An imaging spectro-polarimeter for measuring hemispherical spectrally resolved down-welling sky polarization

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ABSTRACT

A full sky imaging spectro-polarimeter has been developed that measures spectrally resolved (~2.5 nm resolution) radiance and polarization (s_0, s_1, s_2 Stokes Elements) of natural sky down-welling over approximately 2π sr between 400nm and 1000nm. The sensor is based on a scanning push broom hyperspectral imager configured with a continuously rotating polarizer (sequential measurement in time polarimeter). Sensor control and processing software (based on Polaris Sensor Technologies Grave' camera control software) has a straight-forward and intuitive user interface that provides real-time updated sky down-welling spectral radiance/polarization maps and statistical analysis tools.

Keywords: Sky polarization, imaging polarimeter, hyperspectral polarimeter, Stokes vector

1. INTRODUCTION

Polarization is becoming a regular tool for remote sensing and object detection in science, industry, and military sensor systems[1]. Polarization adds extra dimensionality to environmental and scene imaging and provides information and contrast that frequently cannot be detected any other way. This extra dimensionality is difficult to model and hence advanced sensors are needed to measure polarization phenomenology. For polarization imagers operating in the visible part of the spectrum where reflection dominates the source of polarization, one source of polarized light in the environment is polarized skyshine produced by sunlight scattering off of the upper atmosphere. Only a little work has been done understanding the spectral dependence of the sky polarization[1,2] and continuous spectral measurements are needed for model development and comparison.

To address this need for understanding of the scattering processes giving rise to polarized skyshine, a hyperspectral imaging polarimeter was developed using an off-the-shelf hyperspectral imager integrated with a rotating polarizer and pan-tilt unit. The sensor, dubbed Hyperspectral Imaging Polarimeter Sensor (HIPS), was recently completed and initial measurements have been collected. In this paper, sky polarization theory will be presented followed by a description of the hardware and controlling software. Finally, some initial results will be presented along with some suggestions for future work.

2. SKY POLARIZATION – THEORY

Polarization induced by scattering from molecules within the atmosphere is well described using Rayleigh theory, a subset of Mie theory[3]; Rayleigh theory requires that these scattering agents be small compared to the incident wavelengths and that the scattered light experiences a single scattering effect prior to measurement[4,5]. This phenomenon of scattering induced polarization has been understood for many years and is the underlying mechanism in which unpolarized sunlight obtains a defined polarization signature. While the conditions prescribed by Rayleigh scattering can be limiting, Rayleigh's theory often sufficiently describes atmospheric scattering, particularly in clear skies and lightly loaded atmospheres. A full description of the polarization pattern of the sky given all atmospheric conditions, including clouds, haze, aerosols, etc., requires a multiple scattering theory: one example is radiative transfer[6,7]. However, clear sky scattering is well approximated using Rayleigh theory. A polarimeter on the surface of the Earth measures a polarization pattern across the viewable sky hemispherical dome which depends on the positions of the Sun, the polarimeter, and one or more given point(s) in the sky. In the prior literature, the predicted[8,9] and measured[10-15] polarization patterns of both clear and overcast[16,17,18] skies have been investigated.

The theory which describes single scattering of light by a small (compared to incident wavelength), nonabsorbing particle was prescribed by British physicist Lord Rayleigh in the late 19th century[19,20]. Notably, these restrictions can

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be satisfied by a scattering atmosphere due to both the small size and low density of the scatterers. This scattering occurs in the upper atmosphere, so the assumptions break down when secondary and higher order scattering occurs due to more complex conditions, such as overcast skies, patchy clouds, or haze between the upper atmosphere and the polarimeter. According to Rayleigh theory, the scattered light will be linearly polarized at varying degrees with a particular polarization orientation that depends on the geometry of the source-scatterer-sensor arrangement. The relevant polarization properties include the degree of linear polarization (DoLP) and the angle of polarization (AoP) of the scattered light as viewed by the polarimeter. To calculate these polarization components, calculation of the Stokes vector is necessary:

$$\boldsymbol{S} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \langle |E_x|^2 + |E_y|^2 \rangle \\ \langle |E_x|^2 - |E_y|^2 \rangle \\ 2Re\langle E_x E_y{}^* \rangle \\ -2Im\langle E_x E_y{}^* \rangle \end{bmatrix} \propto \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ I_L - I_R \end{bmatrix} \tag{1}$$

