Stray light characterization of an InGaAs anamorphic hyperspectral imager

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Abstract: Compact hyperspectral sensors potentially have a wide range of applications, including machine vision, quality control, and surveillance from small Unmanned Aerial Vehicles (UAVs). With the development of Indium Gallium Arsenide (InGaAs) focal plane arrays, much of the Short Wave Infra-Red (SWIR) spectral regime can be accessed with a small hyperspectral imaging system, thereby substantially expanding hyperspectral sensing capabilities. To fully realize this potential, system performance must be well-understood. Here, stray light characterization of a recently-developed push-broom hyperspectral sensor sensitive in the 1 µm −1.7 µm spectral regime is described. The sensor utilizes anamorphic fore-optics that partially decouple image formation along the spatial and spectral axes of the instrument. This design benefits from a reduction in complexity over standard high-performance spectrometer optical designs while maintaining excellent aberration control and spatial and spectral distortion characteristics. The stray light performance characteristics of the anamorphic imaging spectrometer were measured using the spectral irradiance and radiance responsivity calibrations using uniform sources (SIRCUS) facility at the National Institute of Standards and Technology (NIST). A description of the measurements and results are presented. Additionally, a stray-light matrix was assembled for the instrument to improve the instrument’s spectral accuracy. Transmittance of a silicon wafer was measured to validate this approach.

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References and links
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1. Introduction

The emerging class of lightweight and inexpensive small uninhabited aerial vehicles (UAVs) has advantages over larger platforms due to smaller radar cross-sections, increased air maneuverability, greater portability and decreased monetary and personnel risk if lost. Deploying UAVs with on-board hyperspectral systems would enable improved target detection over current EO/IR (Electro-Optical/InfraRed) systems. Other possible applications include crop monitoring, pipeline monitoring, and ocean color measurements. Advances in the design of small, lightweight hyperspectral imagers are necessary to meet the payload requirements of small UAVs. Additionally, systems utilizing un-cooled InGaAs focal plane arrays (1µm – 1.7 µm) provide access to much of the Short Wave InfraRed (SWIR) spectral regime.

To meet these needs, a small, high-performance imaging spectrometer with an InGaAs focal plane array (FPA) has been developed [1]. To our knowledge, this is the first system that utilizes anamorphic optics (i.e., optics such as cylindrical lenses and mirrors that have different optical power along their two radial axes) that match the asymmetry of pushbroom imaging spectrometers [2]. Advantages of this design include reduced point imaging aberrations, decreased slit tolerance and sensitivity to dust, and the use of low-cost, off-the-shelf, flat gratings. Furthermore, the anamorphic design partially decouples the spectral and spatial axes, which effectively adds an additional engineering parameter as compared to conventional designs.

The radiometric performance of this new anamorphic imaging spectrometer was extensively characterized [3] on NIST’s SIRCUS facility [4,5]. In addition to measurements of the system’s responsivity, response linearity, and electronic gain, the spatial and spectral imaging performance was measured. This paper describes measurements taken at NIST’s SIRCUS facility that were used to construct stray light correction matrices to remove measurement errors introduced by scattered light [6–8]. Validation of this approach was demonstrated by measuring the transmission through a wafer of silicon.

2. Imaging spectrometer description

A general feature of grating-based pushbroom imaging spectrometers is that the signal is imaged through a slit to limit the spatial field-of-view as it enters the spectrometer. For compact imaging spectrometers suitable for deployment on small UAVs, this requires large aperture (low f-number), short focal length, off-axis imaging, which is generally problematic. The anamorphic optical design shown in Fig. 1 was motivated by the observation that the slit in a pushbroom imaging spectrometer only limits the field-of-view in the narrow dimension of the slit. Consequently, the focus (and subsequent re-collimation) along the long dimension of the slit is not required.
The anamorphic imaging spectrometer eliminates the focus along the long axis of the slit by using anamorphic optics that have no optical power along the long dimension of the slit. This optical design eliminates all off-axis field aberrations such as coma, astigmatism, field curvature, and distortion, resulting in decreased wavefront error with fewer and simpler optical components.

