A Snapshot Imaging Spectropolarimeter

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Abstract

A revolutionary technique for snapshot imaging spectropolarimetry has been developed because of the recent availability of large focal plane arrays and fast computers. The technique involves the combination of spectropolarimetry with computed tomography imaging spectrometry (CTIS). This spectropolarimeter uses a modulation to encode the spectral dependence of all four Stokes parameters in a single spectrum. CTIS is a snapshot imaging spectrometry method in which both spatial and spectral information is reconstructed using the inverse mathematical technique of medical computed tomography. The combination of these techniques provides the basis for a snapshot imaging complete Stokes spectropolarimeter that can be implemented with no moving parts. This technique is being applied to the SWIR wavelength region to find targets that are camouflaged.

1. Introduction

Imaging spectrometry and polarimetry are promising techniques for the detection and identification of manmade objects in natural backgrounds. Spectrometry enables detailed comparison of target and background spectra. Polarimetry allows the observer to capitalize on the fact that light emitted from and reflected by smooth surfaces tends to acquire a polarized component. Polarization information then has the potential to highlight manmade objects despite spectral camouflage. In this article we propose a novel instrument architecture which integrates both spectrometry and polarimetry functions. The instrument will be capable of characterizing the state of polarization of radiation from each pixel of a target scene by measuring all four components of the Stokes vector as a function of wavelength. All required data will be obtained in a single camera integration time.

2. Methodology

The data a spectropolarimeter acquires can be interpreted as an image of a four-dimensional volume, since a measure of radiance is obtained for four independent variables or indices: two spatial variables (x, y), wavenumber (σ or $1/\lambda$), and the Stokes vector index (j). It should be noted however that the Stokes vector index has only four possible values (the integers from 0 to 3), whereas the x, y, and σ dimensions will each be segmented into a greater number of intervals. We refer to this four-dimensional volume as the spectropolarimetric hypercube, and illustrate it in Figure 1.

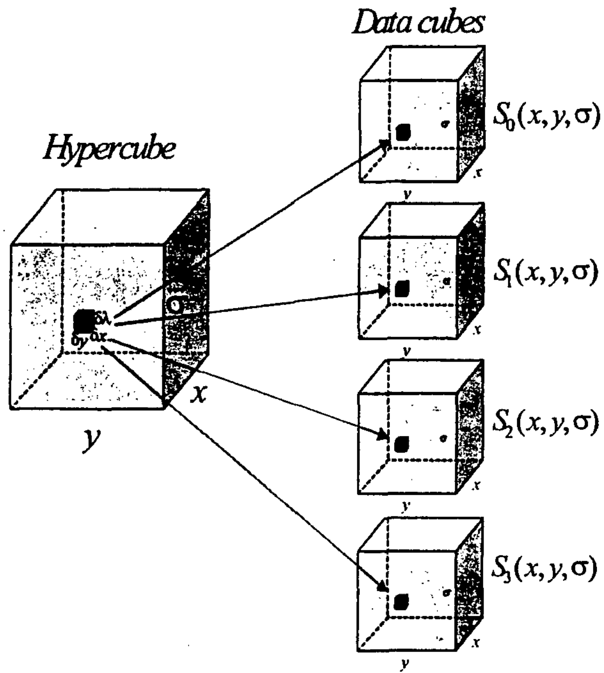

Figure 1: An illustration of the four-dimensional (x, y, σ, j) nature of the data acquired by an imaging spectropolarimeter.

2.1 Standard Techniques

Conventional spectrometers and polarimeters generally have an inability to image all four dimensions of the hypercube at once. Their sensitivity is limited to a one, two, or three-dimensional subset of the volume, and are required to scan out the remaining dimensions in some manner. For example, a camera with a narrow-band filter could be used to obtain a single x,y-slice through the hypercube. In this slice, x and y vary while σ is fixed at the wavenumber passed by the filter and j is held at zero. The entire four dimensions could be swept out by swapping in filters with different transmission wavelengths and sets of polarizers and retarders, using two independent filter wheels in front of the camera. Similar techniques can be used for other systems, such as slit spectrometers and whisk broom scanners (see Figure 2).