In Eq. 1, E_x and E_y are the component electric field amplitudes and I is the radiance collected by the sensor with varying polarization filters. The first two components of the Stokes vector (S_0 and S_1) are measured using a linear polarizer orientated at 0° and 90° (horizontal and vertical). The subscripts of I correspond to the orientation of the linear polarizer. The S_0 component is found by summing the two intensity measurements while the S_1 component is determined by subtracting the two intensity measurements and represents the preference for horizontally polarized light. Similarly, S_2 represents the preference for light polarized at 45° over light polarized at 135°. I_L and I_R refer to the radiance collected by left and right circular polarizers, so S_3 is called the degree of circular polarization. For this application, we are interested in S_0, S_1, and S_2, useful for deriving an important component used by SkyPASS as defined below:

$$\mathrm{DoLP} = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \tag{2}$$

The DoLP is a measure of the normalized magnitude of the polarization vector and ranges from 0 (unpolarized) to 1 (100% polarized) with intermediate values representing partially polarized light. Eq. 2 can also be derived based on the geometry of the source-scatterer-sensor arrangement and is useful for predicting the sky polarization properties:

$$\mathrm{DoLP} = \frac{1 - \mathrm{Cos}^2(\theta)}{1 + \mathrm{Cos}^2(\theta)} \tag{3}$$

Knowing the Sun, target, and sensor positions allows for prediction of the DoLP for any position in the sky using Eq. 3 while Eq. 2 allows for its calculation via polarimetric measurements. Typically, the Stokes vector employed is normalized meaning S_1 and S_2 range over [-1,1] and $S_0 = 1$. As expected, viewing the Sun directly, which implies no scattering, results in DoLP = 0 since $\theta = 0$ and $S_1 = S_2 = 0$. Similarly, viewing a target position where $\theta = 90°$ (i.e., $S_1 = 1$, $S_2 = 0$) results in DoLP = 1. The other important polarization component, which is particularly useful to SkyPASS, is the AoP, which is a measure of the polarization vector's orientation (from 0° to 180°). Previous investigators have demonstrated that the AoP direction is normal to the scattering plane which contains the Sun, target, and sensor. For any given time, sensor position, and target position in the sky, the AoP may be predicted based solely on the geometry of the situation. Additionally, the Stokes vector measurements can be used to determine the AoP:

$$AoP = \frac{1}{2} Tan^{-1}\left(\frac{S_2}{S_1}\right) \tag{4}$$

Employing Eq. 3 at each possible pointing direction results in a predicted DoLP pattern on the visible hemisphere that can be represented with a polar plot obtained through the stereographic projection of the hemisphere down to a 2D surface.

3. SENSOR DESCRIPTION

The HIPS system, shown in Figure 1, is a custom, full sky imaging spectro-polarimeter that measures absolute spectral radiance and polarization (s_0, s_1, s_2 Stokes Elements) of natural sky down-welling over approximately 2π sr. The sensor collects semi-continuously collects data (dawn to dusk) at user defined intervals. The sensor system (sensor head and pan tilt stage) is controlled through custom software. The sensor includes a VNIR hyperspectral imager and rotating polarizer element. HIPS has the following components:

Figure 1 HIPS performing a collection sweep at 56^0 elevation.

1. HIPS sensor including a sun shade assembly and temperature stabilization equipment
2. FLIR D300E motorized pan tilt unit
3. GPS
4. Quickset Hercules tripod
5. ASUS desktop computer, including Sunlight readable, weatherproof monitor and keyboard

The HIPS sensor collects polarimetric data through a division of time approach, which in this case relies on a continuously rotating polarizer. The polarizer position is indexed and the velocity is set so that the polarizer doesn't rotate more than 22.5 degrees in an integration time. Although the polarizer changes position throughout the integration time, the calibration of the sensor still reports accurate polarization data. Because sky polarization is only linearly polarized, circular polarization (the S_3 component of the Stokes vector) is not measured. The specifications of the HIPS sensor are given in Table 1.

Table 1. HIPS specifications.

