

- Two imaging-polarimeter types
  - Light Characteristic Measuring
    - measure Stokes parameters
  - Sample Measuring
    - measure Mueller matrix that describes effect of sample on incident polarization state given by Stokes parameters
- Three types of Stokes-parameter measuring polarimeters:
  - Time Sequential
    - instrument configuration changes between measurements
    - analogy: filter-wheel camera in spectral imaging
  - Amplitude Division
    - beamsplitter (Wollaston)
  - Aperture (wavefront) Division
    - segmented pupil



# **Imaging Polarimeter**



- Objective: Retrieve parameters that describe the state of polarization in every instantaneous field of view (IFOV) of an imaging sensor.
  - Polarization parameters: complete or incomplete description of polarization via, for example, Stokes parameters
  - Imaging sensor can be staring (FPA) or scanning





# **Linear Polarizer Applications**

- Sunglasses
  - car hood reflection
  - fishing trip glare off the water
  - sky
- Car windows, airplane windows (rotated pair to control light)
- LCD displays
- Photoelasticity

**Beatle Demo** 



# Wire Grid Polarizer

- Transmits radiation polarized *orthogonal* to the wires,
- Radiation polarized parallel to wires is reflected;
  - some is lost to heating of wires
- Wire-grid polarizers are suitable for infrared applications
- Typical extinction ratios
  - 40-100



**Source:** P.K. Chen & C.D. Bass, "Efficient wire-grid duplexer polarizer for CO<sub>2</sub> laser," *App. Phys. Lett.*, 18, No. 12, pp. 565-567 (1971).

The incident electric field causes a harmonic oscillation of electrons in the wires. Energy is lost due to heating of wires.



## **Reflection by Wire-Grid Polarizer**



- A wire-grid polarizer reflects linearly polarized light
- Scene viewed through a second polarizer (analyzer)
- Signal minimum at 45°, maximum at 135°



Analyzer transmission axis 0°







135°

Extended-area BB

**Experimental setup**: wire-grid polarizer in front of a **LN2-cooled** piece of foam.

Extended area blackbody in the background at room temperature.

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**Imagine Polarimetry** 

Polarizer
Analyzer



### Polarizer Characterization Set-up



- Wire-grid polarizers tested with a linearly polarized HeNe laser at 3.39 μm
- Visible HeNe used for alignment



**Return** 



## **Stokes Vectors**



**Wavelength Dependent:**  $\vec{S}(\lambda)$ 

- S<sub>0</sub> Total exitance of source
- S<sub>1</sub> preference of horizontal linear polarization over vertical linear polarization
- S<sub>2</sub> preference of +45° polarization over -45° polarization
- S<sub>3</sub> preference of right-circular polarization over leftcircular polarization.





## **Stokes Parameters**

### E-fields (orthogonal)

$$\mathbf{E}_{x}(t) = \hat{\mathbf{x}} \quad E_{ox}(t) \cos\left[\left(\omega t - k \quad z\right) + \boldsymbol{\psi}\right]$$
$$\mathbf{E}_{y}(t) = \hat{\mathbf{y}} \quad E_{oy}(t) \cos\left[\left(\omega t - k \quad z\right)\right]$$

#### In words:

- S<sub>0</sub>: irradiance
- S<sub>1</sub>: horizontal preference
- $S_2$ : +45° preference
- S<sub>3</sub>: right-circular preference

Stokes Vectors  $S_{0} = \left\langle E_{ox}^{2} \right\rangle + \left\langle E_{oy}^{2} \right\rangle$   $S_{1} = \left\langle E_{ox}^{2} \right\rangle - \left\langle E_{oy}^{2} \right\rangle$ 

 $S_{2} = \left\langle 2E_{ox}E_{oy}\cos\psi\right\rangle$  $S_{3} = \left\langle 2E_{ox}E_{oy}\sin\psi\right\rangle$ 

Normalizing  $S_1$ ,  $S_2$ ,  $S_3$  to  $S_0^*$ 

$$S_0 \ge \sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2}$$

\* If light is completely polarized then the equality holds, otherwise the inequality holds. Example: unpolarized light is (1,0,0,0).





