CORRECTION OF STRAY LIGHT IN SPECTRORADIOMETERS AND IMAGING INSTRUMENTS

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ABSTRACT

Measurement errors from stray light, spectral or spatial, are inevitable and are often the dominant source of error in spectroradiometers and imaging radiometers/photometers. We have developed a simple matrix method for correcting spatial stray light in imaging instruments as well as spectral stray-light errors in spectrometers. The stray-light correction method is based on the characterization of an instrument for a set of spectral line spread functions (LSF) or a set of point spread functions (PSF) to derive the correction matrix. The correction is simply done by a matrix multiplication to the measured raw signals, and stray-light errors are reduced by one to two orders of magnitude. By using a stray-light-corrected instrument, significant reductions are expected in overall measurement uncertainties in radiometry, colorimetry, photometry and many other applications.

Keywords: imaging instrument; imaging photometer; imaging radiometer; size-of-source effect; spectrograph; spectrometer; spectroradiometer; spatial stray light; spectral stray light; veiling glare.

1. INTRODUCTION

Optical systems, such as spectroradiometers, imaging radiometers/imaging photometers, and hyperspectral imaging systems, have been extensively used in a variety of applications to acquire spectral and spatial radiometric data. Measurement errors from stray light, spectral or spatial, are often the dominant source of error in spectroradiometers, imaging radiometers, and imaging photometers. Stray-light errors arise when the calibration source and the test source are dissimilar. There are a variety of light sources to measure, while only few types of standard sources are available (e.g., tungsten lamps for spectral irradiance standards and integrating sphere sources for radiance standards), and thus, errors due to stray light are inevitable.

Spectral stray light in a spectroradiometer can cause significant errors in the measurement of ultraviolet (UV) sources, light emitting diodes (LEDs), etc. Spatial stray light in an imaging photometer/radiometer is often the dominant source of error, e.g., in the measurement of contrast ratio of flat panel displays [1]. The error due to spatial stray light in an imaging instrument is called “veiling glare” in photometry [2] and “size-of-source effect” in radiometry [3].

We have developed a simple matrix method for correcting stray-light errors in spectroradiometers (spectral stray light) [4, 5]. Recently, this method has been extended for correcting stray-light errors in imaging instruments (spatial stray light). This stray-light correction method is based on the characterization of an instrument for a set of spectral line spread functions (LSFs) or a set of point spread functions (PSFs) to derive the correction matrix, and the correction is simply done by a matrix multiplication to the measured raw signals. By applying a correction, stray-light errors are reduced by one to two orders of magnitude. The principle of this method, validation results of the stray-light corrections for spectroradiometers and imaging instruments, and application examples of this technique are briefly described below.

2. PRINCIPLE OF STRAY-LIGHT CORRECTION AND VALIDATION RESULTS

2.1. Spectral stray-light correction in spectroradiometers

To correct spectral stray light, a spectroradiometer is first characterized for a set of LSFs covering the spectral range of the instrument. A LSF is a relative spectral response of a spectroradiometer when it is used to measure a monochromatic spectral line source. Each LSF is used to derive a corresponding stray-light distribution function (SDF): the ratio of the stray-light signal to the total signal within the bandpass of the spectroradiometer. By using the set of derived SDFs and interpolating between these SDFs, a SDF matrix is obtained. The SDF matrix is then used to derive the stray-light correction matrix, and the instrument’s response to stray light is corrected by

$$\mathbf{Y}_{\mathrm{IB}} = \mathbf{C}_{\mathrm{spec}}\mathbf{Y}_{\mathrm{meas}}, \tag{1}$$

where $\mathbf{C}_{\mathrm{spec}}$ is the stray-light correction matrix, $\mathbf{Y}_{\mathrm{meas}}$ is a column vector of the measured raw signals, and $\mathbf{Y}_{\mathrm{IB}}$ is a column vector of the stray-light-corrected signals. Note that the development of matrix $\mathbf{C}_{\mathrm{spec}}$ is required only once, unless the dispersion or scattering properties of the spectroradiometer changes. Using Equation 1, the stray-light correction becomes a single matrix multiplication, and thus the correction can be performed in real-time with minimal impact on acquisition speed. Note that the measured LSFs also include other types of unwanted responses from the spectroradiometer (e.g., fluorescence of optical materials), thus, the stray-light correction eliminates other types of errors as well. The details of the spectral stray-light correction method are described in Reference 4.