Property	Value	Units
Waveband	380 - 1000	nm
Lens	9mm, f2.4	
Pixel Pitch	6.5	µm
Spatial resolution	2200	pixels
Spatial FOV	72	deg
Spectral line width	0.64	nm
Bit depth	16	bits
Exposure time	10 – 3,000	ms
Max Frame Rate (varies with exposure)	30	Hz
Camera Input Voltage	12	VDC
Thermoelectric Input Voltage	24	VDC
Pan Tilt Input Voltage	30	VDC
Steady State @ 23°C	300	W
Peak Power @ 23°C	400	W
Data Interface	Camera Link	
Dimensions (LxWxH)	30x7.5x19	in
Sensor Weight	40	lbs
System Weight	100	lbs

3.1 Operation

HIPS can be run in two different modes: static and kinetic. The static collection mode enables the sensor to stare at a scene and collect data in prescribed intervals. The number of polarizer rotations (frame averages) can also be varied. A kinetic collection has the same functionality as the static collection mode but also utilizes the pan tilt stage to sweep the sky, taking samples at prescribed azimuth intervals. At each azimuth collection point, the GPS time is recorded to file. The user inputs the integration time, elevation angle, azimuth start angle, azimuth step and the number of steps. A scan can be performed up to 360°, or a subset thereof. An option of one or two passes at separate elevation angles can be performed. The sensor has a FOV of 72°, therefore to get a complete hemispherical scan of the sky, a second pass must be performed.

The sensor was designed with a sun avoidance mode to allow data to be collected even when the sun is directly in the FOV, which would otherwise saturate a large portion of the focal plane array. Each time an image is taken, the software analyzes the number of saturated pixels in the scene. If the number of saturated pixels exceeds the user defined threshold, the sun centroid is calculated and a sun blocking flag is moved into position and occludes the sun. By doing so, the data adjacent to the sun is not lost, capturing more of the sky. The sun avoidance can be turned on or off in the software before a kinetic collection is started. Additionally, the user can manually control the position of the sun blocking flag.

3.2 Environmental housing

The HIPS sensor is housed in an environmentally controlled enclosure. The environmental control is provided by a combination of a thermoelectric (TE) heater/cooler and a desiccant plug. HIPS is designed to be dust tight and resistant to light moisture contact. The internal environment of the enclosure must be kept at a low humidity to eliminate the risk for condensation when the TE heater/cooler is in cooling mode. This is accomplished using a desiccator plug installed in the side panel of the enclosure. The plug should indicate that the humidity in the box is below 30%RH during operation, assuming the internal set point temperature remains at 20^{o}C.