### Stokes Parameters for Various Ideal Polarization States



STATE OF	STOKES		
POLARIZATION	PARAMETER*		
Unpolarized Light	1, 0, 0, 0		
Horizontal (y-axis)	1, 1, 0, 0		
Vertical (x-axis)	1, -1, 0, 0		
+45, Linear	1, 0, 1, 0		
-45, Linear	1, 0, -1, 0		
Right Circular	1, 0, 0, 1		
Left Circular	1, 0, 0, -1		

\*Forms a column vector





# Poincaré Sphere



Any state of pure polarization can be represented on a 3dimensional surface (unitsphere) where the three axes are the  $S_1$ ,  $S_2$  and  $S_3$ parameters. Pure/ideal polarization at the surface.

$$\theta = ellipse$$
 azimuth

$$\tan |\varepsilon| = ellipticity = \frac{b}{a}$$

Right circular if  $2\varepsilon$  positive Left circular if  $2\varepsilon$  negative





Linear polarization along the equator

Azzam & Bashara 10





## Poincaré-sphere interpretation

Example: incident horizontally polarized light +  $45^{\circ}$  linear +  $\lambda/4$  retarder :

Poincaré Sphere - Move along equator twice the difference between the incident polarization azimuth angle and the 45° linear principal eigenvector (20).

The retardance is found by locating the orientation of the fast axis of the retarder (vertical = -S1). The polarization location on the sphere is then rotated clockwise by the retardance amount about a line defined by the sphere center and the fast axis of the retarder. In this case up to the northpole to right circular polarization.



 $S_1$ 





# Form-birefringent Retarders



- SEM micrograph of 1000-nm pitch grating
- Retarder for 4.2-5 micron range
- Form-birefringent retarder fabricated in GaAs
- Can be made achromatic over limited wavelengths
- 132° retardance @ 3.39 μm



SEM Micrograph courtesy of S. Kemme, SNL





- Birefringent material with two indices of refraction: ordinary and extraordinary indices, n<sub>o</sub> and n<sub>e</sub>,
- Dispersion formulae good over 0.2-5.5 μm range
- Sellmeier dispersion formulae:

 $n_{o}^{2} - 1 = \frac{1.4313493\lambda^{2}}{\lambda^{2} - (0.0726631)^{2}} + \frac{0.65054713\lambda^{2}}{\lambda^{2} - (0.1193242)^{2}} + \frac{5.3414021\lambda^{2}}{\lambda^{2} - (18.028251)^{2}}$ 

• At 3.39 μm, Δ*n* = 0.007

$n_{e}^{2} - 1 = -$	$1.5039759\lambda^2$	$0.55069141\lambda^2$	$6.5927379\lambda^2$
	$\lambda^2 - (0.0740288)^2$	$\frac{1}{\lambda^2 - (0.1216529)^2}$	$\lambda^2 - (20.072248)^2$

**Source:** W.J. Tropf, *et al.*, "Properties of Crystals and Glasses," in *Handbook of Optics*, Ch. 33 (1996).





# Sapphire Window Example

- 3 mm thick
- 3.39 µm wavelength
- $\delta = 0.63$  waves of retardance

$$\delta = \frac{2\pi (n_e - n_o)}{\lambda_0} t$$



### Birefringence of Magnesium Fluoride (MgF<sub>2</sub>)



- Birefringent material with two indices of refraction: ordinary and extraordinary indices
- Sellmeier Dispersion Formula ( $\lambda$  in  $\mu$ m):
- Good over 0.2-5.5  $\mu$ m range

$n^2$ 1 –	$0.48755108\lambda^2$	$0.39875031\lambda^2$	$2.3120353\lambda^2$
$n_{o} - 1 - \frac{1}{\lambda^{2} - (0.04)}$	$\lambda^2 - (0.04338408)^2$	$\lambda^2 - (0.09461442)^2$	$\lambda^2 - (23.793604)^2$

$$n_e^2 - 1 = \frac{0.41344023\lambda^2}{\lambda^2 - (0.03684262)^2} + \frac{0.50497499\lambda^2}{\lambda^2 - (0.09076162)^2} + \frac{2.4904862\lambda^2}{\lambda^2 - (12.771995)^2}$$



