

Design of an LWIR Snapshot Imaging Spectropolarimeter

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ABSTRACT

This paper covers the design and construction of a snapshot imaging spectropolarimeter for use in the long wave infrared, 8 to 12 micron region. This imaging device is unique in the fact that system is non-scanning, contains no moving parts, and in a single integration period is able to record spectral data as well as the polarization state as a function of wavelength from every spatial location in a 2D image. The system is based on the Computed Tomographic Imaging Spectrometer, commonly referred to as CTIS, and has been modified to incorporate components of Channeled Spectropolarimetry. The paper presents an overview of how both the CTIS and the CTICS (Computed Tomographic Imaging Channeled Spectropolarimeter) systems work, details on the specific components used in the LWIR system, and preliminary results from a completed LWIR CTIS system, which is the first of its kind.

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

1. Introduction

The LWIR snapshot imaging spectropolarimeter system presented in this paper is a very unique system. It incorporates some novel techniques that allow it to acquire all of its data in single integration period. Before presenting you the details and specifics of the LWIR system it is important to understand the CTIS and CTICS systems' methods of operation and how these technologies are capable of acquiring both spectral and polarization data for an image in a single snapshot.

2. Theory of Operation

The CTIS and CTICS systems are very similar. In fact the only difference between the two are the three polarization elements added in the CTICS. So the discussion on how the CTIS and CTICS systems work will begin by covering how a CTIS is able to obtain spectral data from an image. A detailed explanation will then follow on how this technique is modified in the CTICS system, which includes two retarders and a polarizer to the system, and of how the addition of these elements allows for the acquisition of polarization data in addition to spectral data from the image will be presented.

2.1 How a CTIS Works

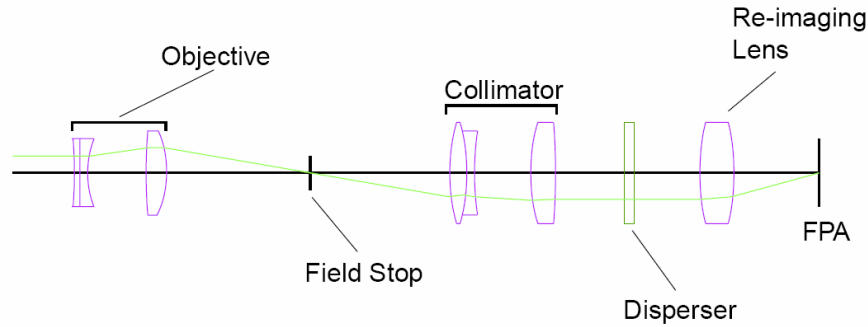


Figure 1: The CTIS Layout

The CTIS is a fairly simple optical system to analyze. It consists of just three lenses, a field stop, a disperser, and a 2D focal plane array. The objective lens forms an image of the scene being studied onto a field stop. The field stop is a small square aperture whose size, in combination with the focal length of the objective lens, determine the field of view of the system. The light from this intermediate image is then collimated, passed through a very specialized two-dimensional disperser or diffraction grating, and reimaged onto the FPA with some minification. The amount of minification is determined by the focal lengths of the collimating and reimaging lenses.

The disperser is designed to send light into a grid of diffraction orders on the focal plane array as shown in figure 2. The light corresponding to the zero diffraction order of the disperser forms a panchromatic image of the scene at the center of the focal plane array. The other diffraction orders contain images that are smeared spectrally due to the fact that the image from each wavelength in the scene is formed at a different spatial location in each diffraction order.

