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See next page for full paper.

SPATIAL AND SPECTRAL CALIBRATION METHODS FOR MONOLITHIC VIS/NIR AND VIS/SWIR HYPERSPECTRAL SENSORS

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ABSTRACT

A set of measurements and fitting procedures is described, that will be used to characterize a new hyperspectral sensor covering the visible-to-extended SWIR spectral range. The procedures produce maps of spatially-resolved spectral resolution across the focal plane, and spectrally-resolved spatial resolution in both the along-slit and cross-slit directions. They also yield spectral calibration, and characterization of the keystone, smile, and slit rotation. Examples are shown for an existing visible/near IR sensor.

Index terms—hyperspectral, smile, keystone, Vis/SWIR, edge-spread function, line-spread function

1. INTRODUCTION

Spectral Sciences, Incorporated (SSI) in conjunction with Corning Special Materials has developed a Hyperspectral (HSI) sensor covering the visible-to-extended SWIR (Vis/SWIR) spectral range [1]. This sensor will be used by climate and ecosystem researchers to develop methods for quantitative mapping of temporal and spatial vegetation traits across the globe. It will be a ready-to-fly, HSI system based on Corning's unique, patented, high-performance solid-block spectrograph technology [2]. The sensor package covers the full extended Vis/SWIR spectral range from 380-2450 nm, is light enough to fly on a small unmanned aircraft (<2.2 kg) and, when combined with appropriate processing algorithms, its' data is sufficiently accurate and reproducible to enable comparison of measurements at different times and locations.

Accurate retrieval of biochemical information requires both a high Signal to Noise Ratio (SNR), and high spatial and spectral fidelity across the focal plane. The new Vis/SWIR sensor has a projected SNR of several hundred to one. The ability to identify vegetative characteristics will most likely be limited not by the SNR, but rather by instrumental effects that confuse the spatial and spectral information due to differential spatial sampling across the image. These effects include: (1) variations in spatial resolution as a function of spectral and spatial location, (2) keystone, which introduces a systematic spatial shift with wavelength, and (3) spectral smile, which introduces a systematic spectral shift with spatial channel.

In preparation for characterizing this device, SSI has developed a set of procedures to fully characterize spatial and spectral resolution as a function of position on the focal plane. This includes spectral calibration with atomic line lamps that yields spectral resolution, slit rotation and smile; and edge-spread measurements to measure the spatial resolution and keystone. Two edge measurement methods are compared. One method is based on Gaussian fits to individual rows and columns of the focal plane. The second, is the more rigorous edge rotation method described by Haefner [2], which uses multiple rows and columns. Edge rotation is able to better sample the line shape, whereas the former method allows for rapid and complete characterization of the spatial resolution in all spectral bands at the expense of a small, systematic error. Similar fast-fitting methods are applied to images of atomic line lamps to measure the spatially-resolved spectral resolution, spectral smile and the sensor's slit rotation.

In preparation for characterizing the new Vis/SWIR sensor, SSI has performed the full suite of measurements on a Corning MicroHSI Model 410 Shark Vis/NIR sensor [2]. The MicroHSI covers the 400-1000 nm spectral range with 582 spatial channels and 154 spectral channels, with 12µm pixels. It also has a 12µm slit. Calibration results for the HSI410 are presented here, while results for the Vis/SWIR sensor in development will be presented in September.

2. SPATIAL CALIBRATION

We characterize the spatial resolution using edge-spread measurements of the image of a slanted knife edge. The knife edge is placed at the focus of a spherical collimator and back-illuminated with a uniform white light source. Spatial resolution along the slit plane is measured using an edge perpendicular to the slit. Cross-slit resolution is measured using an edge parallel to the slit. An example image of a cross-slit knife edge is shown in Figure 1a. A two-dimensional spatial image is obtained by rotating the imager about the sensor's aperture. Each degree of camera rotation is equivalent to a 1.12 mm displacement on the focal plane. The spatial resolution is computed on a wavelength-by-wavelength basis and compared using two methods: an edge rotation method, which allows oversampling of the spatial edge-spread function (ESF), and the single row method, which allows rapid evaluation of the ESF over the entire focal plane.

