Snapshot imaging spectropolarimetry in the visible and infrared

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ABSTRACT

Two imaging systems have been designed and built to function as snapshot imaging spectropolarimeters; one system made to operate in the visible part of the spectrum, the other for the long wavelength infrared, 8 to 12 microns. The devices are based on computed tomographic imaging channeled spectropolarimetry (CTICS), a unique technology that allows both the spectra and the polarization state for all of the wavelength bands in the spectra to be simultaneously recorded from every spatial position in an image with a single integration period of the imaging system. The devices contain no moving parts and require no scanning, allowing them to acquire data without the artifacts normally associated with scanning spectropolarimeters. Details of the two imaging systems will be presented.

Keywords: Infrared, long wave infrared, polarization, spectrometer, imaging, spectropolarimetry, CTIS, CTICS

1. Introduction

The data collected in a single measurement by spectropolarimeters can be viewed as points in a four-dimensional volume. The dimensions of this volume are given by two spatial dimensions (x,y), a wavelength dimension (λ), and an index dimension (j) corresponding to the index of the Stokes vector components. This four-dimensional volume is known as the spectropolarimetric hypercube, and is represented in figure 1.

The aim of imaging spectropolarimeters is to collect enough data to fill this four-dimensional space. Conventional spectrometers and polarimeters can only acquire small subsets of the data within this volume in a given measurement, as depicted in figure 1. To collect data from the entire volume, multiple measurements must be taken. Often times these multiple sets of measurements include scanning across the spatial area, taking images with multiple spectral filters, or using an analyzer and a rotating retarder depending upon the type of system you have.

The Computed Tomographic Imaging Channeled Spectropolarimeter (CTICS) system described in this paper is especially unique and interesting due to its ability to collect data filling the hypercube with just a single measurement of the system.

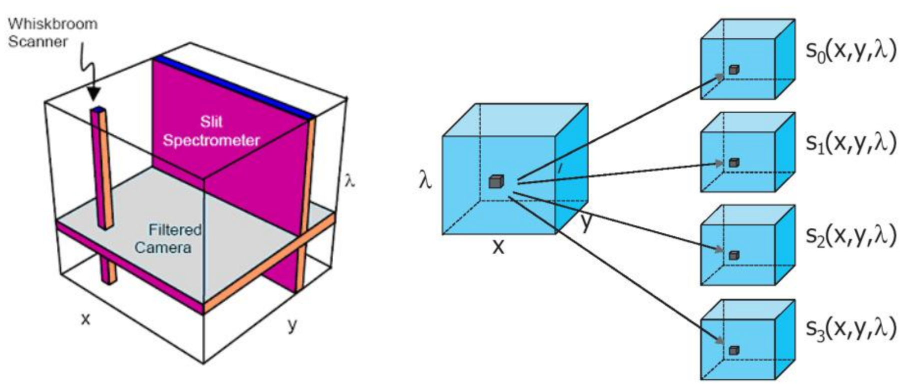

Figure 1: Illustration of data acquired by various types of spectrometers (left) in comparison to the complete set of data from the hypercube collected by a CTICS system (right).

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2. CTIS Design

The CTICS system is a combination of a Computed Tomographic Imaging Spectrometer (CTIS) with a channeled spectropolarimeter. Only three polarization elements need to be added to a CTIS system to incorporate channeled spectropolarimetery, but to understand how the CTICS works we will first review the basic design and operating principles of the Computed Tomographic Imaging Spectrometer (CTIS).

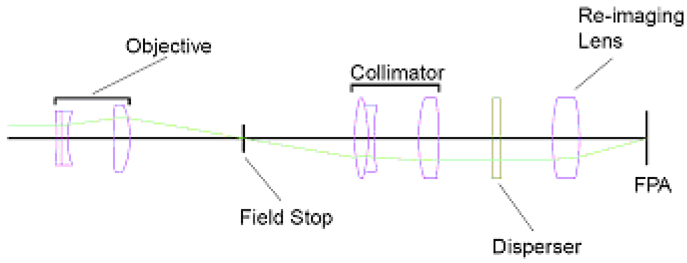

Figure 2: The CTIS Layout

The optical layout of a CTIS system consists of just three lenses, a field stop, a disperser, and a 2D focal plane array, as shown in figure 2. The objective lens forms an intermediate image of a scene onto a small square aperture. The light from this intermediate image is collimated by the collimator lens, and passed through a specially designed two-dimensional diffraction grating. The light exiting the grating is then reimaged onto the FPA.