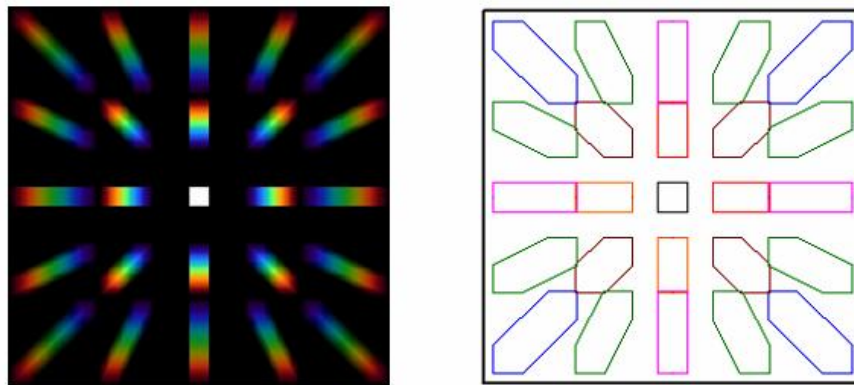


Figure 2: Example image recorded by FPA in a visible CTIS system (left). Diagram illustrating the location of the diffracted orders from the disperser on FPA (right).

The size of the zero order on the focal plane array determines the full spatial resolution of the scene image. The CTIS aims to measure the spectra at each pixel location in the scene over the specified spectral region of interest. One can think of this data as a three-dimensional cube consisting of two spatial dimensions and a third spectral dimension. So each layer of the data cube would consist of all the spatial information of the scene at a given wavelength. The amount of dispersion or spectral spread per pixel in the outer diffraction orders will determine maximum spectral resolution of the CTIS system.

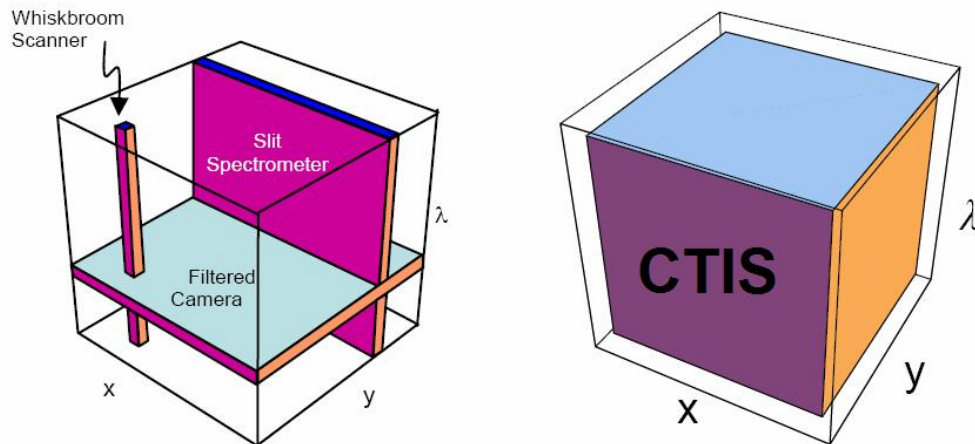


Figure 3: Illustration of data acquired by various types of spectrometers (left) in comparison to the data cube collected by a CTIS system (right).

Using this idea, it is clear that one can interpret the diffraction orders recorded on the focal plane as a collection of projections or shadows of a 3D object cube onto the 2D focal plane. This is illustrated in figure 4. By considering each of the diffraction orders as projections of the 3D object cube on the 2D focal plane we can use the same mathematical procedure of tomographic reconstruction that is used in medical CT, computed tomography, systems to reconstruct an estimate of the original higher dimension 3D object from the multiple the lower dimension 2D projection images. It is this reconstruction process that allows the CTIS to simultaneously capture spectral data at each point in the scene with a single snapshot.

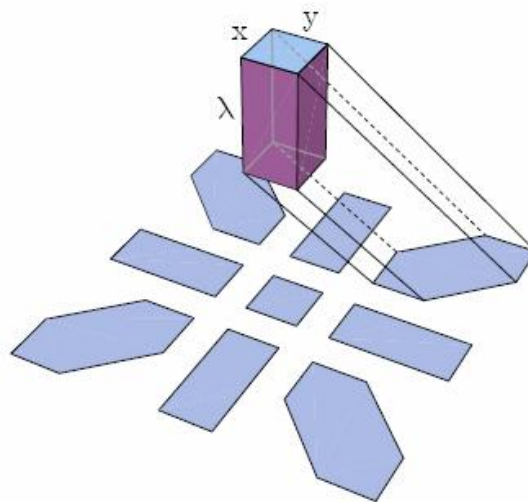


Figure 4: Illustration showing a diffraction order of the CTIS system as a projection or shadow of a three-dimensional object cube (x, y, λ).

