Correction of stray light in spectrographs: implications for remote sensing

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ABSTRACT

Spectrographs are used in a variety of applications in the field of remote sensing for radiometric measurements due to the benefits of measurement speed, sensitivity, and portability. However, spectrographs are single grating instruments that are susceptible to systematic errors arising from stray radiation within the instrument. In the application of measurements of ocean color, stray light of the spectrographs has led to significant measurement errors. In this work, a simple method to correct stray-light errors in a spectrograph is described. By measuring a set of monochromatic laser sources that cover the instrument's spectral range, the instrument's stray-light property is characterized and a stray-light correction matrix is derived. The matrix is then used to correct the stray-light error in measured raw signals by a simple matrix multiplication, which is fast enough to be implemented in the spectrograph's firmware or software to perform real-time corrections: an important feature for remote sensing applications. The results of corrections on real instruments demonstrated that the stray-light errors were reduced by one to two orders of magnitude, to a level of approximately 10^{-5} for a broadband source measurement, which is a level less than one count of a 15-bit resolution instrument. As a stray-light correction example, the errors in measurement of solar spectral irradiance using a high-quality spectrograph optimized for UV measurements are analyzed; the stray-light correction leads to reduction of errors from a 10 % level to a 1 % level in the UV region. This method is expected to contribute to achieving a 0.1 % level of uncertainty required for future remote-sensing applications.

Keywords: array detector; astronomy; CCD array; calibration; colorimetry; correction; laser; LED; ocean color; photodiode array; photometry; radiometry; remote sensing; spectrograph; spectrometer; spectrophotometer; spectroradiometer; stray light

1. INTRODUCTION

Array spectrometers, or so-called spectrographs, are used in many applications in remote sensing and astronomy for radiometric measurements. These measurements are used for obtaining spectral information, for development of algorithms relating the measurements to a desired data product, and for the vicarious calibration of remote sensing instruments. Spectrographs employ array detectors that can simultaneously acquire high-resolution spectra of a source in a matter of seconds, as opposed to typically minutes with mechanical-scanning spectrometers.

The radiometric performance of spectrographs has improved considerably in recent years, reflecting improvements in array detector technology. However, spectrographs are single grating instruments that are susceptible to systematic measurement errors arising from stray light, or stray radiation, within the instrument. This unwanted background signal of a spectrograph is on the order of 10^{-3} to 10^{-5} of the peak signal for a narrow-band source measurement, or on the order of 10^{-1} to 10^{-3} of the averaged signal for a broad-band source measurement, depending on the quality of spectrograph. Stray light can cause significant errors when measuring a low-level spectral component of a broad-band source. For example, a high quality spectrograph that has a stray-light level of 10^{-3} for a broadband source measurement will lead to a relative measurement error of 100 % of the 'true' value when the spectrograph is used to measure a spectral component that is 0.1 % of the averaged signal of the broad-band source. This level of error is significant compared to the acceptable measurement uncertainties in many remote sensing applications, which are on the order of 1 %. Eliminating stray light in spectrographs removes a significant source of systematic error and results in much improved measurement uncertainties. In measurements of ocean color, for example, stray light of the spectrographs has led to significant measurement errors and measurement uncertainty was reduced significantly after it is corrected [1].

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Stray light errors occur in the calibration of the instrument and in subsequent measurements of test sources. Spectrographs are typically calibrated against reference standards that utilize incandescent lamps (and deuterium lamps for UV). In the case where the test source and the calibration source have similar relative spectral distributions, errors arising from stray light are mostly canceled. In most cases, however, the spectral distribution of a test source differs significantly from that of the calibration source and measurement errors due to stray light are inevitable. In fact, stray light is often the dominant source of uncertainty, particularly when single grating instruments measure light sources such as light-emitting diodes (LEDs) and UV sources.

Brown, *et al.* [1, 2], developed an algorithm previously that corrects an array spectroradiometer's spectral responsivity and a test source's spectral distribution for stray-light errors in two separate steps, by characterizing the spectrograph for the slit scattering function (SSF). This iterative approach is robust and not sensitive to measurement noise or small errors in the derived SSF, and was used successfully to correct the stray-light errors in the Marine Optical System (MOS) [1].

In this work, we have developed a method that is simpler and much easier to apply, based on the relative measurement of instrument's response to a set of laser lines. The characterization yields a stray-light correction matrix. The correction of signals for stray light can be done by a simple matrix multiplication. No iterative process is needed, and it is straightforward to implement the correction in the instrument software without impacting the acquisition speed.