After light is focused through the slit, it is collimated with the second anamorphic mirror. The light then passes through a flat transmission grating, used to separate the beam into its spectral components, and is imaged onto a focal plane array. A corrective lens can be used to compensate for distortions introduced by the grating, but does not inhibit the spatial or spectral resolution of the imaging system [9–11]. Spectral information is mapped onto the focal plane array along the axis perpendicular to the grating grooves and the long axis of the slit while spatial information is mapped along the axis parallel to the grating grooves and the long axis of the slit. The second spatial image dimension of information is collected by scanning (i.e. moving) the system (or sample) as subsequent frames are collected.

The specifications for the prototype anamorphic imaging spectrometer are provided in Table 1.

Table 1. Prototype Anamorphic Imaging Spectrometer Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>1,000 – 1,700 nm</td>
</tr>
<tr>
<td>Field of view</td>
<td>6 degrees</td>
</tr>
<tr>
<td>Detector</td>
<td>InGaAs (256 by 320) 25 µm pixel pitch</td>
</tr>
<tr>
<td>Bit depth</td>
<td>12</td>
</tr>
<tr>
<td>Entrance pupil diameter (f/#)</td>
<td>20 mm (2.54)</td>
</tr>
<tr>
<td>Maximum predicted smile</td>
<td>2.9 µm (0.12 pixels)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 frames/sec</td>
</tr>
<tr>
<td>Weight</td>
<td>3.8 lbs</td>
</tr>
</tbody>
</table>

3. Optical characterization

NIST’s SIRCUS facility has tunable, high-power lasers that provide narrow-band sources of radiant flux spanning the spectral range from 210 nm to 5,300 nm [5]. The laser system used for these experiments was a Coherent MIRA (Ti:Sapphire laser) [12] and a MIRA OPO.
(optical parametric oscillator). These high-power tunable lasers enabled measurements of the anamorphic imaging spectrometer’s performance, thereby providing data for assembling stray light correction matrices. The output of the laser (OPO) was fed into an optical fiber and transported to an integrating sphere (for spectral response measurements) or a collimating mirror (point-spread response measurements).

For the spectral response measurements, emission from the tunable, high-power lasers was coupled into an integrating sphere to provide a uniform, quasi-Lambertian optical source. The imaging spectrometer was positioned in front of the exit aperture of the sphere such that the entire entrance pupil of the instrument was uniformly filled by radiant flux from the exit port of the sphere. Scans of at least 100 frames (images) were recorded for each wavelength. Background readings with the laser source blocked were recorded regularly. To determine the net signal for each measurement, the frames from each scan were averaged together and the average background was subtracted. The radiance from the integrating sphere was determined for each measurement using a reference detector situated to the right of the anamorphic imaging spectrometer in Fig. 2.

Fig. 2. Photo of the anamorphic imaging spectrometer and the NIST integrating sphere used for characterization.

4. Constructing Stray Light Matrix

Stray light correction in spectral imaging systems is motivated by the observation that stray light within optical instrumentation is systematic and well-behaved. Consequently, accurate instrument characterization enables one to remove most of the stray light contribution to critical measurements. Detailed discussions of the stray light model used here are described elsewhere [6–8]. In brief, according to this model, the signal measured at a given pixel \( i \), denoted \( y_{\text{meas},i} \), is due to the desired in-band signal, \( y_{\text{IB},i} \), plus unwanted stray light, which depends on the amount of in-band signal at the other \( n \) pixels. The relative fractional scattering coefficient for light scattered from in-band signal associated with pixel \( j \) to pixel \( i \) is denoted \( d_{i,j} \). Thus, the total signal measured at pixel \( i \) can be written:
\[ y_{\text{meas},i} = y_{\text{IB},i} + \sum_j (d_{i,j} y_{\text{IB},j}) \]  \hspace{1cm} (1)

This equation can be written in vector form:

\[ \mathbf{Y}_{\text{meas}} = \mathbf{Y}_{\text{IB}} + \mathbf{D} \mathbf{Y}_{\text{IB}} \]  \hspace{1cm} (2)