2.2 How a CTICS Works

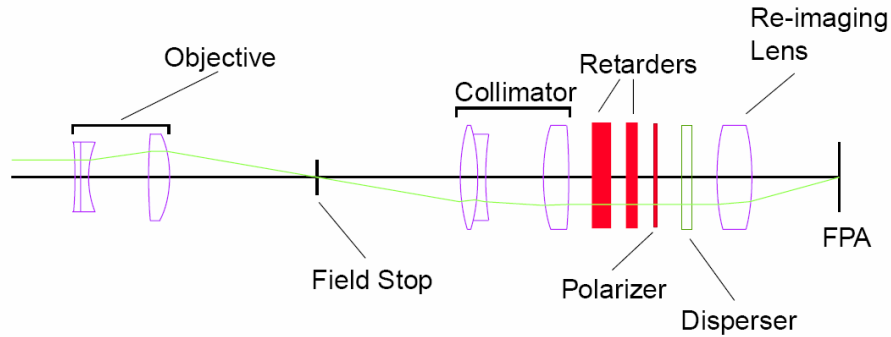


Figure 5: The CTICS Layout

The design of a CTIS system can be modified to record polarization data at each wavelength by using the technique of channeled spectropolarimetry. In this case the polarization data is encoded as an intensity modulation in the spectrum. Two optical retarders and a polarizer are added to the collimated space of the CTIS to achieve this modulation. The layout of the new Computed Tomographic Imaging Channeled Spectropolarimeter (CTICS) is presented in figure 5.

In order to understand exactly what brings about this modulation of the spectrum we must analyze the light as it passes through the system. An easy and informative way to analyze this is by using Stokes vector representation to represent the polarization state of the light and Mueller matrices for each of the optical components.

Each component of the Stokes vector is defined by differences in intensities of orthogonal polarization states of the light.

$$\mathbf{s} = \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} I_{total} \\ I_0 - I_{90} \\ I_{45} - I_{-45} \\ I_{rc} - I_{lc} \end{pmatrix}$$

These vectors are often normalized by dividing by I_{total} . This way the values of s_1 , s_2 , and s_3 are all between +1 and -1. For example, light that is completely polarized horizontal would have an s_1 component equal to 1, while light that is vertically polarized would have s_1 equal to -1.

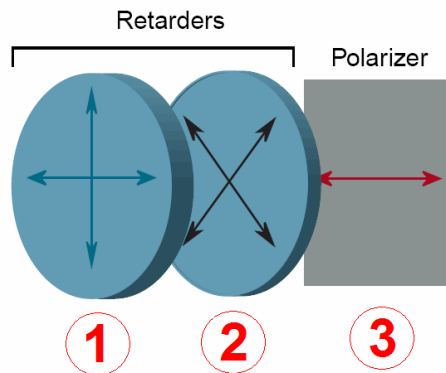


Figure 6: Figure illustrating the orientation of the two retarders and polarizer

The optical retarders added to the system are located in between the collimating lens and the disperser and must be oriented in a particular fashion. The first retarder has its fast axis oriented along the horizontal axis. The second retarder has its fast axis tilted 45° to the horizontal axis. The second retarder is also twice as thick as the first. Keeping this 1:2 ratio of the thickness of the retarders is useful for the system. Further explanation of the 1:2 thickness ratio will be presented later on. Following the second retarder is a linear polarizer whose transmission axis is oriented along the horizontal. By using an arbitrary stokes vector input, Mueller matrices, and basic matrix multiplication we can determine the electric field output of the light leaving the polarizer as presented below.

$$s_{out} = \underbrace{\begin{pmatrix} 1/2 & 1/2 & 0 & 0 \\ 1/2 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}}_{\textcircled{3}} \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\delta_2) & 0 & -\sin(\delta_2) \\ 0 & 0 & 1 & 0 \\ 0 & \sin(\delta_2) & 0 & \cos(\delta_2) \end{pmatrix}}_{\textcircled{2}} \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\delta_1) & \sin(\delta_1) \\ 0 & 0 & -\sin(\delta_1) & \cos(\delta_1) \end{pmatrix}}_{\textcircled{1}} \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