The key element of the CTIS design is the special two-dimensional diffraction grating or disperser. This disperser is actually a computer generated hologram designed to send light into a two-dimensional grid of diffraction orders on the focal plane array as shown in figure 3. The collimated light from the zero order, which is not diffracted by the grating, forms a panchromatic image of the scene at the center of the focal plane. While the light in the other diffraction orders map the image of the various spectral components of the scene to different spatial locations on the focal plane. These monochromatic images of the scene overlap each other forming the outer diffraction orders of the recorded image.

By using the same reconstruction techniques as those used in medical tomography, we can analyze the diffraction orders recorded on the FPA, which can be interpreted as projections of the 3D object cube onto the 2D focal plane, to reconstruct an estimate of the original 3D object cube of the scene. This reconstruction of the 3D object cube (x,y,λ) allows the CTIS to determine the spectral data at each spatial position of the scene based on the single snapshot image recorded by the system..

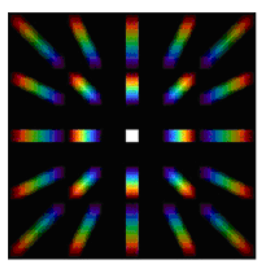

Figure 3: Example image of a broadband white light source recorded by a visible CTIS system.

3. CTICS Design

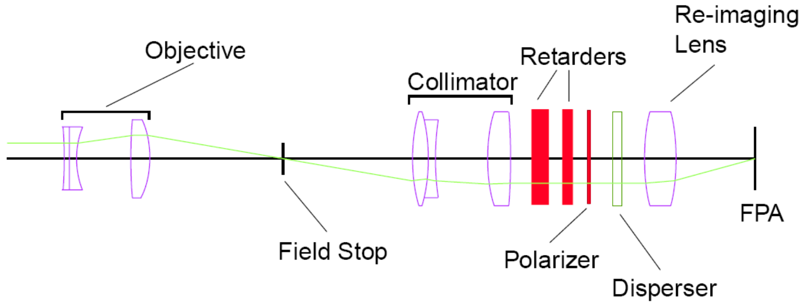

Figure 4: The CTICS Layout

As previously mentioned, the difference between the CTIS and CTICS systems is the addition of three polarization elements that must be added to a CTIS in order to encode the spectral dependence of the four Stokes components into intensity modulations of the recorded spectrum. To be explicitly clear, spectral reconstructions and polarization reconstructions will occur independently in the system. The addition of the polarization elements will cause modulations in the spectra composing each of the diffraction orders. These modulated spectra will be reconstructed using the same tomographic techniques as in a regular CTIS. These reconstructed modulated spectra from each spatial position in the image are then analyzed to reconstruct the four Stokes components across the entire spectrum for each of the spatial locations.

So what is the mechanism that allows the wavelength dependence of the stokes components to be encoded as modulations in the spectrum, and what steps are necessary to reconstruct the four Stokes component spectra from the modulated spectrum?

The mechanism that produces the modulations in the spectra can be found by carefully analyzing the added components of the system. The added components are two thick optical retarders and a polarizer. They are placed in the collimated space of the CTIS such that the first thick retarder has its fast axis oriented along the horizontal axis, the second thick retarder has its fast axis tilted 45° to the horizontal axis, and finally the analyzing linear polarizer is oriented such that its transmission axis is aligned with the horizontal axis. A figure of the optical layout of the CTICS system is shown in figure 4, and a detailed illustration of the orientation of the polarization components is shown in figure 5.