Validation measurements demonstrated the effectiveness of the method. The stray-light error in the measured raw signal (the signal arising from stray light errors) after the correction was reduced by one to two orders of magnitude, typically to a level of 10^{-5} for a broad-band source measurement: a level equivalent to less than one count of a 15-bit resolution instrument. This implies that a stray-light corrected instrument can measure a spectral component that is 0.1 % of the averaged value with a measurement error of 1 %. The error without the correction in such a case can be close to 100 %. Another way of looking at this: the stray-light correction implies that with a fixed error tolerance from stray-light, the instrument's effective dynamic range is extended significantly. In this paper, the method, the correction results, and examples in remote sensing applications are presented.

2. STRAY-LIGHT CORRECTION IN SPECTROGRAPHS

The theory and procedures of the correction method are reported in detail elsewhere [3]. The essence of the method is given below.

The stray-light correction is based on characterization of a spectrograph for the stray-light distribution function (SDF) derived from a measured spectral line spread function (LSF). The LSF is the relative response (signals) of a spectrograph to a monochromatic spectral line source (eg. a monochromatic laser), and is conceptually equivalent to the point spread function (PSF) in an imaging optical system. The SDF is the LSF normalized by the total signal within the bandpass of a spectrograph. The SDF is set to zero within the bandpass. By measuring a set of line sources covering the spectral range of the instrument, and interpolating between these line spectra, an $n \times n$ SDF matrix, denoted $\boldsymbol{D}$, is obtained that describes the scattering properties of the instrument applicable to each element in the array detector with n elements. Based on the SDF matrix, an $n \times n$ stray-light correction matrix, denoted $\boldsymbol{C}$, is derived by

$$\boldsymbol{C} = [\boldsymbol{I} + \boldsymbol{D}]^{-1} \quad , \tag{1}$$

where $\boldsymbol{I}$ is the $n \times n$ identity matrix. The instrument's response for stray light is corrected using the equation:

$$\boldsymbol{Y}_{\text{IB}} = \boldsymbol{C} \cdot \boldsymbol{Y}_{\text{meas}} \quad , \tag{2}$$

where $\boldsymbol{Y}_{\text{meas}}$ is a column vector of n measured signals, and $\boldsymbol{Y}_{\text{IB}}$ is a column vector of n stray-light corrected signals. Using Eq. 2, the stray-light correction becomes a single matrix multiplication operation, and the correction can be performed in real-time with minimal impact on acquisition speed.

A variety of lasers (e.g. gas lasers, dye lasers, diode lasers, etc.) can be used to measure the spectrograph's LSFs to determine the SDF matrix. In principle, other sources, such as a double-monochromator-based tunable source, a tunable filter-based source, a discharge lamp-based line source, or an optical filter-based line source, could also be used as long as the source has negligibly small out-of-band emission, narrow bandwidth, and sufficient power to allow measurements with large signal-to-noise ratios.

It is not required to re-characterize the spectrograph for stray light on an annual or bi-annual basis. The stray-light correction matrix is derived from the LSFs, which are relative functions and tend to be stable after the system is constructed, especially for the spectrographs that are completely sealed after the entrance slit. However, it should be noted that any configuration change of the spectrograph may cause some changes in the LSFs. In principle the changes are small, and changes in the LSFs can be monitored by measuring a few monochromatic sources.

Since the correction matrix is obtained from the measurements by the instruments themselves, the stray-light errors arising from radiation outside the instrument's spectral range are not corrected by this method. These out-of-range stray-light errors may not be negligible in some cases. For example, the out-of-range stray-light errors may be large in a spectrograph that is used to measure a tungsten halogen lamp (a typical calibration source) that has significant infrared spectra beyond the spectral range of the spectrograph where the detector array is still sensitive. To achieve the most effective correction, it is important that these out-of-range stray-light errors are characterized or the off-array radiation of the source is blocked from entering the spectrograph using a proper optical filter.

The principle developed for this stray-light correction method can also be used to correct additional measurement errors resulting from different mechanisms. One example is the error due to fluorescence of optical materials in a measurement system. Signals from fluorescence can be treated in the same way as the spectrograph's stray-light signal, and can be corrected using this method. Such a correction for fluorescence errors has been applied successfully to an integrating sphere-spectrograph system at NIST [4].

