrared and afterwards used to measure the radiance of the ocean. However, differences between the spectral distribution of the calibration source and the test source (e.g. the Sun) should be avoided in spectral stray-light calibration.

The aim of this contribution is to study and correct the effect of stray-light radiation on the response of the two

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referenced CCD and CMOS array-based spectroradiometers. Both miniature fiber optic spectrometers have 3648 and 256 spectral bands respectively and are being considered for underwater radiometric measurement purposes. A characterization of the spectroradiometer's response due to stray-light will be assessed as well as the influence on underwater optical hyperspectral measurements and analysis.

II. Methods

A modified version of the method developed at the National Institute of Standards and Technology (NIST) by Zong et al. [4] has been performed to estimate the spectral stray-light on the response of the two spectrographs considered for underwater optical measurements. The method is based on computing the ratio of the spectral stray-light signal to the total signal within the bandpass of a spectrograph and any response measured outside the instrument's bandpass is assumed to be spectral stray-light signal. In the original method, the ratios are computed using 80 laser lines with wavelengths spaced approximately 8 pixels apart and ratios at the intermediate pixels are obtained by interpolation. In our case, a set of monochromatic spectral line sources has been used for calculating the ratio for each pixel of the array detectors and any interpolation has been necessary. Furthermore, using a narrowband source covering all instrument's operational spectral range has enabled to characterize the stray-light signal regardless of the source utilized during future measurements.

The relative response at every element i of the array detector to a fixed monochromatic excitation wavelength λ_j falling on the element j is called the spectral line-spread function ($f_{LSF\,i,j}$). Therefore, the spectrograph's response can be divided into two regions. The narrow peak region about element j is the instrument's bandpass containing the in-band response (IB) and the remaining broad region of low response that arises from spectral stray-light. The spectral stray-light signal distribution ($SDF_{i,j}$) is derived by normalizing the $f_{LSF\,i,j}$ to the IB area and setting values of array elements within the IB area to zero:

$$SDF_{i,j} = \frac{f_{LSF\,i,j}}{\sum\limits_{i \in IB} f_{LSF\,i,j}} \quad i \notin IB \quad \text{(pixels outside } IB\text{)} \tag{1}$$

$$SDF_{i,j} = 0 \quad i \in IB \quad \text{(pixels inside } IB\text{)} \tag{2}$$

$$i = 1, 2, \ldots\ldots, n \quad \text{(total number of instrument's pixels)}$$

To obtain the spectral stray-light response function for each element i in the array, one computes $SDF_{i,j}$ for every excitation element j. Then a spectral stray-light distribution matrix, denoted D, is generated by filling the columns of an $n \times n$ matrix with each of the computed $SDF_{i,j}$. Once matrix D is obtained, the measurement equation can have the general expression:

$$Y_{meas} = Y_{IB} + D\,Y_{IB} \tag{3}$$

where Y_{meas} is the total measured signal and Y_{IB} is the IB signals. Note that there is a Y_{meas} component at each pixel that arises from the spectral stray-light distribution matrix (D). That matrix measurement expression can be rewritten as follows:

$$Y_{meas} = [I + D]\,Y_{IB} = A\,Y_{IB} \tag{4}$$

where I is the $n \times n$ identity matrix and $A = I + D$. Finally, one can obtain each unknown Y_{IB} by simply inverting matrix A:

$$Y_{IB} = A^{-1} Y_{meas} = C\,Y_{meas} \tag{5}$$

where C is called the spectral stray-light correction matrix.

The main advantages of applying that method are that the development of matrix C is only required once and real-time corrections of spectral stray-light are enabled by simply multiplying the measured spectra and the corresponding correction matrix. Note that light collection conditions determine each computed correction matrix C, which is inherent to each individual device. In that process it is also important to consider the instrument's signal dynamic range and sensitivity within the total operational spectral range.