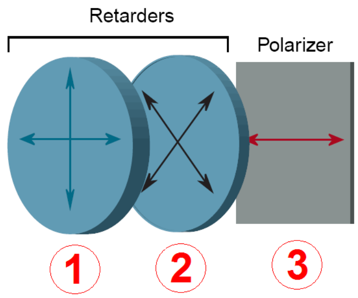

Figure 5: Figure illustrating the orientation of the two retarders and polarizer

We can use Mueller matrices and stokes vectors to analyze to analyze the electric field output of the light leaving the set of polarization elements. This is expressed in the following equation which uses an arbitrary stokes vector as an input.

$$\mathbf{s}_{\text{out}} = \underset{3}{\begin{pmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}} \underset{2}{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\delta_2) & 0 & -\sin(\delta_2) \\ 0 & 0 & 1 & 0 \\ 0 & \sin(\delta_2) & 0 & \cos(\delta_2) \end{pmatrix}} \underset{1}{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta_1) & \sin(\delta_1) \\ 0 & 0 & -\sin(\delta_1) & \cos(\delta_1) \end{pmatrix}} \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

Note that δ_1 and δ_2 correspond to the retardance of the first and second optical retarders, and that both of these quantities vary as a function of wavelength. Specifically the retardance is given by:

$$\delta = 2\pi * d * \Delta n * (1/\lambda)$$

Where d is the thickness of the material and Δn is the difference in index of the ordinary and extraordinary axes of the material at the given wavelegth λ. The quantity $1/\lambda$ is equal to the wavenumber of light and is often expressed with the symbol σ.

Multiplying the matrices reveals that the output Stokes vector is given by:

$$s_{out} = 1/2 \begin{pmatrix} s_0 + s_1\cos(\delta_2) + s_2\sin(\delta_1)\sin(\delta_2) - s_3\cos(\delta_1)\sin(\delta_2) \\ s_0 + s_1\cos(\delta_2) + s_2\sin(\delta_1)\sin(\delta_2) - s_3\cos(\delta_1)\sin(\delta_2) \\ 0 \\ 0 \end{pmatrix}$$

Since the detector itself is only sensitive to intensity and not to a particular polarization state, it only responds to the first component of the stokes vector, which corresponds to the total intensity of the light leaving the polarizer. This recorded intensity is a function of wavelength/wavenumber and is given by the equation:

$$2I(\sigma) = s_0 + s_1\cos(\delta_2) + s_2\sin(\delta_1)\sin(\delta_2) - s_3\cos(\delta_1)\sin(\delta_2)$$

This equation illustrates the mechanism of how the addition of the two retarders and polarizer allow the four stokes components, which also vary as a function of wavenumber, to be encoded as modulations in the resulting spectra in each of the diffraction orders on the focal plane array. Consider the case where you are imaging a uniform broadband whitelight source that has a fixed polarization state, $s_1 = 1$, across the entire spectrum. By examining the equation you can see that the intensity modulation across the spectrum would vary as the cosine of the retardance of the second retarder, which is linear with wavenumber. Figure 6 provides an example of what this modulation would be like in a visible spectrum in a CTICS. If the polarization properties of the object were different, the resulting modulations in the spectra would also be different, given by the previous equation.

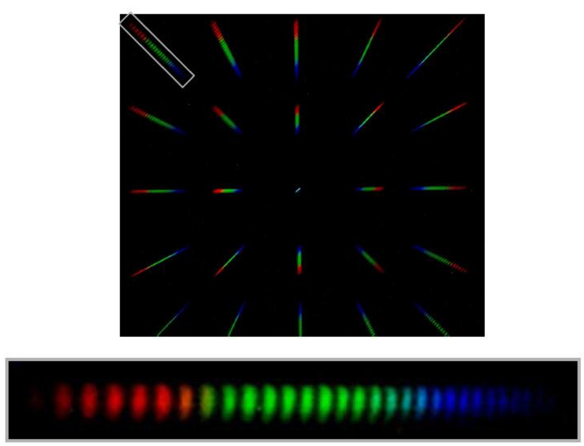

Figure 6: A visible CTICS system with the selected diffraction order enlarged below. Note that the polarization of the object causes a modulation in the diffracted spectrum