Theoretically, this method can also be applied to scanning-type spectrometers by replacing the pixels with the scanning positions of the spectrometer. In this case, it is required that the spectrometer scan in a wavelength interval that matches its bandwidth, or scan with an interval that is a fraction of its bandwidth, in order to ensure the insensitivity of the integrated IB signal to small offsets in laser wavelength [5].

3. EXAMPLE OF STRAY-LIGHT CORRECTION FOR SPECTROGRAPHS

Several commercial array spectrographs have been characterized and corrected for stray-light errors. The stray-light errors are typically reduced to a level of 10^{-5} after the correction for broadband source measurements, a reduction of one to two orders of magnitude. In this section, we describe an example of stray-light correction for a high-grade commercial CCD-array spectrograph that has fairly low stray-light level. The spectrograph had a spectral range from 200 nm to 870 nm, a pixel-to-pixel spacing of approximately 0.65 nm (1024 pixels), and a full-width half maximum (FWHM) bandwidth of approximately 3 nm. The analog-to-digital conversion resolution of the instrument was 15 bits.

Tunable lasers available in the NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) [6] were used as the monochromatic sources. Two types of tunable lasers were used to cover the large spectral range of the instrument. CW tunable lasers were used for the spectral regions of visible and near infrared, and a quasi-CW (7 picosecond pulses, 76 MHz repetition rate) UV laser with a finite bandwidth was used for the deep blue and UV regions. For this characterization, the spectrograph measured a total of 40 laser lines with wavelengths spaced between 15 to 20 nm (24 to 32 pixels). The LSF of the test spectrograph was measured with a large dynamic range by using what is called "bracketing technique". The laser source at each tuned wavelength was measured two times: one with a normal integration time and another with a much longer integration time so that the signals near the peak region were saturated but the low level part of the signal was measured with higher resolution. The LSF with a large dynamic range was obtained by assembling the two measured signal data. Several representative LSFs spanning the detector array are shown in Fig. 1. The levels of the stray-light signals are on the order of 10^{-5} for a monochromatic source, which is a quite low for a spectrograph, and there are no localized features such as detector-window reflection peaks and or second-order diffraction peaks which are often observed in other spectrographs.