## Birefringence of Calcite (CaCO<sub>3</sub>)



- Good over 0.2-2.2  $\mu m$  range for ordinary ray and 0.2-3.3  $\mu m$  range for extraordinary
- Sellmeier Dispersion Formula ( $\lambda$  in  $\mu$ m):

$$n_{o}^{2} - 1 = \frac{0.8559\lambda^{2}}{\lambda^{2} - (0.05888)^{2}} + \frac{0.8391\lambda^{2}}{\lambda^{2} - (0.141)^{2}} + \frac{0.0009\lambda^{2}}{\lambda^{2} - (0.197)^{2}} + \frac{0.6845\lambda^{2}}{\lambda^{2} - (7.005)^{2}}$$

$$n_{e}^{2} - 1 = \frac{1.0856\lambda^{2}}{\lambda^{2} - (0.07897)^{2}} + \frac{0.0988\lambda^{2}}{\lambda^{2} - (0.142)^{2}} + \frac{0.317\lambda^{2}}{\lambda^{2} - (11.468)^{2}}$$



### Birefringence of Lithium Yttrium Fluoride (LiYF<sub>4</sub>)



- Good over 0.2-2.6  $\mu$ m range
- Sellmeier dispersion formula

$$n_o^2 = 1.38757 + \frac{0.70757\lambda^2}{\lambda^2 - 0.00931} + \frac{0.18849\lambda^2}{\lambda^2 - (50.99741)}$$

$$n_e^2 = 1.31021 + \frac{0.84903\lambda^2}{\lambda^2 - 0.00876} + \frac{0.53607\lambda^2}{\lambda^2 - (134.9566)}$$



## Complete vs Incomplete Polarimeters



- Instrument that measures the polarization state of light
  - Complete polarimeter provides S<sub>0</sub>, S<sub>1</sub>, S<sub>2</sub>, S<sub>3</sub>
  - Incomplete polarimeter provides  $S_0$ ,  $S_1$ , and  $S_2$  or less...
- Optimization of a complete polarimeter
  - Based on rotating retarder and a fixed linear polarizer



### **Incomplete Imaging Polarimeter**



- Simple system:
  - PtSi camera,
  - Filter wheel
  - Linear polarizer
     in manual
     rotation stage
- Sapphire window in dewar:
  - no problem since detector is *not* polarization selective





### **MWIR Complete Imaging Polarimeter**

• Linear polarizer at COLD STOP

**2011** 

- Rotating retarder wave plate in front
- Measure Stokes vector for all pixels



#### Ray colors denote field angles



### Optimization of a Rotating Retarder Polarimeter: Optimal Retardance



- Choose retardance to ensure favorable conditioning of measurement matrix.
- Each row of measurement matrix corresponds to point on Poincaré sphere.
- Each trajectory represents a retardance value
- System design corresponds to choice of 4 points on one trajectory.
- Volume of resulting tetrahedron gives system matrix determinant
- Maximize volume; maximize determinant





## **Optimal Retardance**

- To maximize determinant (maximize volume), want regular tetrahedron.
- A retardance of approx.
   3λ/8 facilitates a regular tetrahedron with maximum volume.
- The corners of the tetrahedron indicate optimal retarderorientation angles: ±51.7° and ±15.1°



Reference: D. S. Sabatke, *et. al.*, "Optimization of Retardance for a Complete Stokes Polarimeter," <u>Opt. Lett. 25, 11, June 1, 2000</u>





### **Complete Imaging Polarimeter**

- WG polarizer(s) and 4.42-5.46 μm filter inside dewar
- Retarder in front of lens assembly
- Take a minimum of four measurements by rotating wave plate
- Output: Stokes parameters





# Form-Birefringent Retarder



- •132<sup>0</sup> Retardance
- •Achromatic Form-Birefringent Retarder
- •MWIR region on GaAs
- •Fabricated by S. Kemme, SNL





## **Practical Lessons Learned\***



- Beware of reflections from a wire grid polarizer
- Polarizer in transmission has nearly 100 % extinction, however in reflection component does not!!
- Multiple reflections can invalidate the Mueller matrix for a system
- Emitted light along beam path will introduce a randomly polarized component
  - Zero radiance reference location critical

\*Zingers in polarization measurements

### Polished Cu Alloy Measurement







## **Complete Polarimetry Data**



- Profiles along indicated line across aircraft image
- Change in sign of S<sub>2</sub> across windshield indicates curved shape
- No circular polarization components (i.e., S<sub>3</sub>) observed







## Narcissus Effect





Caravaggio, 1573-1610 Galleria Nazionale dell'Arte Antica, Rome

**Source:** J.A. Shaw & M.R. Descour, "Instrument effects in polarized infrared images," *Opt. Eng.*, **34**, No. 5, pp. 1396-1399 (1995) Detector "sees" itself in polarizing element preceding objective lens.