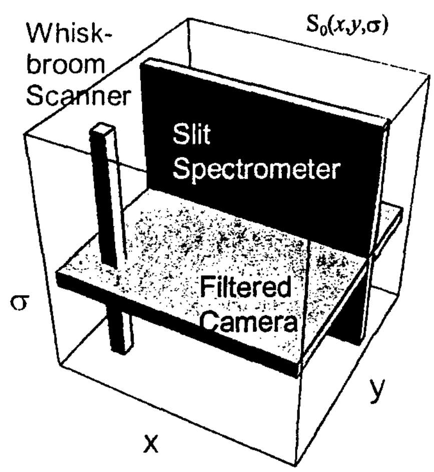

Figure 2: The lower-dimensional volumes which various spectrometer types are capable of imaging without scanning. Such spectrometers could be used with scanning to obtain spectral and spatial data on the S_0

polarization component, with additional measures (*e.g.* swapping of polarizers and retarders) necessary to obtain complete polarimetric data.

Two drawbacks of systems that require scanning are immediately apparent. First, moving parts (such as rotating filter wheels and dithering mirrors) are generally employed, and these are undesirable from the standpoint of reliability. Second, a relatively long time is required for the capture of a complete data set, since multiple exposures are made sequentially in time. Changes in the target scene during the scanning manifest themselves as artifacts in the results. Scanning systems thus have limited ability to acquire data on rapidly changing scenes, such as moving targets or targets viewed from moving platforms. A brut force method for avoiding scanning is to use several separate systems viewing the same scene in parallel, possibly with beam splitters to direct light to each. Such systems tend to be expensive, however, since multiple focal plane arrays (FPAs) and a considerable amount of optics are generally necessary. Furthermore, registration of the images from the separate systems is problematic.

The system that we propose to develop promises to circumvent these difficulties via snapshot capability. It will capture all the data necessary to reconstruct the hypercube in a single integration time with a single FPA.

2.2 Computed Tomography Imaging Spectrometry

The instrument will operate through the fusion of two techniques: channeled spectropolarimetry[1,2] and computed tomography imaging spectrometry.[3] Accordingly, it is referred to hereafter as a computed tomography imaging channeled spectropolarimeter (CTICS). The computed tomography imaging spectrometer (CTIS) is a snapshot imaging spectrometer. CTIS obtains spatial and spectral data simultaneously by imaging through a computer-generated holographic disperser and carrying out a reconstruction using the algorithms developed for medical tomography.

The basic layout of the CTIS architecture is shown in Figure 3. The objective lens forms an image of the scene under study in the field stop. This defines the instrument's field of view. The light from this image is then collimated, passed through a computer-generated holographic disperser (CGH), and imaged onto a camera's FPA. The image from each wavelength present in the scene is dispersed into a grid of diffraction orders on the focal plane array, with the separation between orders increasing with wavelength.