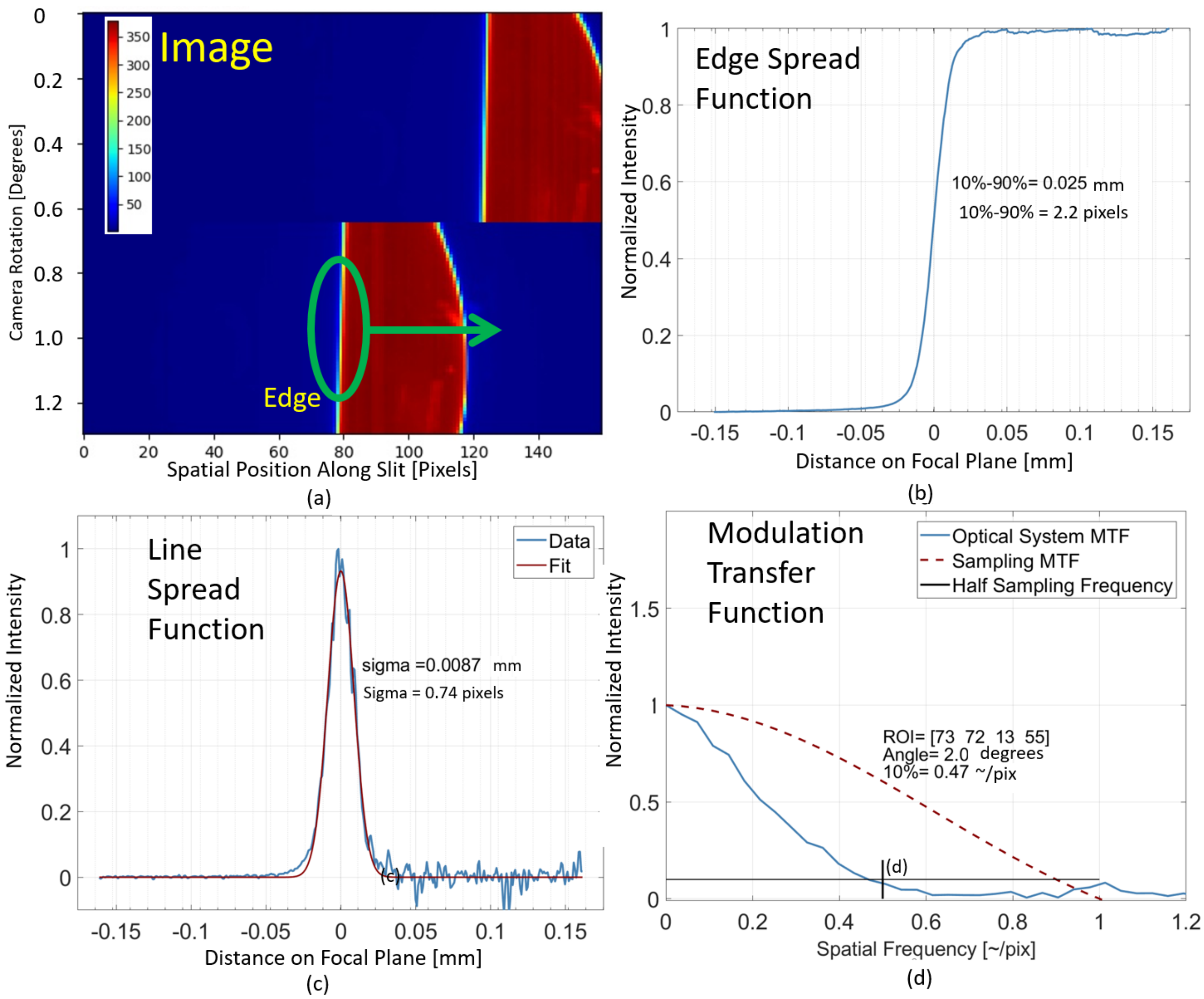

Figure 1. Spatial resolution measurement along the slit for spectral channel 95 (779 nm) using the edge rotation method. (a) Raw image for a cross-slit edge. (b) ESF, (c) LSF, (d) MTF.

2.1. Edge Rotation Method

Figure 1b shows the normalized edge-spread function (ESF), as determined by the rotation method using software developed by Haefner [3]. The image of the edge is slightly tilted on the focal plane. The data from several adjacent rows is rotated into the edge frame of reference and then registered to the spatial displacement along a line perpendicular to the rotated edge. This produces an oversampled version of the ESF with a resolution of order 1 micron. The line spread function (LSF), shown in Figure 1c, is determined by the finite differential of the ESF, sample-to-sample. The modulation transfer function (MTF) shown in Figure 1d is the Fourier transform of the LSF.