But how do we reconstruct the variation of the four Stokes components across the spectrum just from this recorded modulated spectrum? We begin by using Euler's identity to rewrite the equation describing the spectral intensity modulation function, which is rewritten below.

$$I(\sigma) = \tfrac{1}{2}s_0 + \tfrac{1}{4}s_1(e^{i\delta_2} + e^{-i\delta_2}) + \tfrac{1}{8}[(s_2 - is_3)e^{i(\delta_2+\delta_1)} + (s_2 + is_3)e^{-i(\delta_2+\delta_1)} + (-s_2 - is_3)e^{i(\delta_2-\delta_1)} + (-s_2 + is_3)e^{-i(\delta_2-\delta_1)}]$$

In this rexpressed form of the equation we see that the intensity is composed of seven different frequency components based on the retardance of the two added optical retarders: 0, $\pm\delta_2$, $\pm(\delta_2+\delta_1)$, and $\pm(\delta_2-\delta_1)$. If the same material is used for both retarders, and the second retarder is twice as thick as the first, then these seven frequency channels will be evenly spaced apart. By taking the fourier transform of the measured intensity pattern, we can easily see the seven separated frequency channels as seen in figure 7.

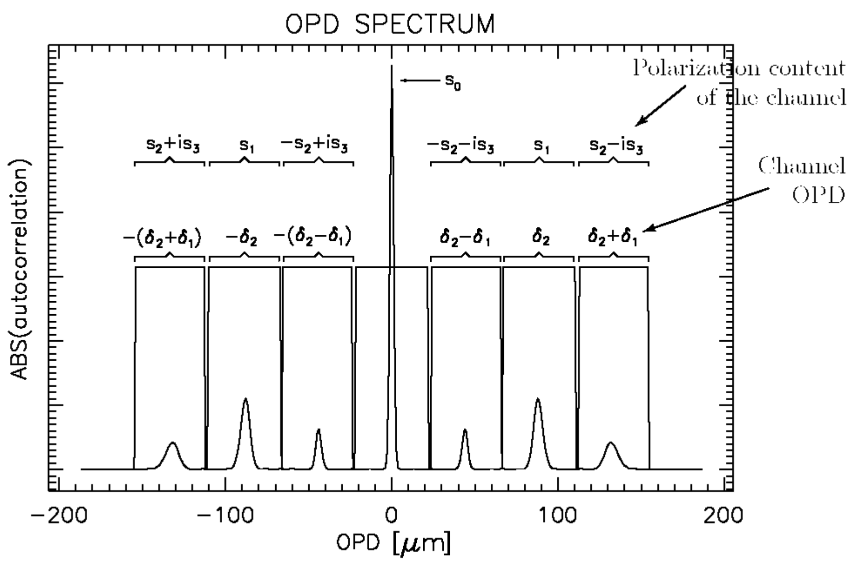

Figure 7: Plot showing the 7 frequency channels that compose the wavelength intensity function.

It is also important to note that each of these seven frequency channels correspond to a particular polarization state or a combination of polarization states. For example, the zero frequency channel is composed of just unpolarized light, s_0, while the $\pm\delta_2$ frequency channels are only composed of light that is s1 polarized. To reconstruct the polarization data across the spectrum for a given stokes component, we must first select the desired frequency channel, multiply by an appropriate windowing function to isolate the channel, and then inverse fourier transform to see how that polarization state varies in wavenumber/wavelength. To reconstruct the s_2 and s_3 stokes components you must add or subtract data from the appropriate frequency channels before applying an inverse fourier transform.

It is the fact that the different stokes components encode modulations of the spectra at different frequencies, that allows us to reconstruct the spectral dependence of the four stokes components across spectrum. By incorporating these three elements and the reconstruction technique into a CTIS system we can now acquire data from the complete hypercube with a single integration period of the imaging system.