Both miniature hyperspectral sensors employed for the present study are commercial spectrographs (Fig. 1). The first is the Ocean Optics USB4000 Spectrometer, a new device commonly used for precise measurements and calibration tasks. The USB4000 uses a Toshiba TCD1304AP 3648-element one-dimensional CCD-array detector, has a pixel-to-pixel spacing of approximately 0.24nm and a FWHM bandwidth of approximately 6nm. The second considered spectrograph is the Boehringer Ingelheim MicroParts GmbH UV/VIS Microspectrometer, a lower cost and energy-consuming device more suitable for being part of a node in a monitoring sensor network. The MicroParts uses a Hamamatsu S8378 256-element one-dimensional CMOS-array detector, has a pixel spacing of 3.5nm and a FWHM bandwidth <10nm. The analog-to-digital conversion resolution of both instruments is 16 bits.

(a) (b)

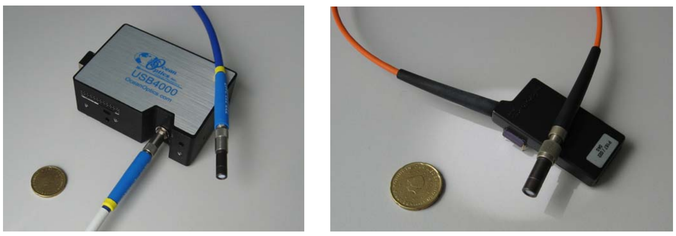

Fig. 1. Miniature hyperspectral sensors. (a) Ocean Optics USB4000 Spectrometer (CCD-array detector, dimensions 89.1 × 63.3 × 34.4mm). (b) Boehringer Ingelheim MicroParts GmbH UV/VIS Microspectrometer (CMOS-array detector, dimensions 54 × 32 × 9.5mm).

The magnitude of the spectral stray-light signal within both spectroradiometers considered has been experimentally quantified measuring the response to a set of monochromatic line sources. A Digikrom 240 Monochromator with a slit width of 25um has been used. The system is also composed of an adjustable halogen lamp (Philips 15V 150W) attached to a stabilized DC power supply (Hewlett Packard 6642A) and a focusing lens, which allow to light the monochromator's entrance slit with a rather uniform luminous field. As it has been defined, the stray-light radiation for each element of the array detector is estimated as the response measured outside the instrument's bandpass. In Fig. 2a several spectra obtained when the CCD-array detector instrument's input optics has been illuminated by uniform monochromatic radiation at many wavelengths are shown. By successive measurements of the response of both spectrographs to the wavelength tunable single monochromatic lines over the entire operational spectral range (370-725nm), each device's stray-light correction matrix C has been implemented. Each measurement has been collected as an average of 15 readings to reduce signal noise and dark current signal has also been extracted before measuring.

For each spectrograph, each column of the correction matrix C has been filled with the ratio, shown in Fig. 2b, of the spectral stray-light signal to the total signal within the bandpass (BP) of the spectrograph to the corresponding fixed monochromatic excitation j (i.e. each spectral stray-light signal distribution, $SDF_{i,j}$). The diagonal elements of the matrix and surrounding elements within the instrument's bandpass have been then all set to zero.

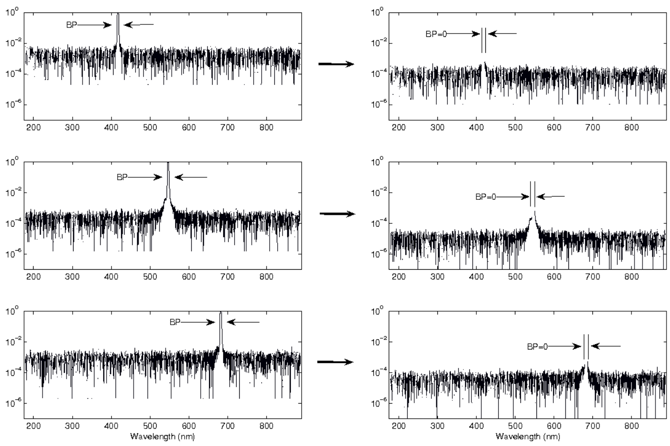

Fig. 2. (a) Spectral responses as the incident monochromatic wavelength was tuned over the spectral coverage of the CCD array-based spectrograph. (b) Corresponding ratio of spectral stray-light response to the total signal within the bandpass (BP) shown in (a). Y-axis are a logarithmic scale.