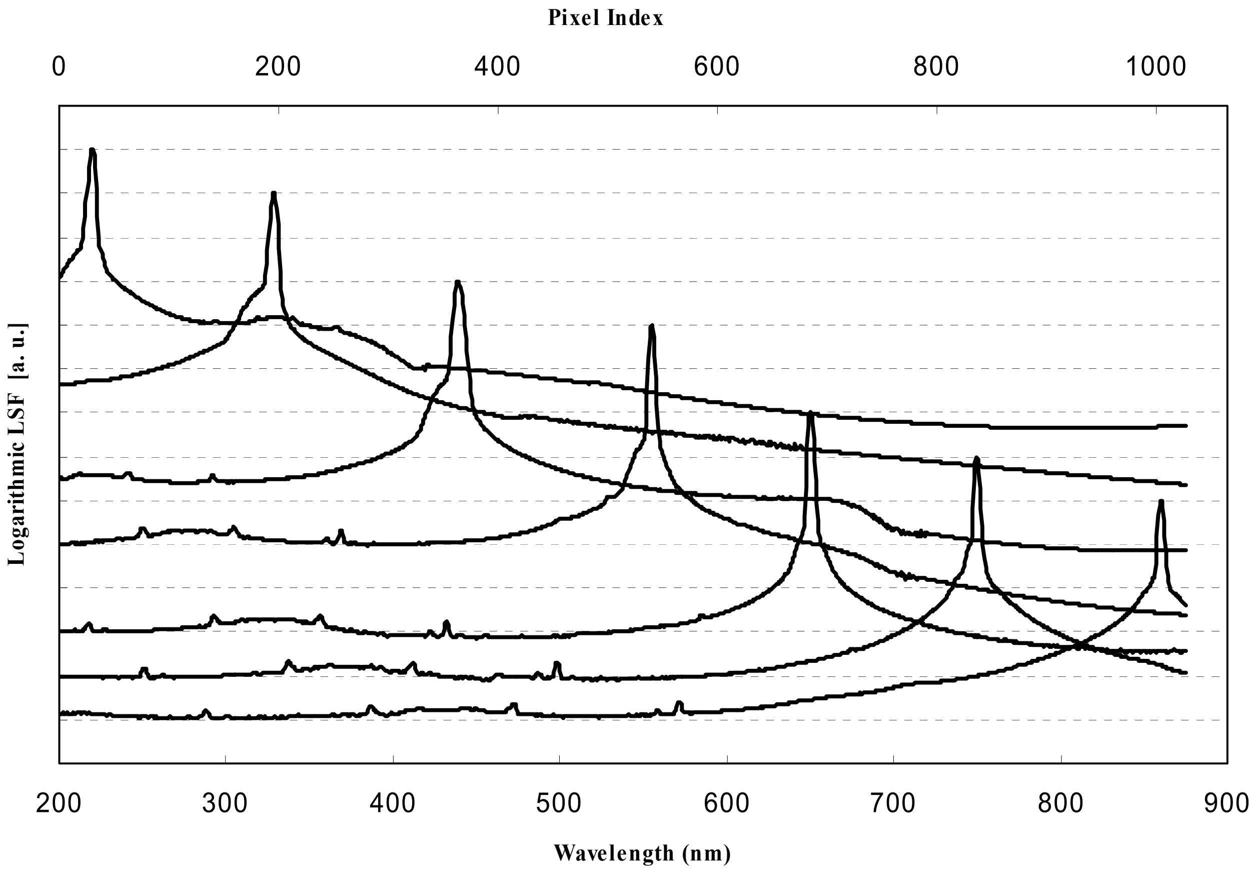

Fig. 1. Plots of representative LSFs spanning the test spectrograph's detector array. Each gridline corresponds to one order of magnitude.

The effectiveness of the stray-light correction method was validated by measuring broad-band sources with the spectrograph. Figure 2 shows the result of stray-light correction for the measurement of a broad-band source equipped with a green bandpass filter. The broad-band source was a quartz-tungsten-halogen lamp with a color temperature of approximately 3100 K. The transmittance of the green bandpass filter is lower than 10^{-10} at wavelengths below 420 nm and at wavelengths above 770 nm. This condition makes the stray-light component from the out-of-spectral-range source emission negligible, which would otherwise be present in this instrument when measuring a quartz-tungsten-halogen lamp. As shown in Fig. 2, the original relative stray-light signals were approximately 5×10^{-4} of the maximum value at wavelengths below 400 nm. After the correction, the relative stray light signals were reduced by approximately two orders of magnitude, or a level of approximately 1×10^{-5} that is a much lower level than that of one count of the 15-bit spectrograph.

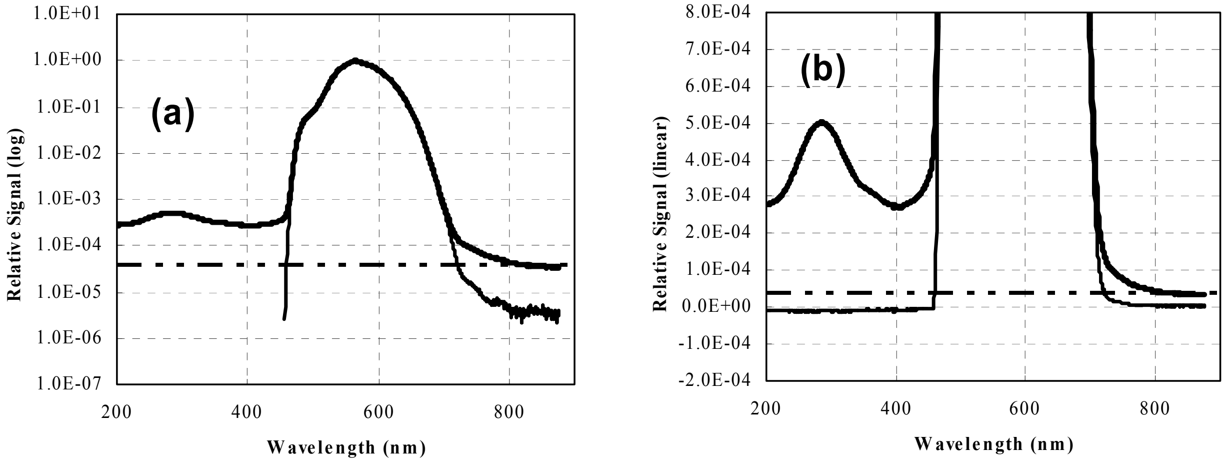

Fig. 2. Validation result of the stray light correction for a broad-band source with a green bandpass filter: (a) log scale, (b) linear scale; the thick solid line (top): measured raw signals from the spectrograph, the thin solid line (bottom): stray-light corrected signals, and the horizontal dashed line: one-count level of the 15-bit spectrograph.