Effect manifests itself as a non-uniform dark spot within the image

**Imagine Polarimetry** 

Narcissus spot is not uniform: on-axis detectors see radiance of cold detector, offaxis detectors see radiance from warmer ambient surroundings. Tilt polarizer, move narcissus spot



Fig.2 Infrared image of the polarizer in front of the blackbody source. The dark spot near the top of the polarizer is caused by nervissus.



## Photodetectors

- Nominal assumption:
  - detector is not polarization sensitive
  - acts as a depolarizer
- Photodetectors can be made polarization selective
  - EXAMPLE:

Typical WG polarizers: period/wavelength < 0.2



Aluminum wire grid is fabricated on a GaAs photodiode; larger period allowable because all diffraction orders detected by photodetector; period (600 nm) approaches wavelength (715 nm)

 $\mathbf{O}$ 

 $M_{\rm det} =$ 

**Source**: T. Doumuki & H. Tamada, "An aluminum-wire grid polarizer fabricated on gallium-arsenide photodiode," *App. Phys. Lett.*, **71**, No. 5, pp. 686-688 (1997).

**Imagine Polarimetry** 

()

()

()

0



## **Photodetectors-QWIP**

- Quantum well infrared Photodetector:
  - detector is polarization sensitive
  - Structure inherent
  - EXAMPLE:



**Source**: Levine, B.F., G. Hasnain, C.G. Bethea, and Naresh Chandm "Broadband 8-12 μm high-sensitivity GaAs quantum well infrared photodetector," <u>Appl.</u> <u>Phys. Lett 54(26)</u>, 26 June (1989).



### **Terrestrial Imaging Polarimeter: MISIP**



- Multispectral Infrared Stokes Imaging Polarimeter (MISIP) of Army's Night Vision Lab (Simultaneous 3-5, 8-12 micron acquisition)
  - two rotating retarder polarimeters fed from a dichroic beamsplitter
  - overdetermined data set = 16 images
  - average retardance value (achromatic quarter waveplates) is used over spectral bandpass (85-102 degrees)
  - wire grid polarizers
  - maximum predicted Stokes parameter error = 0.02, avg~0.005
  - calibration: iteratively rotate calibration polarizer to seven positions and then select retardance, fast axis orientation and pedestal offset until DLP and DCP variations are minimized for the seven positions

(M. Smith et.al. SPIE Vol. 3754, pg 137, 1999)



### Rotating Retarder Polarimeter: Beam Wander Considerations



- Rotating retarder type imaging polarimeters, as well as multiple discrete analyzer devices, can suffer from pixel and sub-pixel level image misregistration between successive images up to 15 arc seconds of wedge measured in retarders
- worst for sharp edges in scene: evidence is artificial edge enhancement
- reduce image misregistration to < 1/20th pixel (difficult)

(M. Smith et.al. SPIE Vol. 3754, pg 137, 1999)



#### **AFRL Near-IR Rotating Retarder Imaging Polarimeter: System Specifications**



#### CAMERA

InGaAs array **Detector pitch** Spectral response **Digital output** Analog output **Exposure time** 

#### FRAMEGRABBER

A/D converter

**STAGES** 

Max velocity Resolution **POLARIZATION ELEMENTS NIR sheet polarizer** 

NIR SiO<sub>2</sub>/MgF<sub>2</sub> retarder

#### FILTER

Silicon window

Sensors Unlimited, Inc. 320 x 240 **40** µm .9 - 1.7 μm 12 bit uncorrected **RS170** 127 µs - 16.3 ms

#### National Instruments PCI 1408

8 bits Newport 495B

.001°

8°/s

Ealing Lambrecht

Slide courtesy Dr. Dennis Goldstein



### **Near-IR Rotating Retarder Imaging Polarimeter**



Slide courtesy Dr. Dennis Goldstein



### NEAR INFRARED LINEAR POLARIZER TRANSMISSION CURVE





### **NIR Retarder Characterization**







### **IMAGING POLARIMETER DATA REDUCTION**





### **Spectral and Stokes Object Cubes**







Polarization generation

### **CTISP** Calibration Facility





#### Full Calibration Facility

All aspects of polarization generation and X-Y positioning are under computer control.