III. Results and discussion

The effectiveness of the spectral stray-light correction method has been validated using different entrance spectral stimuli, obtained by using different sources and filters. In Fig. 3 the result of applying the spectral stray-light correction method to the CCD-array spectrograph when a broadband source (an halogen lamp) and a green absorption bandpass filter are used is shown. As it can be seen, the stray-light signals outside the filter's bandpass region are clearly reduced after applying the correction (dashed signal). Similar results have been obtained using other bandpass filters with different spectral features.

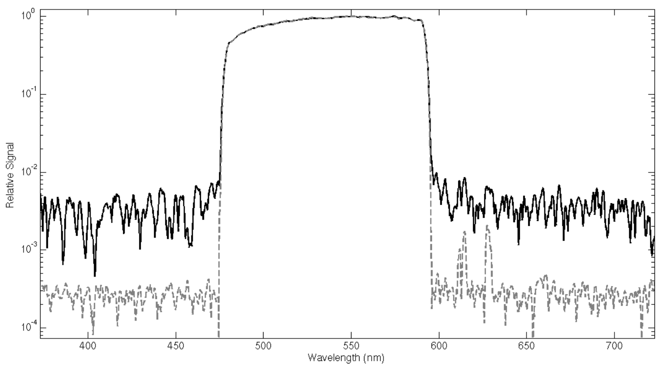

Fig. 3. Spectral stray-light correction for a broadband source with a bandpass filter. Normalized measured and corrected signals from the CCD-array spectrograph. Y-axis are a logarithmic scale.

A spectral wavelength calibration source, which produces low-pressure Mercury-Argon atomic emission lines from 253-1700nm, has also been used to validate the effectiveness of applying the spectral stray-light correction method to the CCD-array spectrograph. Fig. 4 shows the results obtained when using that other source. The stray-light errors are reduced as it can be noticed, specially in the spectral regions between the emission lines of the calibration source.

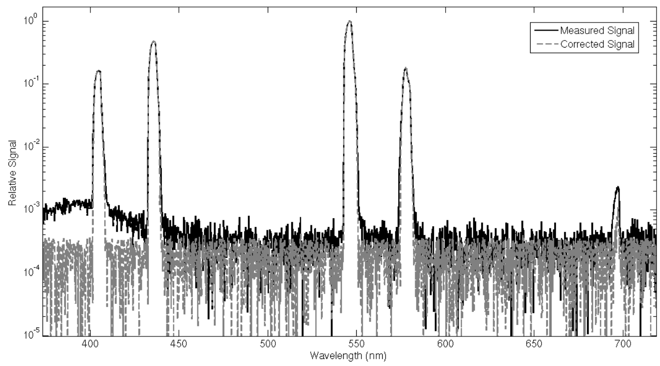

Fig. 4. Spectral stray-light correction for a spectral wavelength calibration source. Normalized measured and corrected signals from the CCD-array spectrograph. Y-axis are a logarithmic scale.

The spectral stray-light correction method has been applied and validated as well for the CMOS-array spectrograph using a broadband source (an halogen lamp) and a green absorption bandpass filter. In that case, the relative spectral stray-light signals are reduced more than two orders of magnitude, to a level of 10^{-4}, as it can be seen in the bottom panel of Fig. 5 where the reduction is shown in logarithmic scale.