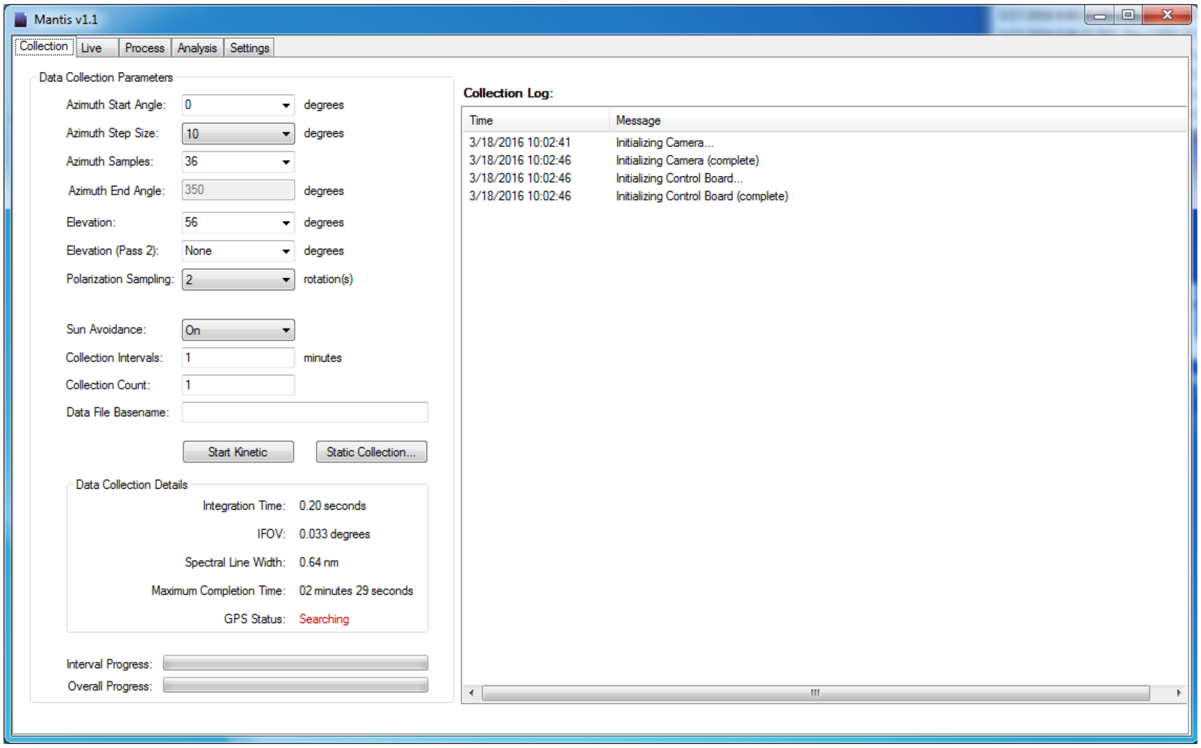

Figure 2 Collection screen.

4. USER INTERFACE

A custom user interface is provided with the HIPS sensor system with five actions that can be performed: Collection, Live, Process, Analysis, and Settings. Each of those activities are detailed below.

4.1 Collection

The “Collection” function is the default action upon launching the software. The Collection screen gives the user full control of the sensor for kinetic and static collections described above and is shown in Figure 2. Many of the parameters are self-explanatory but a few parameters bear some further explanation. The azimuth step size can be set from 2 - 45°. Polarization sampling refers to the number of polarizer rotations (1-8) averaged at each azimuth angle. Finally, the number of collections is specified by the Collection Count with an interval between each collection specified by the Interval parameter.

4.2 Live

The “Live” function allows for data to be streamed directly from the camera for live video. This mode is what is initially used to set the integration time and sight the sensor. Regions of interest can be selected for analysis on the live data display output to help in initializing the sensor. The pan tilt unit can also be set in this mode using the keyboard’s keypad. This is particularly useful to sight the system before collecting data. In this mode, the user can also manually position the sun shield and set the sensor integration time. Analysis tools described below are also available in the Live mode to aid in initial set up or for spot measurements.

4.3 Process

The “Process” function allows the user to select a Data File for hyperspectral polarimetric processing. This activity may require some time depending on the extent of the scan and the corresponding size of the data file so it is called out separately to give the user the best control over the processing.

4.4 Analysis

The “Analysis” screen gives the user the ability to analyze a processed data file in terms of spectrum and polarization. Figure 3 shows the Analysis screen displaying sample data taken at Polaris. The user selects a processed data file to analyze using the processed “Data File” drop down menu. In the upper middle portion of the screen is a polar plot.