4. Constructed Systems and Results

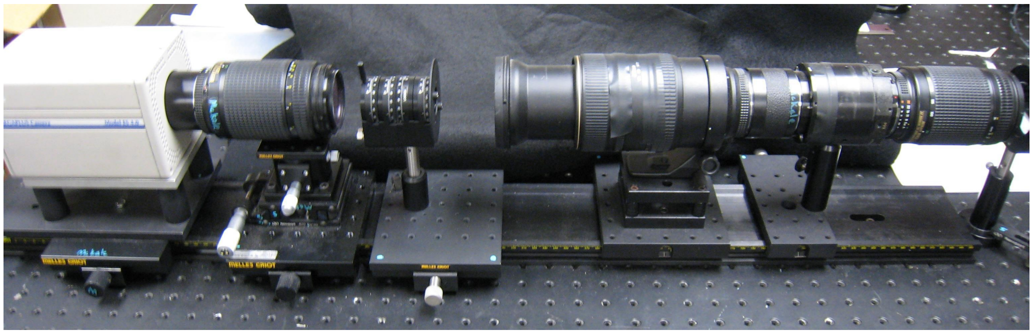

Figure 8**:** Photo of the assembled visible CTICS system

Two snapshot imaging spectropolarimeter systems based on Computed Tomographic Imaging Channeled Spectropolarimetry have been constructed; one system made to operate in the visible part of the spectrum, the other for the long wavelength infrared, 8 to 12 microns. The following pages will provide some initial results obtained from each of the two systems.

A photo of the constructed visible CTICS system is shown above in figure 8. This system was used to image a point-like broadband visible object whose output was polarized by a linear polarized. The orientation angle of linear polarizer was changed for each test, to compare the Stokes component reconstructions of the system with the known polarized output from the object. Some of the results from these tests are presented below.

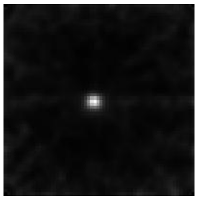

Figure 9: Zero order image of point like broadband linearly polarized source viewed by visible CTICS system.

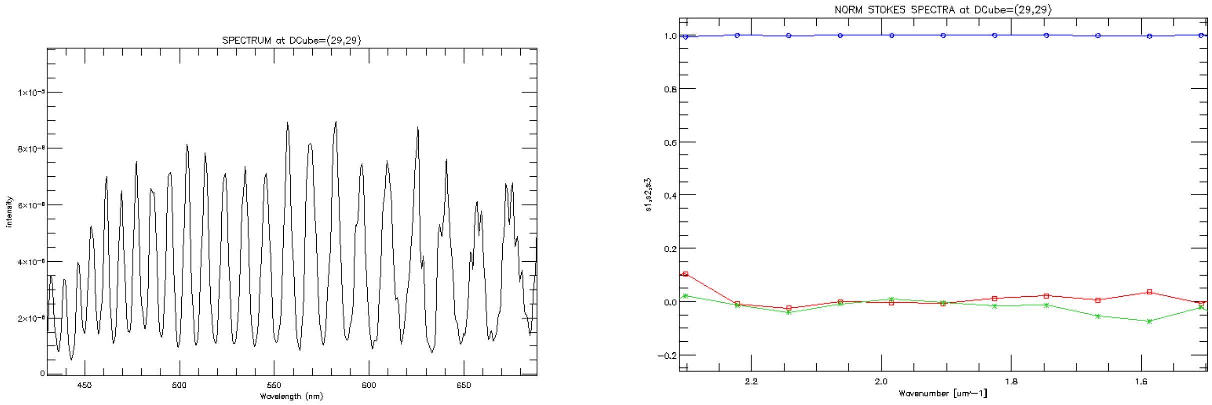

Figure 10: (left) Spectral reconstruction of object, demonstrating the modulated spectra due to polarized input into the CTICS system from the broadband white object linearly polarized at 0 degrees, (right) Stokes component reconstruction of object. Note that the s1 component is 1 across the entire spectra, as expected for a horizontally polarized source, and the s2 and s3 components are very close to zero.