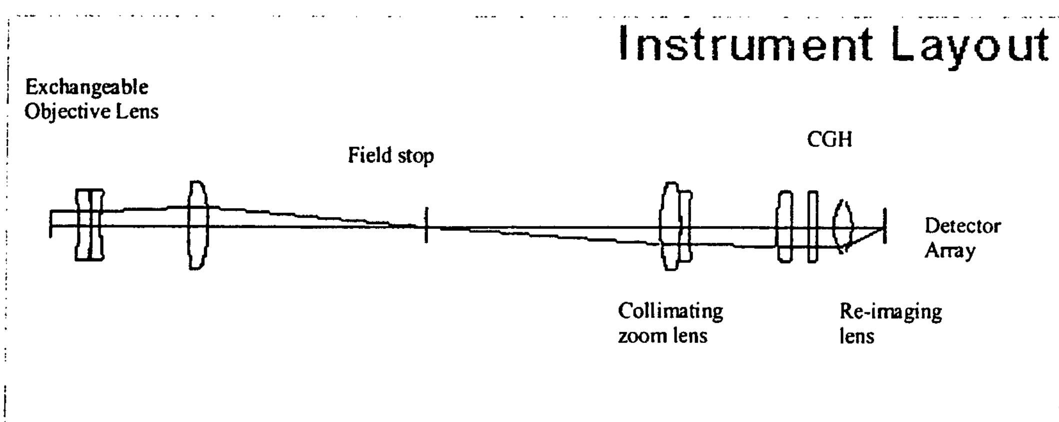

Figure 3: The CTIS Layout.

Imaging spectrometers gather data over a three-dimensional (x, y, and σ or λ) volume, sometimes referred to as the data cube. The data cube is a subset of the four-dimensional hypercube discussed earlier. The effect of the dispersion of the CGH can be viewed as generating projections from various angles through the data cube onto the FPA, as illustrated in Figure 4. An estimate of the data cube is reconstructed from these projections by computed tomography. The reconstruction is quite computationally intensive and is carried out on a high-performance computer workstation. The spatial and spectral resolution achieved is constrained in part by the number of pixels in the focal plane array. As one would expect, increasing the number of pixels allows finer sampling of the spatial and spectral content of the image and therefore better spatial and spectral resolution.

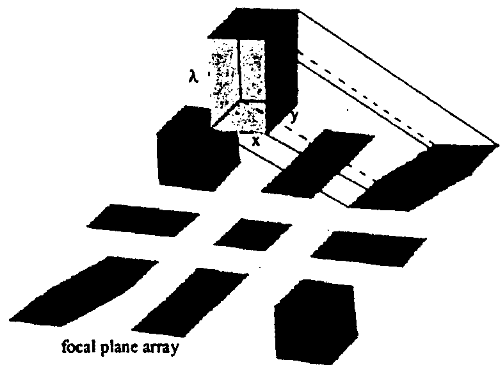

Figure 4: The dispersion of the CGH causes the separation of diffraction orders to increase with wavelength, resulting in several projections of the data cube onto the FPA.

The topic of resolution of the CTIS system can also be addressed in the Fourier domain. The central slice theorem[4] indicates that the data acquired in each projection of the data cube is sufficient to determine the values of the Fourier transform of the data cube in a section through the origin of the three dimensional Fourier domain. Figure 5 illustrates these sections. The range of angles at which projections can be taken through the data cube in the CTIS system is limited. The lines-of-sight cannot become perpendicular to the λ-axis. In the Fourier domain there is then a corresponding approximately conical volume which is not sampled. Termed the missing cone, this volume lies along the axis conjugate to λ. As a consequence of the missing cone, objects of low spatial frequency and high spectral frequency are difficult to reconstruct with CTIS. When used in conjunction with a channeled spectropolarimeter, the dimensions of the missing cones need to be taken into account to ensure sufficient spectral resolution is available for reconstruction of polarization data.

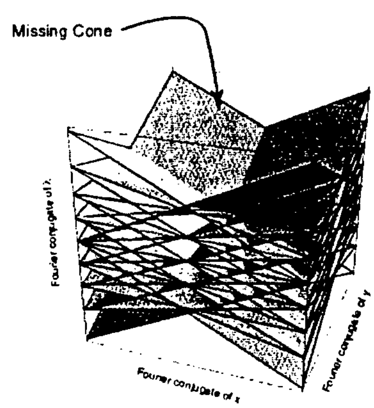

Figure 5: The missing cone is a region in the Fourier transform domain of the data cube which is not sampled.