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:

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

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 wavelength 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 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 describes how the four stokes components, which can also vary as a function of wavelength, are each encoded or modulated into the recorded spectral intensity pattern on the focal plane array. This modulation will be present in each of the diffraction orders of the CTICS. Figure 7 provides an example of what the modulation of a uniform visible spectrum in a CTICS would look like if the entire spectrum has a given polarization state. For example if the light were completely s_1 polarized, the intensity would vary like the cosine of the wavenumber.

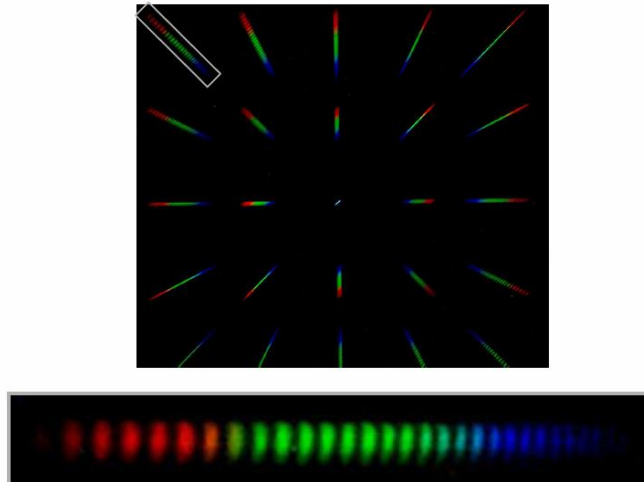


Figure 7: A visible CTICS system with the selected diffraction order enlarged below. Note that the polarization of the object causes a modulation in the diffracted spectrum

Using the Euler's identity, the equation describing the spectral intensity function can be rewritten as follows.

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

Note that in this new equation the intensity is composed of sever different frequency components: $0, \pm\sigma_2, \pm(\sigma_2 + \sigma_1)$, and $\pm(\sigma_2 - \sigma_1)$. Also note that if the retardance of the second retarder is twice that of the first, then the seven frequency channels will be evenly spaced apart. The seven frequency channels are made more clear by taking the fourier transform of the measured intensity patter, as seen in figure 8.

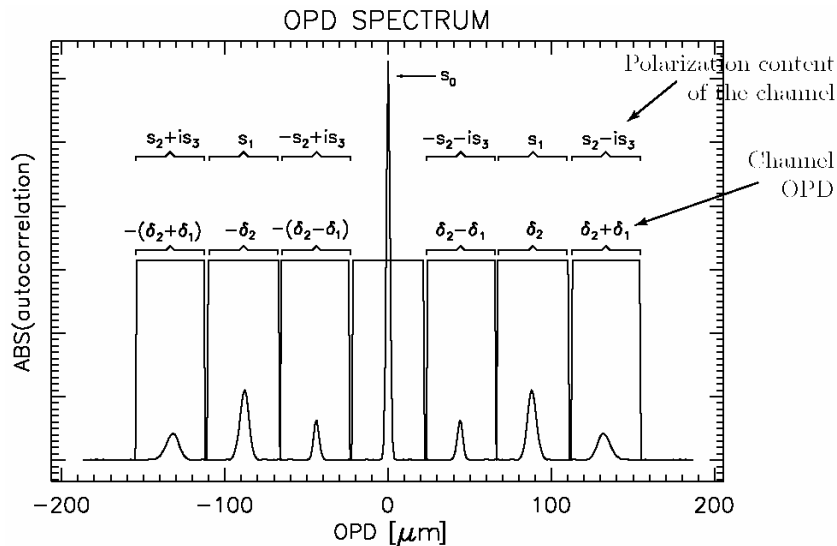


Figure 8: Plot showing the 7 frequency channels that compose the wavelength intensity function.