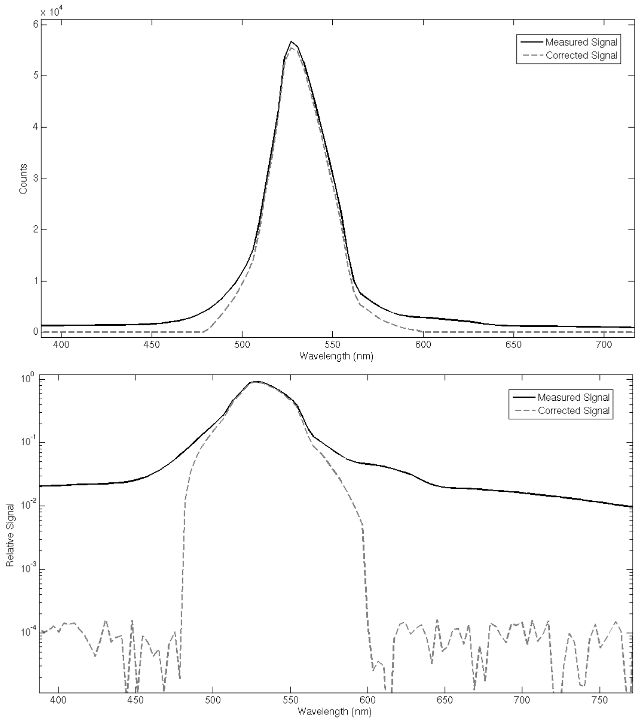

Fig. 5. Spectral stray-light correction for a broadband source with a bandpass filter. Normalized measured and corrected signals from the CMOS-array spectrograph. Y-axis are a linear scale (top) and a logarithmic scale (bottom).

An alternative method to correct the spectral stray-light radiation based on the use of cut-off filters (e.g. GG495) is proposed by the manufacturer of the CMOS-array spectrograph [5]. A comparison between the results of spectral stray-light correction obtained using that manufacturer's compensation algorithm and the method implemented in this study has been made. Fig. 6 shows how better stray-light corrections are achieved with the implemented method. The use of a set of monochromatic line sources allows to accurately cover the entire instrument's operational spectral range and perform a better spectral stray-light correction.

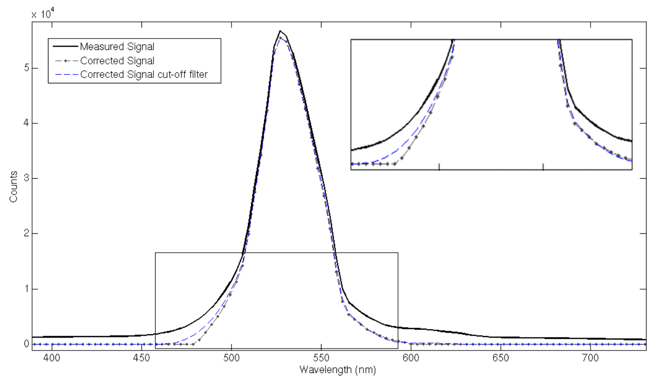

Fig. 6. Spectral stray-light correction using cut-off filters (dashed line) and monochromatic line sources with a correction matrix (dash-dot line). Measured and corrected signals from the CMOS-array spectrograph.

The implemented spectral stray-light correction method has been proved as effective for both considered miniature hyperspectral sensors. The spectral stray-light contributions to the measured output signals of these spectrometers have been corrected using the spectral stray-light correction matrix and a simple matrix multiplication. Now, in order to assess the effect of that unwanted radiation, corrections have been applied to underwater light field measurements. Fig. 7 shows measured and spectral stray-light corrected signals corresponding to data collected by the CCD-array spectrograph at two different depths at a test site in the Alfacs Bay (Ebre Delta, NW Mediterranean). As it can be observed, higher is the attenuation suffered by the signal as deeper the data collection (depth 2) and a reduction of the signal is appreciated in the corrected signals at both depths.

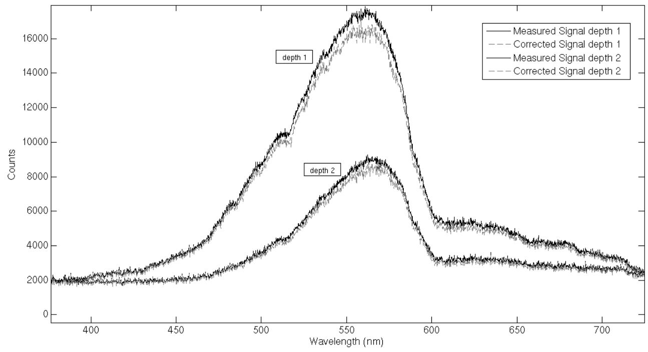

Fig. 7. Spectral stray-light correction of underwater light field measurements at two depths. Measured and corrected signals from the CCD-array spectrograph.

Even an overall reduction is observed when spectral stray-light correction is applied to underwater light field measurements, it must be pointed out that the correction has an spectral dependency, i.e. it is not the same for each spectral band. Fig. 8 shows the difference in percentage (%) between measured and spectral stray-light corrected data at each depth. These differences in percentage take values from 3 to 14% at depth 1 and from 2 to 15% at depth 2, depending on the wavelength considered and the most common reduction is approximately $4-5\%$ at depth 1 and 2.