2.3 Channeled Spectropolarimetry

If used in combination with the channeled spectropolarimetry technique, the snapshot imaging spectrometer acquires polarimetric capability. Figure 6 illustrates the basic operation of a channeled spectropolarimeter[1]. The incident radiation is described by a four-element Stokes vector spectrum $S(\sigma)$, which describes the irradiance and polarization over wavenumber. The radiation passes through two thick (high order) retarders and a polarizer, and the irradiance spectrum of the exiting light is recorded by a spectrometer. The fast axis of the first retarder is aligned with the transmission axis of the polarizer, and the second retarder is oriented with its fast axis at 45° to the polarizer's axis. The recorded spectrum is a linear superposition of the Stokes component spectra of the incident light, in which the coefficients are sinusoidal terms depending on the retardances of the retarders. Since each retardance is nominally proportional to wave number σ, the Stokes component spectra are modulated. With proper choice of modulation frequencies (*i.e.* proper choice of retarder thicknesses and materials) the Stokes component spectra can be separated in the Fourier domain. This technique is analogous to sideband modulation in radio communications.

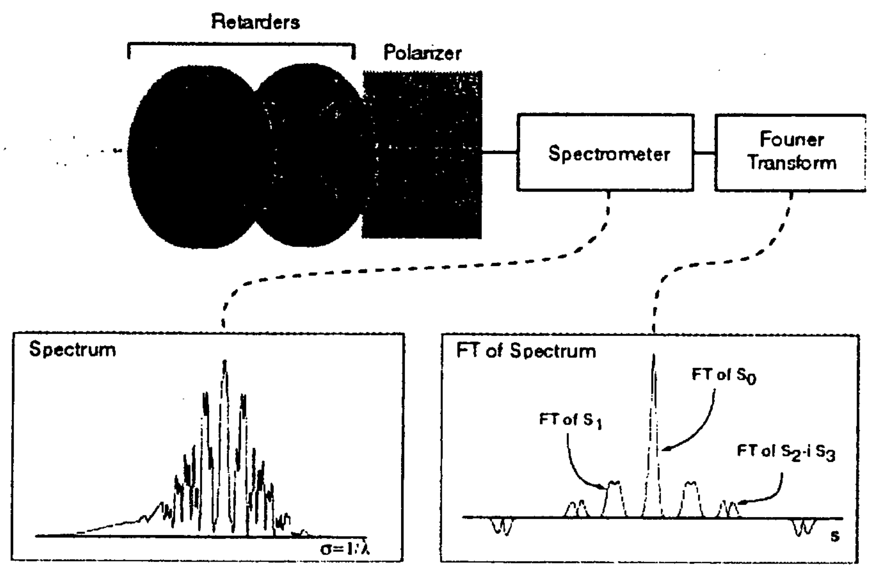

Figure 6: The channeled spectropolarimeter. The complicated spectrum recorded at the output of the polarization optics is formed by a superposition of the Stokes component spectra after modulation. With proper choice of modulation frequencies, the Stokes components can be isolated in the Fourier domain.

By multiplying out the Mueller matrices representing the retarders and polarizer, it is possible to express the modulation of the Stokes components as

$$E(\sigma) = \sum_{j=0}^{3} \sum_{k} a_{jk} e^{i2\pi h_{jk}\sigma} S'_k(\sigma). \tag{1}$$

Here $E(\sigma)$ represents the irradiance spectrum at the spectrometer, and following Ref. 1 a simple transformation of the Stokes components has been carried out as in Eq. 2.

$$\begin{aligned} S'_0(\sigma) &= S_0(\sigma) \\ S'_1(\sigma) &= S_1(\sigma) \\ S'_2(\sigma) &= S_2(\sigma) - iS_3(\sigma) \\ S'_3(\sigma) &= S_2(\sigma) + iS_3(\sigma) = [S'_2(\sigma)]^* \end{aligned} \tag{2}$$

Table 1 enumerates the amplitude a_{jk} and modulation frequency h_{jk} for each term. The frequencies are determined by the difference in optical path length (OPD) experienced by rays polarized along the slow axis of each retarder relative to that of the fast axis. d_1 and d_2 represent the thicknesses of the front and rear retarders respectively, and Δn_1 and Δn_2 are the corresponding index differences for the retarder materials used. The effects of dispersion will be discussed later. It should be noted that the modulation frequencies have units of length in this context.