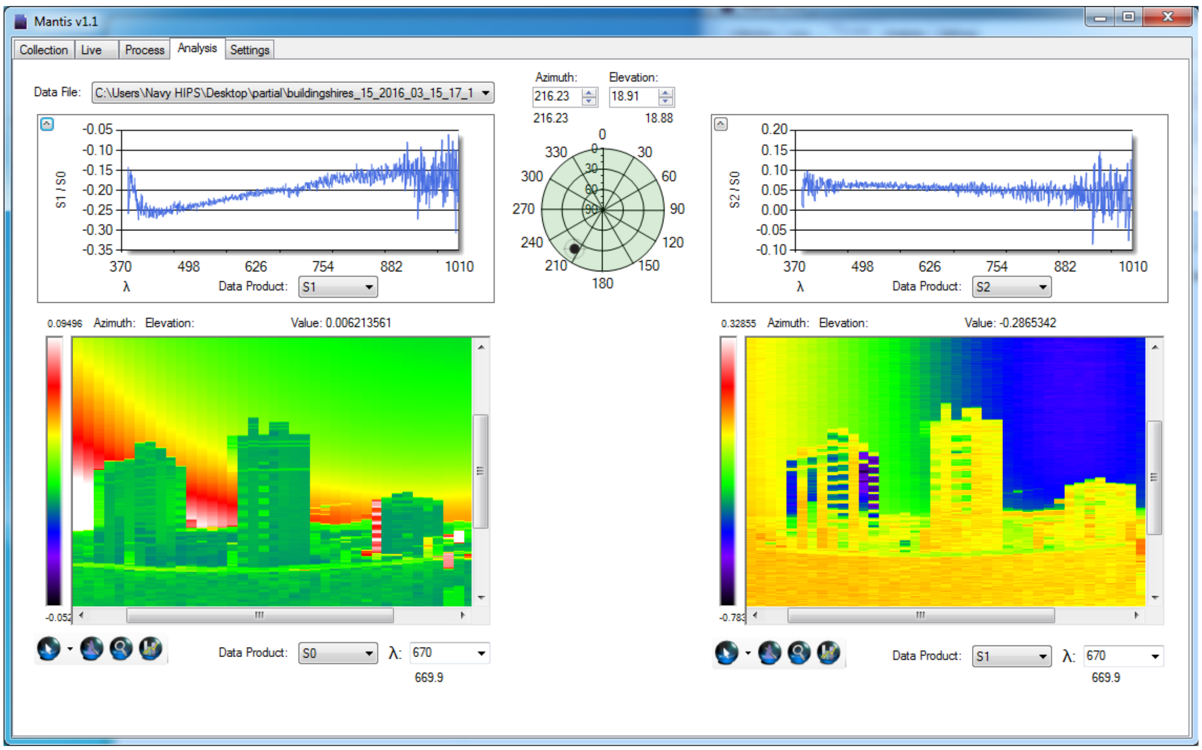

Figure 3. Analysis screen.

Around the circumference of the polar plot is the azimuth angle, while the elevation angle is along the radial lines. The user can select anywhere in the polar plot to change the data that is displayed. The user can select anywhere in the polar plot to change the data that is displayed. Note that the azimuth and elevation angles will update in the boxes above the plot. Alternatively, specific angles can be input into the Azimuth and Elevation input boxes above the polar plot.

On the top of the screen, there are two line plots that show the data product of choice at those particular azimuth and elevation angles across the spectrum from 370nm to 1010nm. Data products can be selected in the drop down menu embedded in the graph. Data product choices include: S0, normalized S1, normalized S2, DoLP and Orientation. S1 and S2 are normalized by the S0 value. The drop down menus for Wavelength and Data Product allow the user to select the wavelength for each image and to choose the data product desired: S0, S1, S2, DoLP or Orientation. The left and right each have the same functionality so that two different data products can be compared simultaneously, or the same data product at two different wavelengths. The lower left and lower right images plot the image at a user selected wavelength in terms of the data product desired. These images can be manipulated with the image tools located below each image. The image plots have the same function so that two different data products can be compared simultaneously. The image tools enable the user to change the color scales, change the dynamic range of the color scales or set to auto scaling, and to zoom in and out on different regions of the imager. Figure 4 shows the Adjust Display window with the histogram plot and scaling tools.

Further image tools enable the user to define a point, box or line as a region of interest (ROI) using the Select tool. Under the ROI Table function, the statistics related to that ROI can be analyzed. Real time statistics are available in a table format at the top of the window. Values include mean, standard deviation, maximum, minimum, sum, maximum location and minimum location. The values are given in terms of counts or location (pixel_x, pixel_y) accordingly. By highlighting the ROI of interest, then clicking the "Plot Configuration" icon under the tabular data display, a real time graph of the ROI data can be viewed. Scrolling down in the ROI window gives access to time based graphs for the mean, standard deviation, maximum, minimum, sum and a histogram of the data within the ROI. Figure 5 shows the ROI Table window.