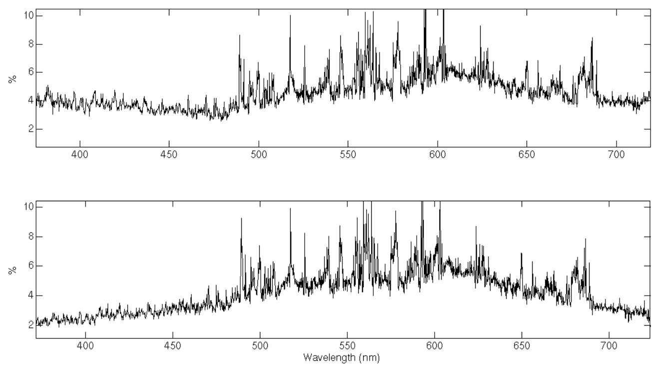

Fig. 8. Difference in percentage between measured and corrected signals shown in Fig. 7. Differences obtained at depth 1 are shown at the top and at depth 2 at the bottom.

The spectral dependent stray-light correction applied and shown in Fig. 7 and 8, modifies the amplitude of signals at each spectral band. That can be critical when the level of signals is low (e.g. blue region). However, it can be important as well given that the spectral dependency of that correction modifies the shape of signals. Several studies have been recently carried out using processing techniques based on the shape analysis of spectral data, such as derivative spectroscopy or wavelet analysis [6], [7]. These techniques permit to enhance minute fluctuations in the spectra and separate closely related spectral features. The aim of applying them to underwater hyperspectral measurements is extracting more qualitative and quantitative information regarding water components. In that framework, the spectral stray-light correction applied to the signals should be taken into account and its effect on the results of the spectral shape analysis should be considered. As an example, derivative spectroscopy has been applied to the signals shown in Fig. 7. As derivative spectroscopy is notoriously sensitive to noise, a previous smoothing based on a mean filter has been necessary. The revealed combination of peaks in Fig. 9 are associated with spectral features of spectra collected.

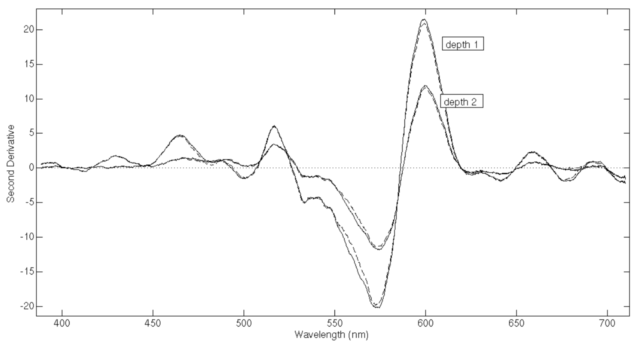

Fig. 9. Second derivative analysis of the measured and corrected signals shown in Fig. 7.

Even though the pre-smoothing applied before derivative analysis, some differences can be observed between the results of derivative analysis from measured and stray-light corrected signals. These differences can be specially appreciated in the amplitude of peaks.

IV. Summary and Conclusions

The main goal of this study is to point out that extraordinary calibration maintenance procedures are needed to assure low uncertainties in system's radiometric measurements. Specially spectral stray-light corrections must be considered in case of underwater optical measurement purposes, where very weak signals are collected. A new method to correct the unwanted spectral stray-light radiation has been developed and applied to two miniature hyperspectral sensors that are being considered to become part of a marine observatory system. This method is based on computing the ratio of the spectral stray-light signal to the total signal within the bandpass of a spectrograph, using a set of monochromatic spectral line sources. A narrowband source covering all instrument's operational spectral range has enabled to characterize the stray-light signal regardless of the source utilized during future measurements. The effectiveness of the spectral stray-light correction method has been proved for both considered miniature spectrographs using different calibration light sources. However, the preliminary results in underwater light field measurements point out that further studies should be done to evaluate the influence of the spectral stray-light correction on underwater optical hyperspectral measurements and its later spectral shape analysis.

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