Table 1: The frequencies and amplitudes of modulation in a channeled spectropolarimeter.

Polarization component	Modulation frequency h	Amplitude a
S_0'	0	$\frac{1}{2}$
S_1'	$-d_2\,\Delta n_2$	$\frac{1}{4}$
S_1'	$d_2\,\Delta n_2$	$\frac{1}{4}$
S_2'	$d_1\,\Delta n_1 - d_2\,\Delta n_2$	$\frac{1}{8}$
S_2'	$d_1\,\Delta n_1 + d_2\,\Delta n_2$	$-\frac{1}{8}$
S_3'	$-d_1\,\Delta n_1 - d_2\,\Delta n_2$	$-\frac{1}{8}$
S_3'	$-d_1\,\Delta n_1 + d_2\,\Delta n_2$	$\frac{1}{8}$

The modulation frequencies are controlled by the choice of retarder thicknesses and materials. If $d_1\,\Delta n_1$ is chosen to be three times as great as $d_2\,\Delta n_2$, the modulation frequencies are arranged at equally spaced intervals as illustrated in Figure 6. Let s denote the frequency variable that is conjugate to wavenumber σ under the Fourier transform. If a 3:1 ratio of retarder thicknesses is chosen, an s-bandwidth of $d_2\,\Delta n_2$ is available to each S_j's polarization component. The spectrum registered by the spectrometer will have a bandwidth of $9\,d_2\,\Delta n_2$ with this s-bandwidth allotted to each channel. Thus the specification of the retarders is dictated by the system requirements for the resolution of each spectral stokes component, and the resulting total s-bandwidth determines the spectral resolution required of the spectrometer.

Dispersion in the retarder materials may cause the modulation terms of Eq. 1 to cease to be strictly sinusoidal. As a result the basic reconstruction technique of masking each component in the Fourier domain, shifting it to zero frequency, and inverse Fourier transform may be insufficient to retrieve the spectral Stokes vector. Other techniques of reconstruction are under investigation. As an example, consider the requirements of a system for the near infrared spectrum, spanning a σ-band of .48-.83 μm^{-1}, with 10 samples for each Stokes component across the spectrum. The Nyquist condition indicates that an s-bandwidth of $d_2\,\Delta n_2 \sim 31$ μm is nominal. The effects of dispersion can be quantified in terms of the variation in local modulation frequency, calculated as

$$h_{local} = \tfrac{d}{d\sigma}(d\,\Delta n\,\sigma) \qquad (3)$$

As shown in Figure 7, dispersion in a sapphire retarder designed for 31 μm nominal OPD would have a variation of about 0.2 μm or 0.6% in modulation frequency across the near infrared spectrum. Figure 7 also shows the improved performance that can be achieved through the use of several materials to achromatize the retarder. The total thickness of such combinations tends to be somewhat cumbersome, however. Dispersion data for these curves were taken from Ref. 5.

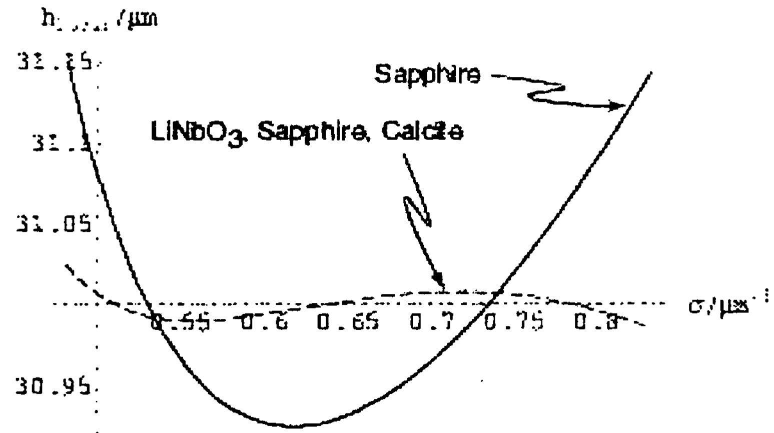

Figure 7: Dispersion in the modulation frequencies of retarders designed for a nominal value of 22 μm using several different combinations of materials.