The effectiveness of the stray-light correction method for measurements of narrow-band sources was also evaluated. An ultraviolet (UV) LED, a blue LED, a green LED, and a red LED were measured with the spectrograph. A heat-absorbing-type bandpass filter (330 nm to 680 nm, half maximum) was used in order to block incident flux outside the spectrograph's spectral range. Figure 3 shows the uncorrected (the thick lines) and the stray-light corrected signals (the thin lines) for the measurement of the red LED. The stray light signals in this case were reduced by more than one order of magnitude below 500 nm and above 750 nm, to a level of $\approx 2\times10^{-6}$, where the radiant flux from the LEDs is negligible.

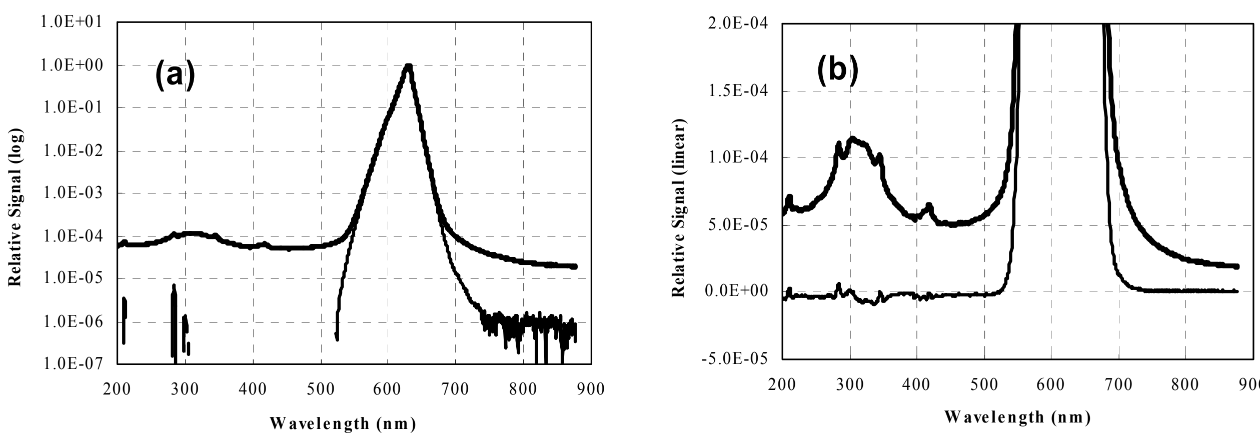

Fig. 3. Stray-light correction for a red LED measurement, (a) log scale, (b) linear scale; the thick lines: measured raw signals, and the thin lines: stray-light corrected signals.

The same bracketing technique as used for stray-light characterization was used for the measurements of the validation sources in order to evaluate the very low level residue stray-light signal after the correction.

4. APPLICATION EXAMPLES

Once a spectrograph is characterized for stray light, the measurement errors arising from stray light can be analyzed for any specific source. As an example, the stray-light-corrected spectrograph was calibrated against a spectral irradiance incandescent standard lamp with a color temperature of approximately 3100 K. Assume that the calibrated spectrograph was used to measure the solar spectral irradiance. The 'measured' raw data for the solar irradiance can be calculated based on the spectral irradiance responsivity of the array spectrograph and the stray-light signal contribution can be analyzed. Figure 4 shows the relative spectral power distributions of the calibration source and the Sun [7]. Figure 5 shows the relative spectral responsivity of the spectrograph after the stray-light correction applied. The spectral responsivity in the UV region is fairly high since the spectrograph is optimized for UV measurement; this high responsivity reduces stray-light errors in the UV region. Figure 6 shows the difference before and after the stray-light correction and the corresponding solar irradiance errors from stray light relative to the stray-light corrected true values. The stray light causes significant error in the system calibration for spectral responsivity. Though part of the calibration error is canceled by the error in the source measurement in this case, the measured raw solar spectral irradiance is still significant in the UV region below 350 nm. The relative solar spectral irradiance error is 4 % at 350 nm, but it reaches 20 % at 300 nm and 70 % at 250 nm. The reason for these large errors in measured solar spectral irradiance is that the spectral components from both the calibration source and the Sun is small and rolls off rapidly towards short wavelength with different slopes due to the dissimilarity in relative spectral power distributions, which results in large uncanceled stray-light errors.