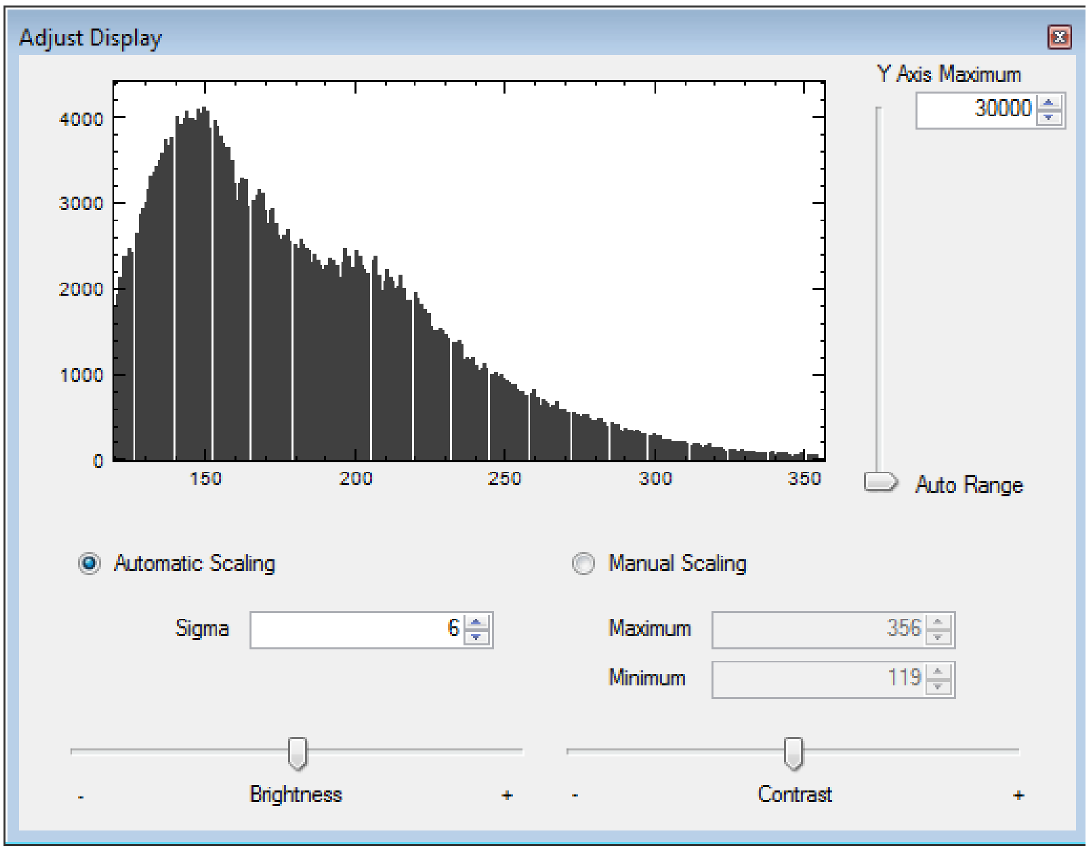

Figure 4 Adjust Display window.

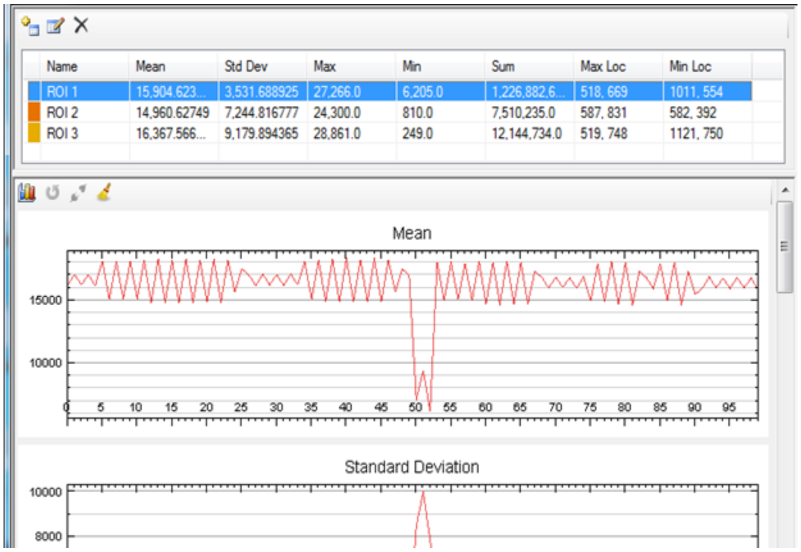

Figure 5 ROI Table window.