Two traditional metrics are used for the spatial resolution: the limiting resolution, defined as the distance between the 10% and 90% intensity points of the ESF, and the standard deviation, sigma, of a Gaussian fit to the LSF.

Figure 1 shows a measurement along the slit at wavelength 779 nm (spectral channel 95). For this case, the 10-90% limiting resolution is about 26 microns or 2.2 pixels for a 12μm pixel. The line spread function can be described by a Gaussian with sigma=8.7 microns (0.74 pixels), and the MTF falls to 10% of the original intensity at the spatial frequency of about 0.47 inverse pixels, or 25.9 cycles/mm. All these values are consistent.

2.2. Single Row/Column Method

This method was deployed for the rapid characterization of the spatial and spectral resolution. Rather than rotating the image and fitting multiple rows, or columns at once, this method fits a single row/column at a time. This method gives results similar to those calculated using the edge rotation method (see Figure 2), but was accomplished in a fraction of the time. In addition, this method provides the advantage of looking at all spectral channels simultaneously.

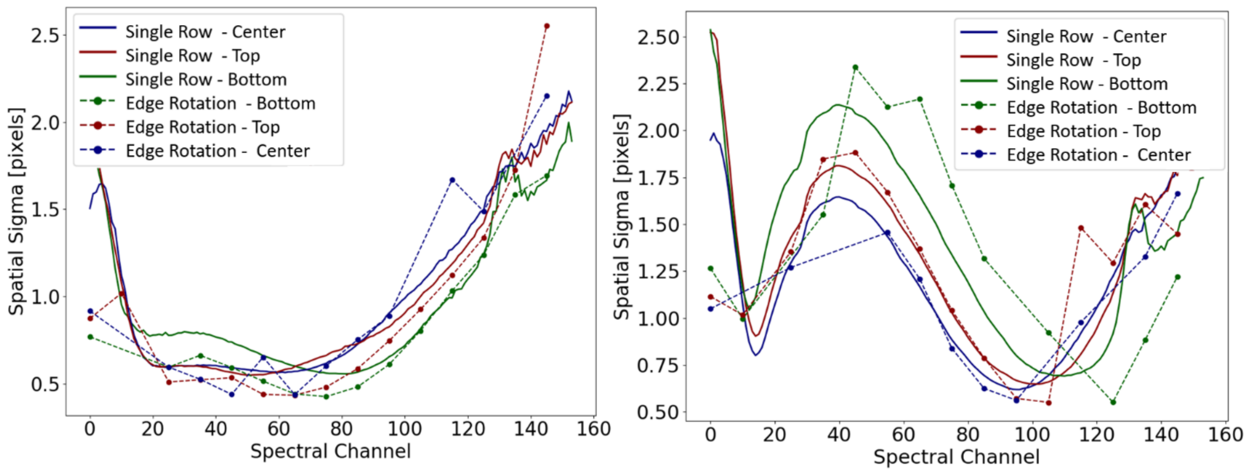

Figure 2. Plots comparing the limiting spatial resolution along the slit (left) and across the slit (right) using two methods.

2.3. Comparison of Methods

Figure 2 compares the spectrally-resolved spatial resolution along the slit (left) and across the slit (right). Results for the edge rotation method are denoted by individual data points connected by dashed lines. Those computed using the single row/column method are shown as solid lines. The metric of choice is defined by the standard deviation of a Gaussian fit to the LSF. We have found that a Gaussian is a reasonable estimate for the spatial resolution (see Figure 1c). The resolution is fairly consistent across the slit dimension (shown by the focal plane position reported in Figure 2), but varies by a factor of three across the spectral channels. The variation along the spectral channels is primarily due to the chromatic aberration of the collimating lens. In the absence of this aberration, the sensor will have a limiting resolution similar to that seen in the center spectral channels. This is why the new Vis/SWIR system used an all-reflective fore-optic.

Figure 4 shows the systematic variation in the fit error due to sampling, using the single row method. The data of Figure 1a was fit as a function of row address for three spectral channels (solid lines), and compared to the edge rotation results for the ensemble of rows (dashed line). Overall, the methods return similar results for $\sigma \geq 0.4$ pixels. There is a systematic bias due to sampling error in the single row method. The returned line-width oscillates about the true value, with a period given by the repeat distance of the pixel sampling (see Figure 1a). The sampling error amplitude is about +/- 10% for $\sigma \geq 0.5$, decreases with increasing linewidth, and approaches zero for $\sigma \geq 1$ pixel, when the single-row method adequately samples the LSF.