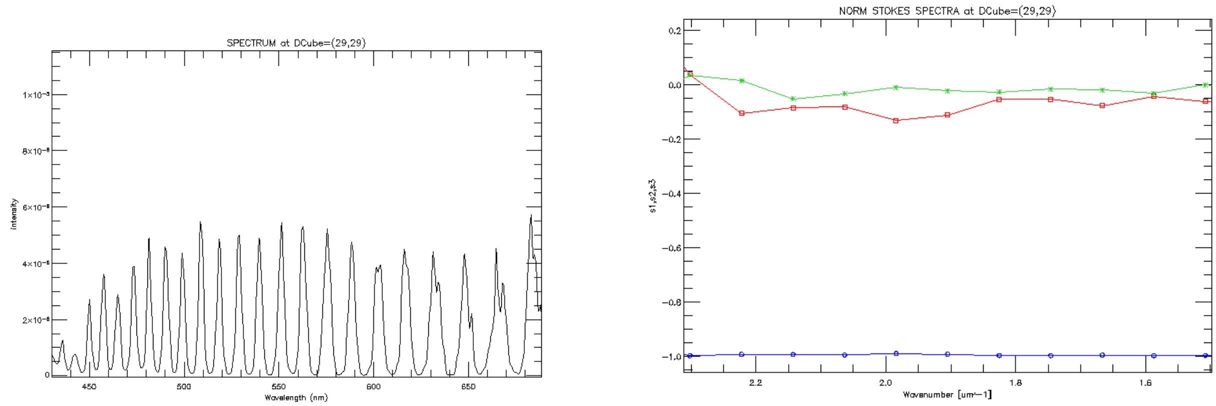

Figure 11: (left) Spectral reconstruction of object, again with modulations due to the polarized input from the broadband point object linearly polarized at 90 degrees, (right) Stokes component reconstruction of object. Note that the s1 component is -1 across the entire spectra, as expected for a vertically polarized source, and the s2 and s3 components are still close to zero.

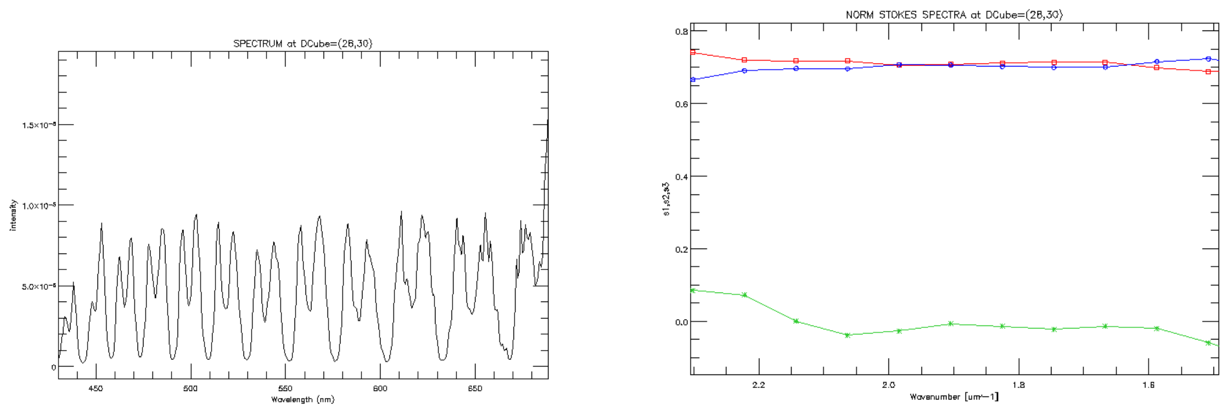

Figure 12: (left) Spectral reconstruction of broadband point object linearly polarized at 22.5 degrees, which has equal s1 and s2 components. This modulated spectrum is quite different than the previous two examples since the modulations are now due to frequencies from multiple frequency channels. (right) Normalized Stokes vector reconstruction of object. Note that the s1 and s2 values are equal for all the wavelengths across the spectrum. They both maintain a value close to 1/sqrt(2) since the stokes vector is normalized. The s3 components remains close to zero across the spectrum.