Also note that each of the seven channels corresponds to a particular polarization state or a combination of polarization state. For example, the zero frequency channel is composed of unpolarized light while the ± 1 frequency channels are only composed of light that is s1 polarized. To reconstruct the polarization data across the spectrum, we simply multiply by an appropriate windowing function to isolate the our desired frequency channel and then inverse fourier transform to see how that polarization state varies in wavelength. The s2 and s3 polarization state data can found by adding or subtracting the required frequency bands.

3. The LWIR CTIS

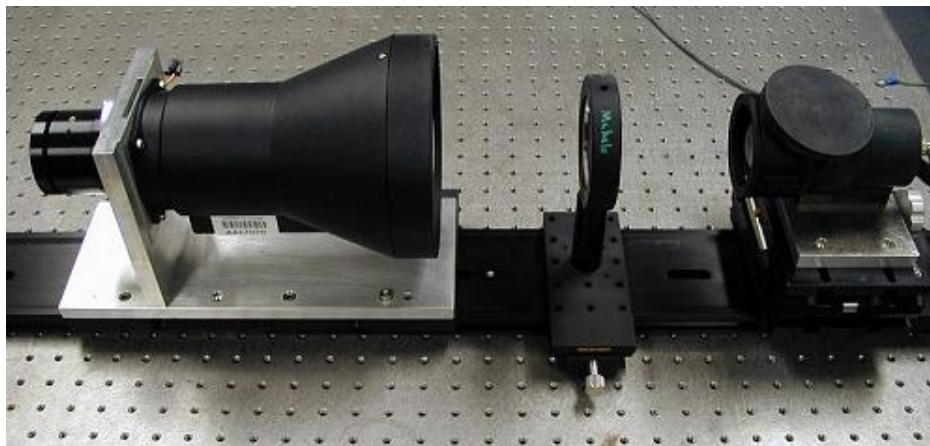


Figure 9: Photo of the assembled LWIR CTIS system

Now that the theory and operation of the CTIS and CTICS systems have been covered, the challenge of this project has been to design and construct a snapshot imaging spectropolarimeter that works in the 8 to 12 micron LWIR region. The design was approached in two steps. Step one was design, construct, and test a basic CTIS system in the LWIR. Step two is to incorporate the three necessary polarization elements into the functioning CTIS to acquire polarization data. Currently, step one is nearly complete. An LWIR CTIS has been constructed and is currently being tested.

The setup of the CTIS is the same as previously described: 3 lenses, a field stop, a focal plane array, and a specialized Computer Generated Hologram (CGH) dispersing element. The objective and collimating lenses are commercial lenses from Axsys IR systems, with focal lengths of 50mm and 150mm respectively. The two lenses are placed in a custom made mount that also houses the small 2.2mm x 2.2mm square aperture field stop at the intermediate image plane. The CGH disperser has been etched onto a 3-inch wafer of GaAs and will be described in more detail later. Finally the reimaging lens and focal plane array are found in the high resolution 640 x 480 uncooled silicon microbolometer camera system from DRS-Nytech with its 62mm focal length imaging lens.

The specifications of all of the optical components have been carefully chosen to work in conjunction with the other elements to ensure that the CTIS pattern of 25 diffraction orders fits onto the focal plane array with minimal overlap as in figure 2. The design and specifications of each element are inherently tied to the specification values of the other optical elements in the CTIS. Many elements actually serve as system constraints due to limited choice and availability from manufacturers, such as focal plane size and available focal length lenses. The goal of achieving a CTIS pattern that most effectively fills a focal plane array with minimal overlap of diffraction orders involves a balancing of all of these parameters and system constraints.

4. Preliminary Reconstruction Results

Some preliminary tests of the LWIR CTIS systems ability to generate spectral reconstructions from actual scenes have been completed. In the example presented below, the CTIS system is imaging the monochromatic output of the exit slit of a monochromator. The reconstructed spectrum from a pixel of the slit is shown in figure 12, showing that the LWIR CTIS system works.