Where \( \mathbf{Y}_{\text{meas}} \) is a measured column vector from the detector array, \( \mathbf{Y}_{\text{IB}} \) is a column vector of the desired in-band signal values, and \( \mathbf{D} \) is a two dimensional stray light distribution matrix. This can be rewritten as:

\[ \mathbf{Y}_{\text{meas}} = (\mathbf{I} + \mathbf{D}) \mathbf{Y}_{\text{IB}} = \mathbf{A} \mathbf{Y}_{\text{IB}} \]  \hspace{1cm} (3)

Where \( \mathbf{I} \) is the \( n \) by \( n \) identity matrix. To obtain the desired in-band signal, the matrix \( \mathbf{A} \) can be inverted to obtain:

\[ \mathbf{Y}_{\text{IB}} = \mathbf{A}^{-1} \mathbf{Y}_{\text{meas}} = \mathbf{C} \mathbf{Y}_{\text{meas}} \]  \hspace{1cm} (4)

The matrix \( \mathbf{C} \), known as the stray light correction matrix, applied to the measured values removes the stray light contribution to obtain the desired in-band results.

The signal due to stray light is typically much weaker than the primary signal. To accurately measure the relatively weak stray light, two sets of data were collected for each laser wavelength as described in Section 3, one at low gain and another at high gain with the laser line saturated. This is much like bracketing techniques used for enhancing the dynamic range in digital photography. The low gain measurement results were multiplied by the gain value to match the high gain data after subtracting the average dark current contribution. Using this ‘bootstrap’ technique to increase the dynamic range of the measurements, a more accurate measurement of the relatively weak stray light was obtained.

A Gaussian fit of the low gain data was used to determine the full width half maximum (FWHM) of each low gain laser spectrum. The data from the two measurements were then stitched together, with the low gain data inside the 2.5* FWHM as the peak data, and the high gain data outside the 2.5* FWHM as the wing data. Figure 3 shows the stitched data for three laser wavelengths (1078 nm, 1302 nm, and 1572 nm) for three of the 320 spatial pixels of the instrument, (pixels 20, 160, and 250) which correspond to pixels near the bottom, middle, and top of the field of view. The black curve in each plot is that of the low gain data multiplied by detector gain, which was 16 for these measurements. The red curve is the stitched laser spectrum that is used for stray light analyses.
Fig. 3. Stitched data for three laser wavelengths, 1078 nm (left), 1302 nm (middle), and 1572 nm (right), for three representative spatial pixels. The x-axis is the wavelength dimension and the y axis the laser line intensity in digital number (DN).

Ideally, the stray light distribution function would be measured with laser excitation wavelengths corresponding to every pixel in the dispersion direction on the focal plane array, which would be extremely time-consuming. Fortunately, stray light is well-behaved so measurements can be extrapolated or interpolated and the stray light distribution matrix can be constructed with relatively sparse spectral coverage. In addition, the approach described in Section 3 effectively collected the data needed to construct the stray light distribution function for all spatial pixels at a particular spectral channel simultaneously.

Note that with this approach, the stray light generated along the spatial axis was not well determined and the measured stray light was assumed to be associated with the spectral axis of the instrument (that is, potential cross-track coupling due to a finite point spread response is not considered in this work). Point spread measurements, not described here, indicate this approximation was valid, as very little stray light was observed along the spatial axis of the instrument. Correcting stray light along the spatial axis would require extensive additional...
matrix manipulation. Although much smaller than the spectral stray light (~2 pixel FWHM spots were observed), stray light correction along the spatial axis will be addressed in future work. It is worth noting, however, that if the point-spread response can be measured accurately, a full 2-d correction of the scattered light in the instrument can be developed. Data from 18 laser measurements ranging from 995 nm to 1,572 nm were used to construct stray light distribution function matrices $D$. Data were interpolated between the laser wavelength measurements and extrapolated at the endpoints to form a 256 by 256 light distribution function matrix for each of the 320 spatial elements of the imaging spectrometer. A stray light distribution function matrix for each pixel was formed by normalizing each spectrum to the in-band sum, then setting the in-band region of the array (+/− approximately 13 pixels along the matrix diagonal) to zero. Figure 4 shows a surface plot and a contour plot of the stray light distribution function matrix corresponding to pixel number 160. Note that stray light distribution function matrices were determined for all 320 spatial pixels of the instrument.