Figure 5 shows the analysis screen with an S0 (or radiance) spectrum in the upper left line plot, a spectrum of Degree of Linear Polarization in the upper right line plot, images of S1 and DoLP at 470 and 670 nm in the bottom left and right images and a live plot of the selected line in the S1 image at 470 nm in the middle left. Figure 6 shows the user interface and ROI window for a single data set.

5. SUMMARY

Polaris Sensor Technologies has built a Hyperspectral Imaging Polarimeter Sensor or HIPS for capturing spectral polarimetric imagery of the sky in the visible. The user interface is mature and can easily provide direct comparison of a number of different parameters in both spectral and polarization domains. The breadth of data that this sensor takes is quite large and there is a great deal of data collection and analysis that could be done with the HIPS providing significant insight into aerosol scattering and effects of clouds and aerosol loading on sky polarization.

The effort to date has been focused on developing the hardware and most data collected to date has been with clear skies and no clouds or with characterization of any particular level of aerosol loading. A great deal of work remains to collect data under a variety of sky and atmospheric conditions. After that, a significant modeling effort will allow the refinement of Rayleigh scattering theory to higher fidelity with appropriate scattering parameters.

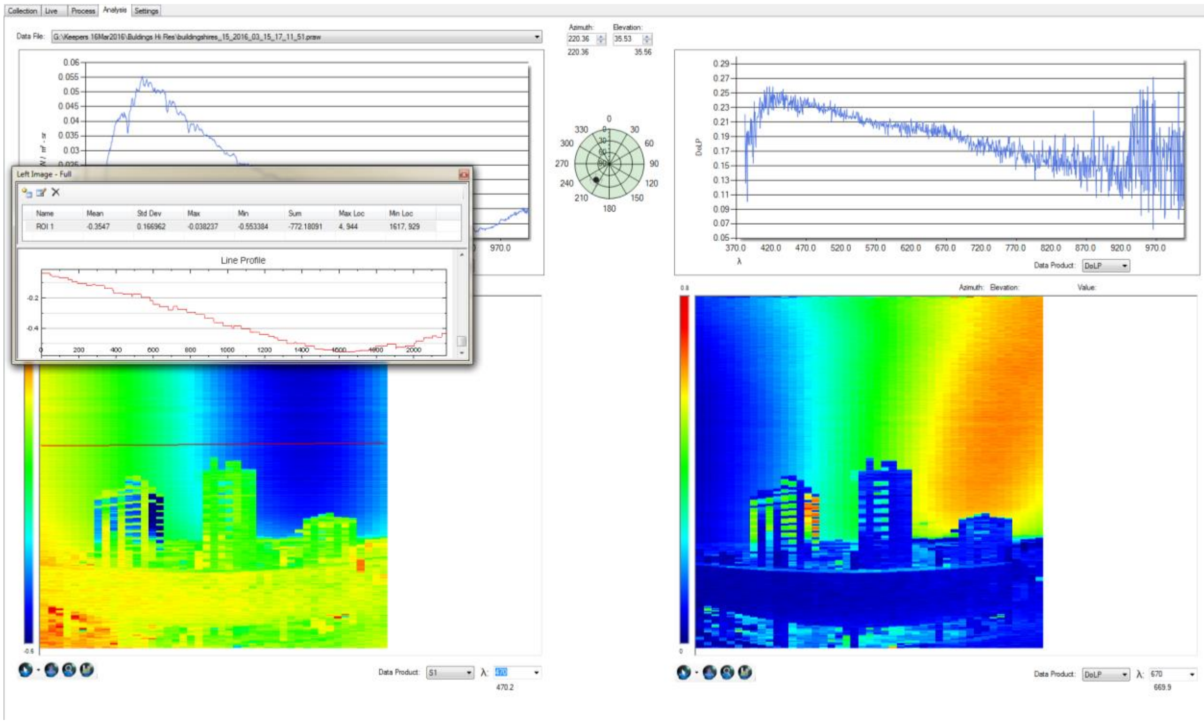

Figure 6 Analysis window showing the radiance spectrum for a point in the sky looking to the southwest (azimuth 220) at an elevation angle of 35 in the upper left line plot, the DoLP at the same point (upper right line plot), images of S1 and DoLP on the bottom, and a line profile across the image of S1.

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