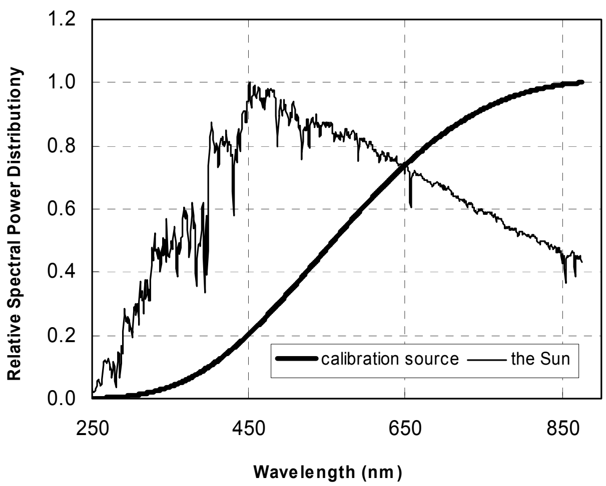

Fig. 4. Plot of the relative spectral power distributions of the calibration source (the thick, smooth curve) and the Sun (the thin, spiky curve).

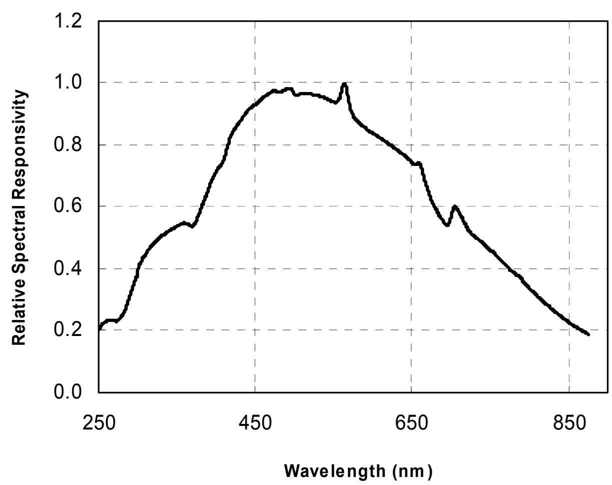

Fig. 5. Plot of the relative spectral responsivity of the array spectrograph.