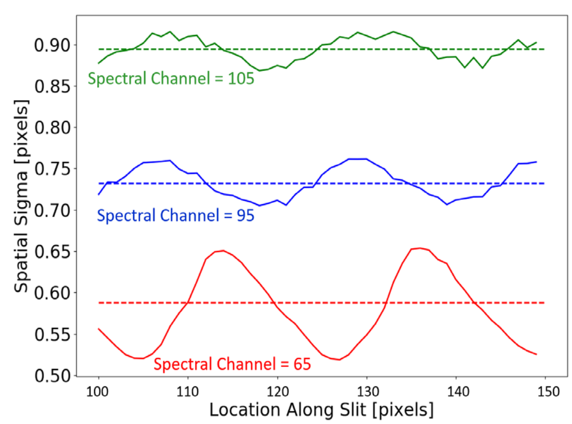

Figure 3. Single-row sigma (solid line) varies systematically about the edge-rotation value (dashed line).

In addition to the spatial resolution, the single row/column method provides an accurate estimate of the sensor's keystone. Keystone is the wavelength-dependent stretching of the dispersed image along the slit direction. The location of the slit image varies systematically with spectral channel as shown in Figure 4. Here you can see that the Gaussian peak location is changing by ~1.2 pixels at both the top and bottom of the focal plane. The maximum keystone is calculated as the difference of these two curves, giving the MicroHSI 2.4 pixels, or 30 microns of keystone across the spectral field. The new Vis/SWIR sensor is designed to have <0.3 pixels of keystone.

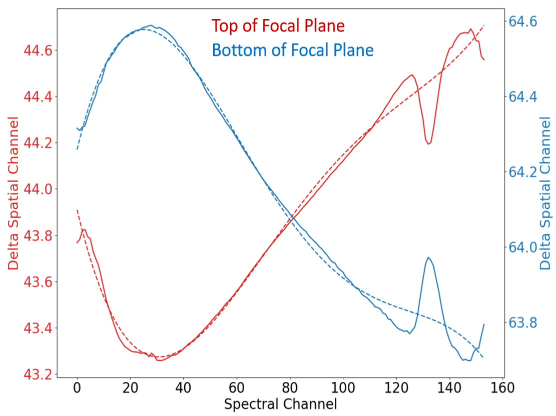

Figure 4. Keystone measurement of a knife edge along the slit at the top and bottom of the slit image.

3. WAVELENGTH CALIBRATION AND SPECTRAL RESOLUTION

Spectral calibration is accomplished using images of monochromatic atomic line lamps inserted into an integrating sphere. Spectral lines appear as stripes along the spectral axis of the focal plane. Data is compiled from images of HgAr, Xe and Kr line lamps and a HeNe laser in order to cover the full spectral range. For each row the lines are fit to a Gaussian shape, and the line centers and standard deviation (sigma) values are mapped as a function of spatial position along the slit as shown in Figures 5 and 6.

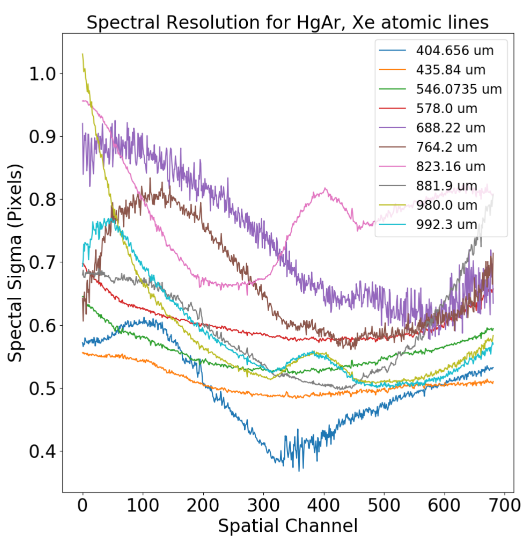

Figure 5. Spectral resolution for HgAr and Xe atomic lines as a function of spatial channel.

The standard deviation of the Gaussian fit is a reasonable measure of the spectral resolution, based on the rules of thumb developed above. The spectral resolution varies smoothly across spatial and spectral dimensions with the Gaussian half width in the range of 0.4-1.0 pixels as shown in Figure 5.