The effectiveness of the spectral stray-light correction method has been validated by using many different spectroradiometers. As an example, a spectral stray-light-corrected CCD array spectroradiometer with a spectral range of 200 nm to 870 nm was used to measure a quartz tungsten halogen lamp equipped with a green bandpass filter. The transmittance of the green bandpass filter was lower than 10^{-9} at wavelengths below 420 nm and was lower than 10^{-5} at wavelengths above 770 nm. When measuring this green light source, the spectral stray-light signals arising from the source spectra outside the spectral range of the spectroradiometer were negligible, and thus the stray-light corrected signals of the spectroradiometers below 420 nm should approach zero. The result of the test is plotted in Figure 1, in which the peak (not plotted) of the measured raw spectral signals is normalized to one. By applying the stray-light correction, the stray-light errors below 420 nm are reduced from larger than 4×10^{-4} to approximately 5×10^{-6}, a reduction of approximately two orders of magnitude in this case.

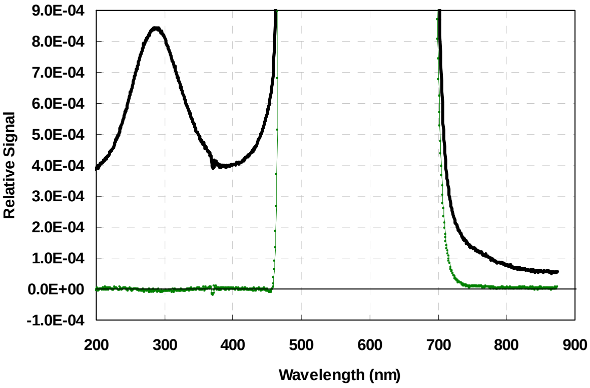

Figure 1. Result of spectral stray-light correction for a measurement of a green bandpass filter with a CCD array spectroradiometer. Thick solid line: measured raw signals; thin symbol line: stray-light corrected signals.

2.2. Spatial stray-light correction in imaging instruments

For spatial stray-light correction, an imaging instrument is first characterized for a set of PSFs covering the imaging instrument's field-of-view. A PSF is a 2-dimensional relative spatial response of an imaging instrument when it is used to measure a point source (or a small pin-hole source). Each PSF is used to derive a SDF: the ratio of the stray-light signal to the total signal within the resolving power of the imaging instrument. By using the set of derived SDFs and interpolating between these SDFs, all SDFs are obtained. Each of the obtained 2-dimensional SDF is transformed to a 1-dimensional column vector. By using all the column vector SDFs, a SDF matrix is obtained. Similar to the spectral stray-light correction [4], the SDF matrix is then used to derive the spatial stray-light correction matrix, and the instrument's response to stray light is corrected by

$$\mathbf{Y}_{\mathrm{IR}} = \mathbf{C}_{\mathrm{spat}}\mathbf{Y}_{\mathrm{meas}}, \tag{2}$$

where $\mathbf{C}_{\mathrm{spat}}$ is the spatial stray-light correction matrix, $\mathbf{Y}_{\mathrm{meas}}$ is the column vector of the measured raw signals obtained by transforming a 2-dimensional imaging signals, and $\mathbf{Y}_{\mathrm{IR}}$ is the column vector of the spatial stray-light corrected signals. Note that development of matrix $\mathbf{C}_{\mathrm{spat}}$ is also required only once, unless the imaging characteristics of the instrument changes. Using Equation 2, the spatial stray-light correction also becomes a single matrix multiplication. Note that the measured PSFs also include other types of unwanted responses from the imaging instrument (e.g., CCD smearing), thus, the stray-light correction eliminates other types of errors as well.

To validate the spatial stray-light correction method, a spatial stray-light corrected CCD imaging photometer was used to measure luminance on the port of an integrating sphere source. A black spot (a small piece of black aluminium foil) was placed at the center of the port of the integrating sphere source. The size of the sphere port was adjusted to be smaller than the field-of-view of the imaging photometer, so that the spatial stray-light signals arising from the source outside the field-of-view of the imaging photometer were zero; thus the stray-light corrected signals on the black spot were theoretically zero. The result of the validation test is shown in Figure 2, which is a plot of 1-dimensional signals along a center line across the sphere port. The maximum signal (not plotted) is normalized to one. Figure 2 shows the level of spatial stray light of the imaging photometer is approximately10^{-2} and it is reduced by more than one order of magnitude after the spatial stray-light correction.

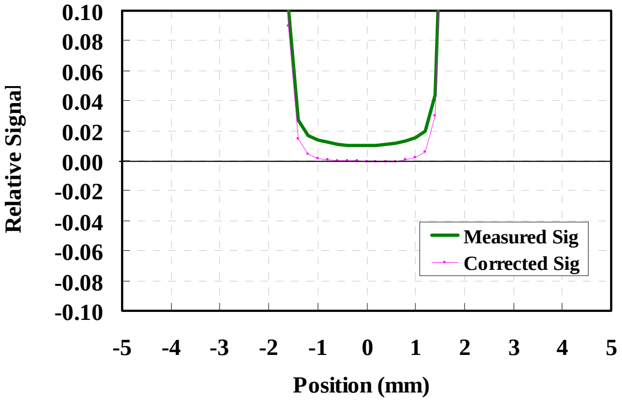

Figure 2. Result of spatial stray-light correction for a measurement of a black spot with bright surrounding area with an imaging photometer. Thick solid line: measured raw signals; thin line: the stray-light corrected

3. EXAMPLES OF STRAY-LIGHT CORRECTION

Stray-light errors exist in both instrument calibrations and test source measurements. In many applications it is critical to correct the stray-light errors.