The construction of CTICS system functioning in the 8 to 12 micron LWIR region was divided into two steps. The first step was to initially construct a functioning CTIS system, and the second step was to add the necessary polarization elements to incorporate channeled spectropolarimetry into the system. Both steps are now complete. The constructed LWIR CTICS is shown in figure 13. Results of spectral reconstructions done on images taken with the system and preliminary images taken with polarization components in place are shown on the following pages.

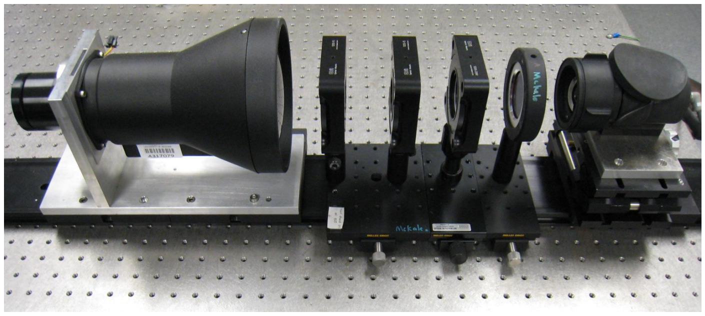

Figure 13: Photo of the assembled LWIR CTICS system

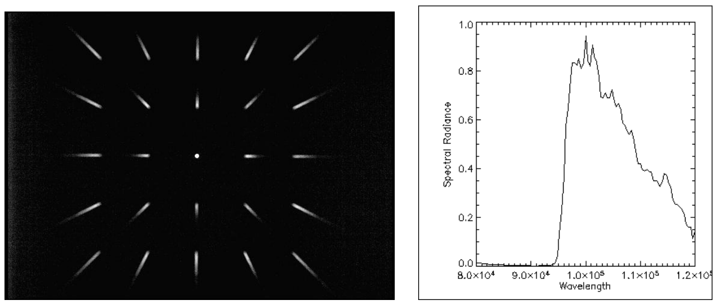

Figure 14: (left) The raw image captured by the CTIS when viewing a 1000 degree C blackbody through a 9.4 micron cut on spectral filter (right) The spectral reconstruction of the exit port of the filtered blackbody.

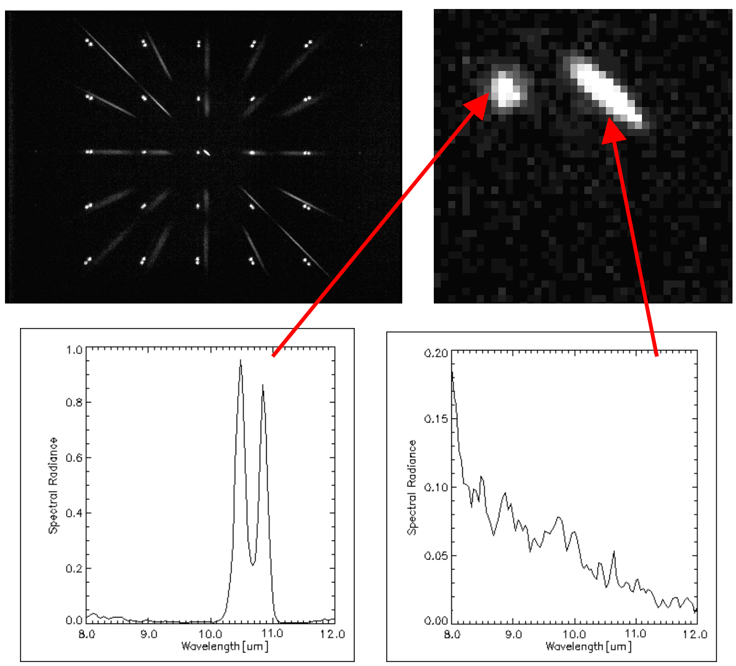

Figure 15: (top left) The raw CTIS image viewing the tip of a soldering iron and output of a CO2 laser (top right) Zero order image. (bottom left) The spectral reconstruction of light from the CO2 laser. The light output from the laser wasn't stable, and the lasing wavelength of the laser would vary in time. In this instance you can see that the laser was actually lasing in two spectral modes, which only occured for a short period of time, providing an excellent demonstration of the snapshot capability of the CTIS system. (bottom right) The blackbody like spectral output from the tip of the soldering iron.