The stray light distribution function matrices were used to determine stray light correction matrices for the imaging spectrometer, which were then used to correct each hyperspectral image produced by the imaging spectrometer. Figure 5 shows the original (black) and the stray light corrected (red) results for pixels 20, 160, and 250 at laser wavelengths 1078 nm, 1302 nm, and 1572 nm. The plots have been expanded near the baselines to show the details of the stray light correction.
Fig. 5. Expanded stray light corrected laser spectra. The x-axis is the wavelength dimension and the y axis the laser line intensity in digital number. The laser wavelengths for these plots are 1078.7 nm (left column), 1302.3 nm (center column) and 1572.6 nm (right column). Peak intensities were on the order of $3 \times 10^4$ on this scale.

5. Corrected measurement

Transmission measurements through a silicon wafer were made, corrected, and analyzed to assess the impact of stray light correction for a typical measurement. In this experiment, the anamorphic imaging spectrometer imaged the output from a calibrated, lamp-illuminated integrating sphere (Optronic Laboratories OL 420) [13] with and without a silicon sample in the beam path. The silicon sample was smaller than the entrance window to the anamorphic imaging spectrometer. Consequently, an aperture was placed in front of the imaging spectrometer that matched the size of the silicon sample. Stray light corrected and uncorrected measurements with the silicon wafer in the optical path are shown in Fig. 6. In the left panel, the black curve is the original measurement and the red curve shows the stray light corrected results. The middle panel is the plot of the magnitude of the stray light correction (in DN) as a function of wavelength; the right panel shows the percent correction to the measurement due
to stray light. It should be noted that no baseline adjustment is applied to this data set; results shown are for spatial pixels 20, 160, and 250. Note that the amplitude for measurements taken at pixel 250 are substantially reduced as compared to pixels 20 and 160; this was likely due to vignetting from the aperture used to match the size of the silicon wafer. As one would expect, the percent correction is largest in regions where the signal is relatively small, and consequently even low levels of stray light produce a large relative error.

Fig. 6. Stray light correction of silicon data. For each panel, the x-axis is the spectral dimension (in nm). The light intensity in DN, correction magnitude in DN, and the percent of the stray light correction to the measurement data are plotted along the y-axis respectively.

The stray light corrected and uncorrected results were also used to determine the silicon transmittance, as shown in Fig. 7. Again, the black curve is the original measurement and the red curve is the corrected result; data are shown for spatial pixels 20, 160, and 250.
The relative effects of stray light correction on the silicon transmittance are shown in Fig. 8. Note that greatest impact of the stray light correction occurs in spectral regions where there is very little signal and where there is a large change in transmittance.
Fig. 8. Percent change in silicon transmittance due to stray light corrections for pixel 250 (top), 160 (middle) and 20 (bottom).

6. Discussion and conclusions

A prototype anamorphic imaging spectrometer with an InGaAs detector has been characterized at NIST’s SIRCUS facility. Stray light measurements were used to develop correction matrices for 320 spatial pixels of the instrument. The efficacy of stray light correction was validated by measuring the transmission of a silicon wafer. These measurements indicate that stray light corrections have the largest impact for spectral signatures that have regions of both high and low transmission or have sharp spectral features, which are often the most important characteristics of measured spectra.

An important point to note is that measurements at only 17 laser wavelengths were made to assemble the stray light matrices that provided correction for all 320 spatial channels and all spectral channels. Because stray-light is generally well-behaved, this relatively modest number of measurements was sufficient to accurately remove much of the impact of stray light within the instrument. Consequently, this effort demonstrates the practicality of the approach used here for improving results from spectral imaging instrumentation in general. Moreover, additional point spread response measurements could be measured to further improve the stray light correction by accounting for cross-track coupling.