Figure 3 shows the spectral stray-light errors in a calibration of a high-grade CCD-array spectroradiometer optimized in the UV region for spectral irradiance responsivity, using an incandescent standard lamp. Spectral stray-light errors are significant in the UV region, reaching 32 % at 300 nm. This spectral stray-light error resulting from the spectroradiometer's calibration is the dominant source of error in the measurement of UV sources. After applying the spectral stray-light correction, the errors at 300 nm were reduced from 32 % to less than 1 %.

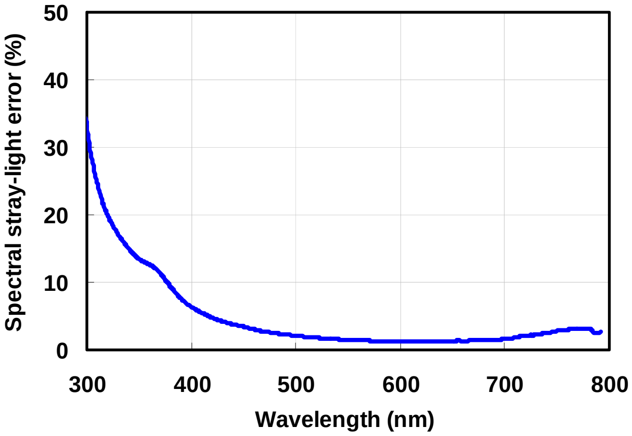

Figure 3. Plot of relative spectral stray-light errors in the calibration of a high-grade CCD-array spectroradiometer.

Figure 4 shows the measurement results of a green LED using the same CCD-array spectroradiometer. The signals are normalized to the measured raw peak signal, and are plotted in both logarithmic scale (left), and in linear scale (right). In this green LED measurement, the error in the measured chromaticity coordinates (*x*, *y*), resulting from the spectral stray light, is significant. After applying the spectral stray-light correction, the level of the spectral stray-light signal is reduced approximately two orders of magnitude in the UV region (see the left plot), and the error in the *y* chromaticity coordinate is reduced from 0.01 to less than 0.001.

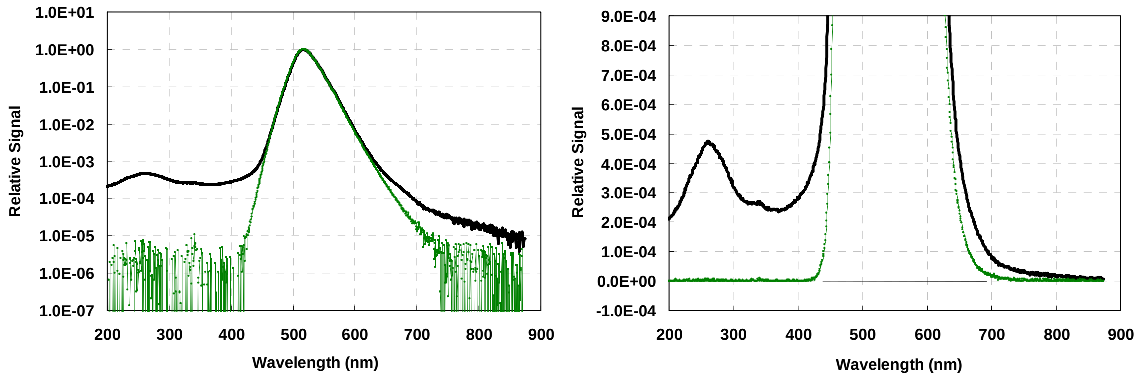

Figure 4. The measurement results of a green LED using a high-grade spectroradiometer. Thick solid line: measured raw signals; thin symbol line: the stray-light corrected signals.

4. CONCLUSION

We have developed a simple stray-light correction method using a stray-light correction matrix for correcting spectral stray-light errors in spectroradiometers and spatial stray-light errors in imaging instruments. This method is based on the characterization of a spectroradiometer for a set of LSFs or an imaging instrument for a set of PSFs to derive the correction matrix, and the correction is simply done by a matrix multiplication to the measured raw signals. Stray-light errors are reduced by 1-2 orders of magnitude.

This fast spectral stray-light correction matrix approach can easily be implemented in an instrument's software for real-time corrections with minimal degradation in acquisition speed. By applying stray-light corrections, significant reductions are expected in overall measurement uncertainties in radiometry, colorimetry, photometry and many other applications.

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