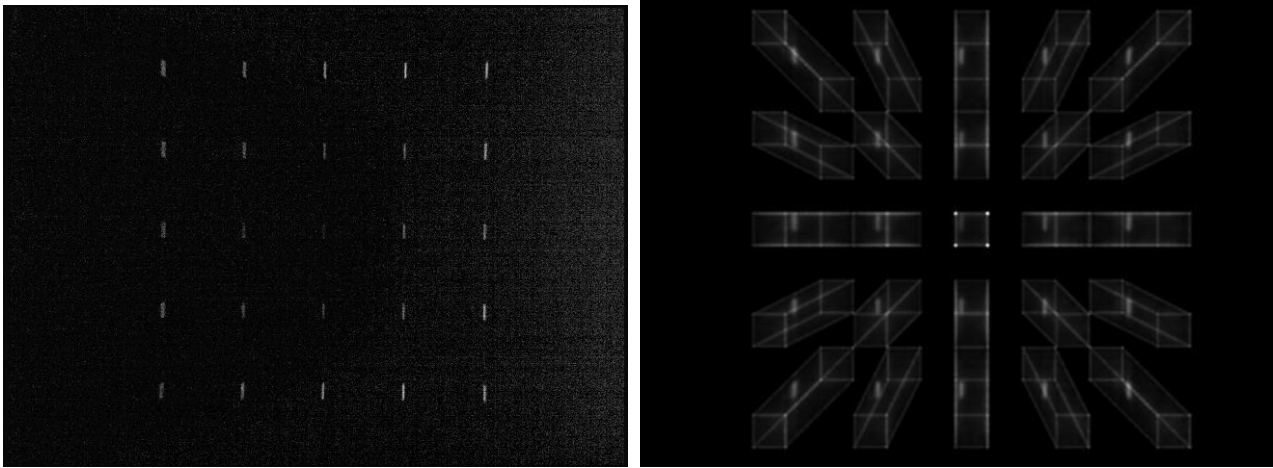


Figure 11: Image recorded from the LWIR CTIS system when the system is viewing the exit slit of a monochromator set to have spectral output at 10 microns (left). The same image loaded into the reconstruction program, illustrating where the monochromatic slit falls in the 25 diffraction orders (right).

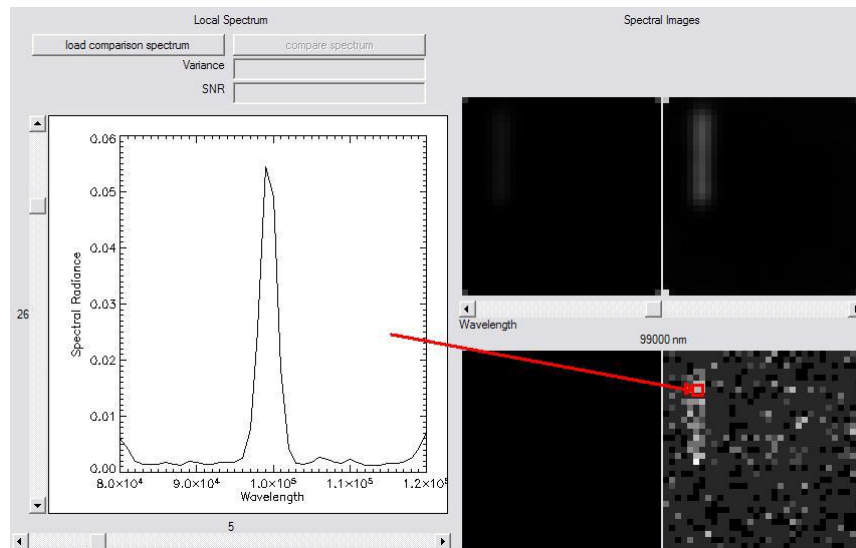


Figure 12: This image shows the spectral reconstruction of the slit at the highlighted pixel of the “zero order” image. The slit was set to have a spectral output of 10 micron.

5. Conclusions

It is clear from the preliminary example above that spectral reconstruction with the LWIR CTIS system works. The next step for the project is to add in the necessary components to simultaneously acquire both polarization and data from images. Further tests of the current system also need to be carried out to improve the calibration of the instrument and the accuracy of its reconstructions, but for the first time snapshot imaging spectrometry has been demonstrated in the 8 to 12 micron long wave infrared region.

References

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