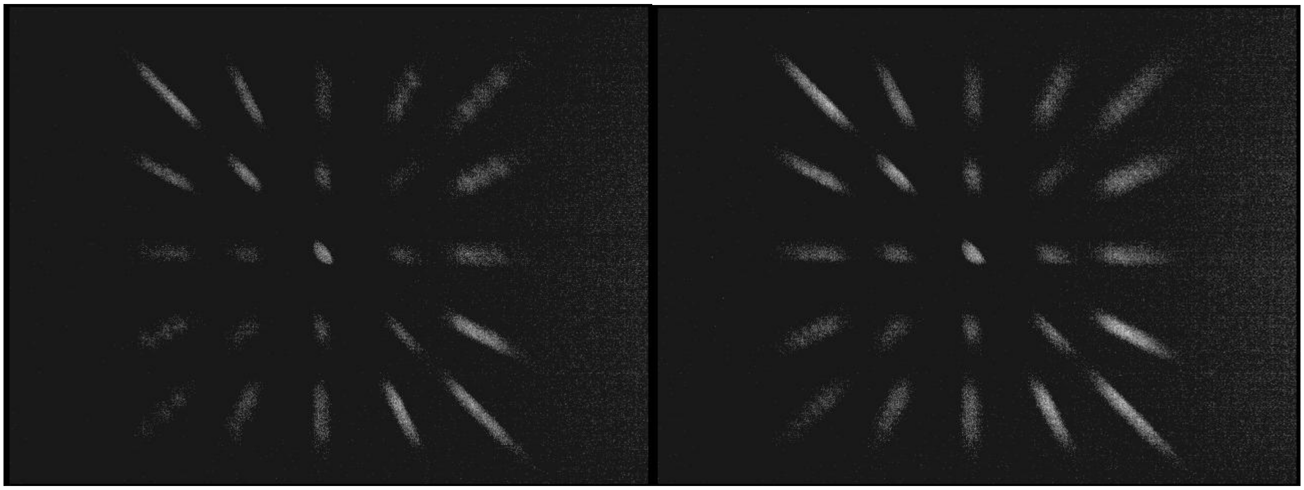

Figure 16: (left) The raw CTICS image recorded when viewing a blackbody object polarized at 45 degrees. (right) The raw CTICS image recorded when viewing the same blackbody object, but now polarized at 90 degrees. Note the different intensity modulations across the spectra in the outer diffraction orders between the two images. The difference is especially clear in the top right diffraction order in each of the images. It makes sense that the left image corresponds to 45 degree polarized light. If you refer to figure 7 you find s2 component contributions in the center-most and outer-most frequency channels, which should result in. You can clearly see the lower frequency modulation across the diffraction order, while the higher frequency modulations are probably being washed out due to the spatial extent of the source. The image on the right of the 90 degree polarized object clearly has a higher frequency modulation, which again is expected based on the mathematical analysis of the added channeled polarimetry components. The spatial extent of the source is also what causes the fringes to become washed out in the top left and bottom right diffraction orders.

5. Conclusions

Two Computed Tomographic Imaging Channeled Spectropolarimeter (CTICS) systems have been designed, built, and tested. One system operates in the visible part of the spectrum, while the other operates in the 8 to 12 micron long wave infrared region. These systems are unique in the fact that they contain no moving parts and are able to acquire full spectropolarimetric hypercube data (x, y, λ, and the four Stokes components) in a single snapshot. Prelimary results have shown that both systems work as expected based on the operation of CTIS spectrometers and the mathematical analysis of channeled spectropolarimetry presented in this paper.

References

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