Figure 6 shows the slit rotation for the MicroHSI 410. This is determined by plotting the line center as a function of spatial channel. Each line pertains to a HgAr or Xe atomic line as labeled on the plot. The lines have a common slope. The mean linear slope of the atomic lines yields the slit rotation, which is 1.02×10^{-3} mrad per spatial channel for this sensor.

The spectral smile, is a spectral distortion that in common in sensors such as this. The smile is a non-linear spectral shift that occurs along the slit direction. An estimate for the spectral smile is determined by the deviation of individual spectral lines from the linear slit rotation. Figure 7 shows the residual spectral shift, which includes spectral smile, and systematic errors in the spectral fit. These deviations are generally small, amounting to less than 0.3 pixels. The DOE sensor is expected to have a maximum smile of <0.25 pixels, which will easily be measurable with this method.

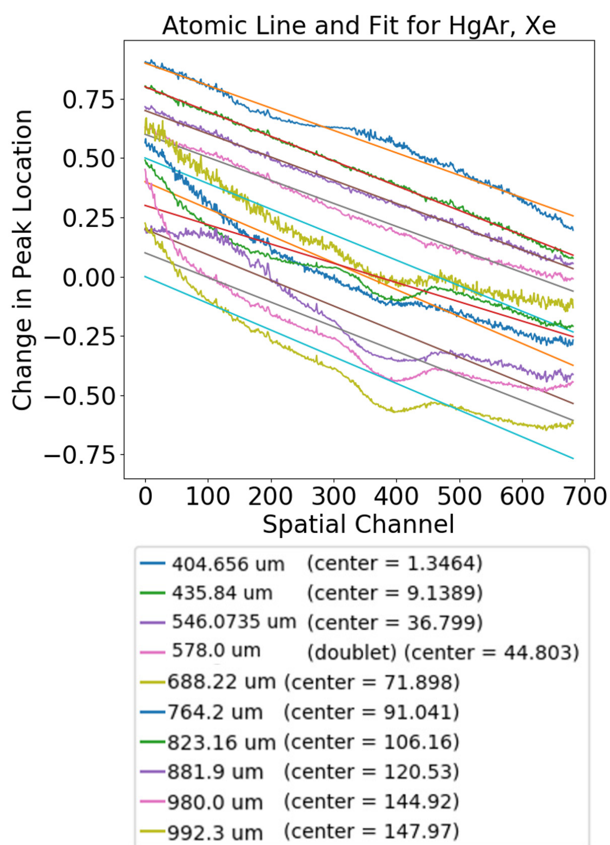

Figure 6. Line centers as a function of the slit position for HgAr and Xe atomic lines. Curves have been displaced for ease of reading.

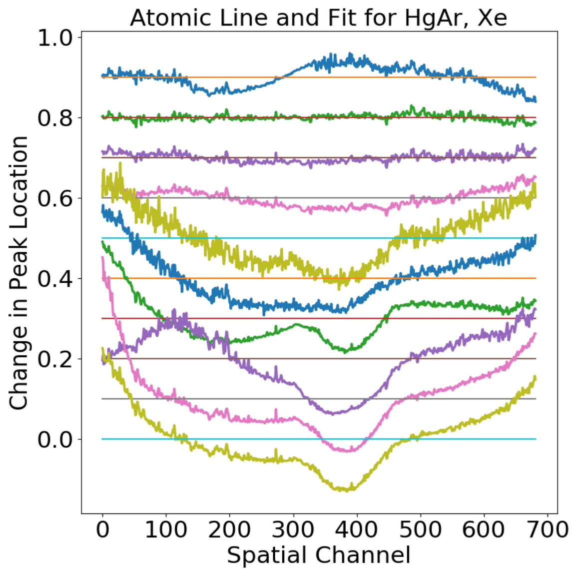

Figure 7. Data of Figure 6 after correction for slit rotation.

4. SUMMARY

SSI has demonstrated a series of measurements that provide the precision needed to accurately calibrate hyperspectral instruments with high spectral and spatial fidelity. An automated row-by-row and column-by-column fit to the line spread function provides useful estimates of the spectral and spatial resolution. Comparison of single-row fits to edge rotation methods indicate that for sigma $\geq$ 0.5 pixels, the single-row method is accurate to within 10%. In addition, these same fits provide an accurate measure for optical keystone, spectral smile and slit rotation. These single-row/column fits can be automated to provide spatially resolved spectral measurements from a few simple measurements of line lamps, and spectrally-resolved spatial measurements from a series of hyperspectral images of knife edges.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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