The concept of channeled spectropolarimetry can be implemented and tested through the use of non-imaging spectrometers, as illustrated in Figure 8.

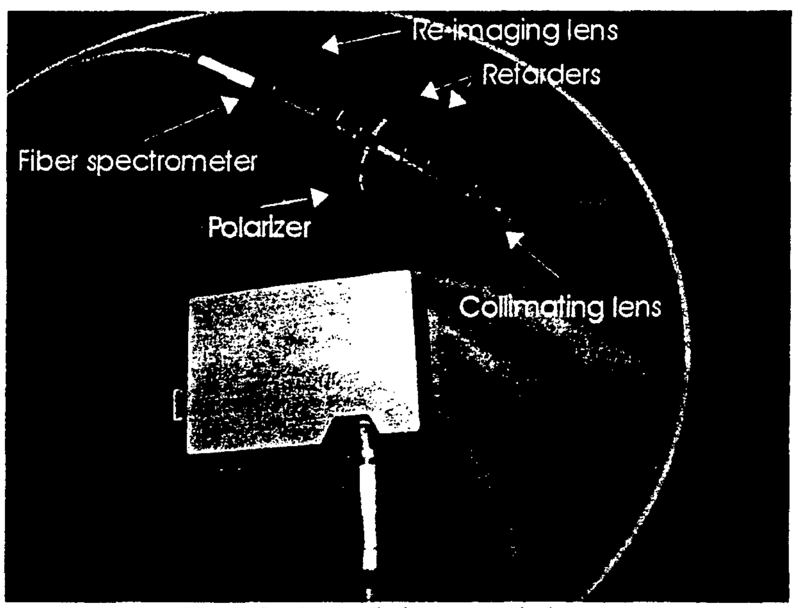

Figure 8: Channeled spectropolarimeter

2.4 Fusion of techniques

The complete CTICS system is obtained through the combination of the channeled spectropolarimeter and CTIS systems, as illustrated in Figure 9. The polarization components are placed in collimated space with the disperser. Angular dependence in retardances may require pixel-by-pixel calibration of the system's polarization properties.

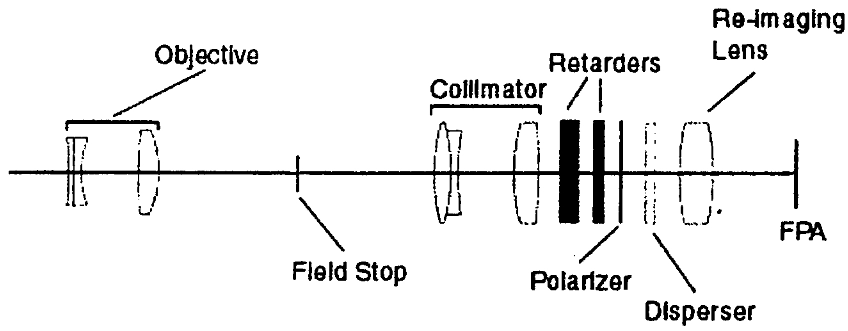

Figure 9: Optical layout of the CTICS.

3. Conclusion

With the addition of a few polarization elements to the CTIS architecture, the spectral dependence of all four Stokes vector components is encoded in the measured spectrum. This synthesis of computed tomography imaging spectrometry and channeled spectropolarimetry holds great promise for a new imaging spectropolarimeter, CTICS. With a single focal plane array and snapshot capability, CTICS offers a novel solution to the limitations of conventional spectrometers and polarimeters. It is particularly well suited to the demands of rapidly changing scenes, as encountered in the identification and tracking of moving targets. Design and prototyping efforts for CTICS systems for the visible and near-infrared spectral bands are currently underway.

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