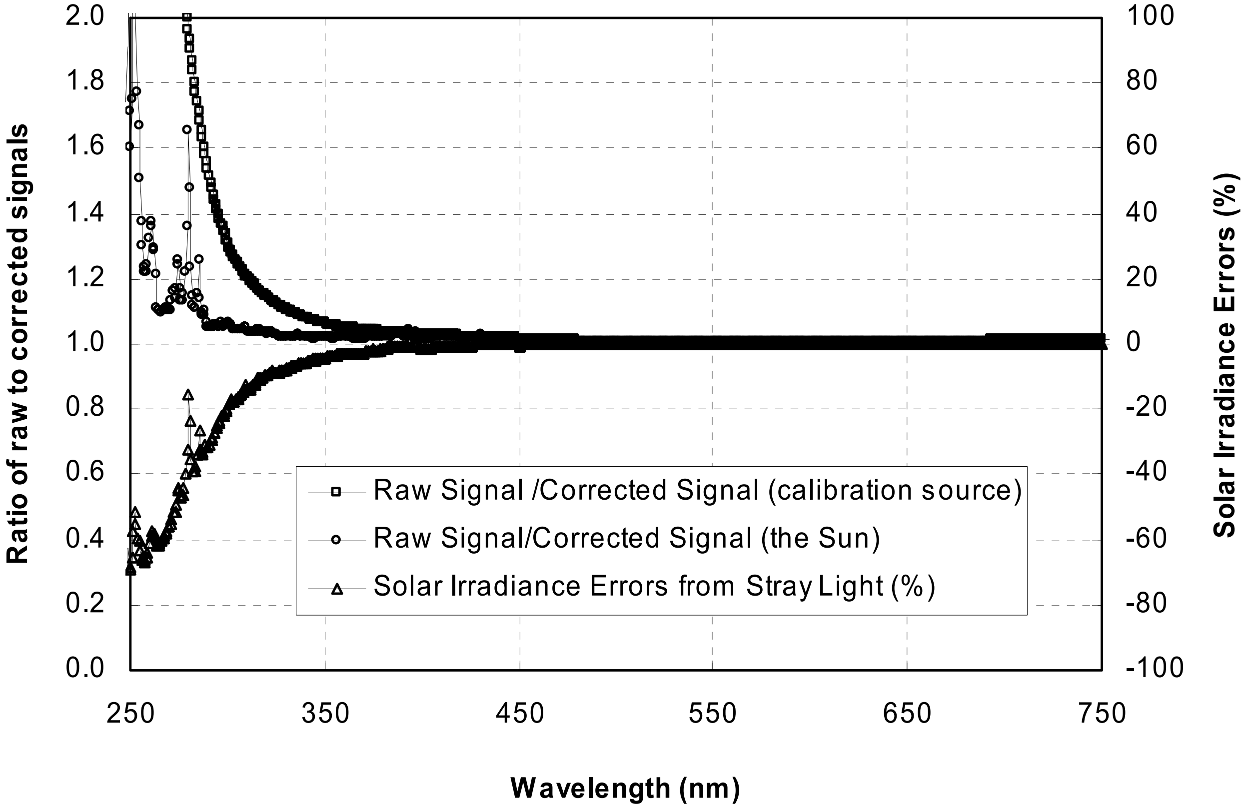

Fig. 6. Ratio of the raw signal to stray-light corrected signal and the corresponding solar irradiance errors from stray light; the top curve is the plot of the ratio of the measured raw signal to the stray-light corrected signal from the spectral responsivity calibration using the incandescent standard calibration source, the middle curve is the plot of the ratio of the measure raw signal to the stray-light corrected signal from the measurement of the solar irradiance, and the bottom curve is the plot of the solar irradiance errors in percentage from stray light relative to the stray-light corrected 'true' solar irradiance.

As an additional example, the calibrated spectrograph was used to measure the blue sky for spectral radiance, and an error larger than 10 % in the spectral range below 320 nm was observed as well.

The errors arising from stray light as demonstrated above when measuring solar spectral irradiance and the sky are much higher than the existing measurement uncertainties for solar spectral irradiance and for the earth reflected radiance which are 1 % to 5 % and 2 % to 5 %, respectively. The measurement errors from stray light are approximately 2 orders of magnitude higher than the anticipated future measurement uncertainty goals, which are 0.1 % and 0.2 %, respectively. This implies that the stray light in a spectrograph must be characterized and corrected in order to achieve a 0.1 % level of measurement uncertainty required for future remote-sensing applications.

5. CONCLUSIONS

A simple, practical method has been developed to correct a spectrograph's output signals for stray-light errors. The method is based on the characterization of a spectrograph for a stray-light distribution function derived from the spectral line spread function, which is obtained by measurements of monochromatic spectral line sources. Once characterized, the stray-light contributions to the raw output signals of the spectrograph can be corrected with a simple matrix multiplication using the stray-light correction matrix.

For validation, this method has been applied to correct stray-light errors for several commercial spectrographs using monochromatic tunable lasers. Measurements of both broad-band sources and narrow-band sources demonstrated that the magnitude of the stray-light signals in measured raw signals can be reduced by one to two orders of magnitude, to a level approximately 10^{-5} when measuring a broad-band source. Such a level is equivalent to less than one count of the 15-bit instrument.

Analysis for the measurement example of solar spectral irradiance demonstrates that errors in the UV region from stray light are significant compared to the required measurement uncertainty, even though a high grade spectrograph with a low level of stray light ($\approx 10^{-5}$ when measuring monochromatic sources), optimized for UV measurements was used. Errors are introduced in both the instrument calibration and the measurement of the source. By applying the stray-light correction to both the instrument calibration and the measurement of the source, errors can be reduced by one to two orders of magnitude. Thus, this method is expected to make a significant contribution toward achieving a 0.1 % level of uncertainty required for future remote-sensing applications. This fast stray-light correction matrix approach can be easily implemented in an instrument's software for real-time stray-light corrections with minimal degradation in acquisition speed: an important feature for remote sensing applications.

The principle can be used to correct other types of errors resulting from different mechanisms, for example, fluorescence of optical materials used in a spectrometer system. We are also extending this technique to correct stray-light errors in hyperspectral imaging instruments.

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