#### X-Y translatable polarization generation section





# Prism-based Imaging Polarimeters



- Angle in pupil plane of optical system equals position in image plane
- Use a Wollaston prism or a Rochon prism to split light in angle according to polarization



Source: Shurcliff, Polarized Light, 1962.



Less advantageous because of the smaller (~half) separation angle  $\phi$ 



# **Snapshot Incomplete Polarimeter**

- When circular polarization not expected,  $s_3 = 0$ :
- Wedged double Wollaston (WeDoWo),
- Simultaneous imaging to measure  $s_0$ ,  $s_1$ , and  $s_2$ .





**Source**: E. Oliva, "Wedged double Wollaston, a device for single shot polarimetric measurements," *Astron. Astrophys. Suppl. Ser.* **123**, 589-592 (1997).



## **Snapshot Polarimetry**



- The Checkerboard Polarization Filter Array
- Every pixel has its own polarization-selective filter



- Ideal detection size
- Airy disc should be on two pixels
- If pixels are too large, then we see different parts of scene

## Division of wavefront polarimeter







# Separation in Fourier Domain









- Snapshot complete polarimeter
- Two thick retarders and a polarizer
- Stokes components modulate carriers
- Stokes components encoded in (complicated) spectrum at output



K. Oka and T. Kato, *Opt. Lett.* **24**, 1475 (1999).



# **Mueller Analysis**



#### spectrum $\infty$

Here  $\sigma = 1/\lambda$  is wavenumber.

Usually try to avoid this dispersion. In this application, exploit it.

Retardances have form

$$\delta_k = 2\pi d_k \Delta n_k \sigma$$

Hence get sines and cosines in  $\sigma$ , *i.e.* modulation.





# **Modulation Frequencies**

The recorded spectrum can be expanded as

$$E(\sigma) = \sum_{i=0}^{3} \sum_{k} a_{jk} e^{i2\pi h_{jk}\sigma} S'_{j}(\sigma)$$

$S'_0(\sigma) = S_0(\sigma)$
$S'_1(\sigma) = S_1(\sigma)$
$S'_{2}(\sigma) = S_{2}(\sigma) - iS_{3}(\sigma)$
$S'_{3}(\sigma) = S_{2}(\sigma) + iS_{3}(\sigma) = [S'_{2}(\sigma)]$

Polarization	Modulation	Amplitude
component	frequency h	a
s;	0	$\frac{1}{2}$
Sí	$-\mathbf{d}_2 \Delta \mathbf{n}_2$	1 4
S <sub>1</sub>	$a_2  m_2$	<u>1</u> 4
$\mathbf{S}_2'$	$\mathfrak{a}_1 \Delta \mathfrak{n}_1 - \mathfrak{a}_2 \Delta \mathfrak{n}_2$	1 B
S <sub>2</sub>	$\mathbf{d_1} \Delta \mathbf{n_1} + \mathbf{d_2} \Delta \mathbf{n_2}$	$-\frac{1}{8}$
S <sub>3</sub>	-d₁∠n₁ - d₂∆n₂	$-\frac{1}{8}$
S <sub>3</sub>	$-d_1 \Delta n_1 + d_2 \Delta n_2$	<u>1</u> 8



# Requirements



• Convenient to choose

 $d_1 \Delta n_1 = 3 (d_2 \Delta n_2)$ 

- s-bandwidth d<sub>2</sub> ∆n<sub>2</sub> of each channel needs to be sufficiently large (otherwise get aliasing between channels).
- Spectrometer spectral resolution to resolve detail of complicated spectrum corresponds to 9 d<sub>2</sub> ∆n<sub>2</sub> total s-bandwidth.

Fourier transform of the spectrum recorded by the spectrometer.





### snapshot imaging spectropolarimeter

University of Arizona Proprietary



# 2D CTIS



View the target scene through a 2D grating. The diffracted images are prismatic versions of the zero-order image.

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Figure: CTIS LAYOUT

The diffracted orders can be considered as projections of the 3D data cube onto the 2D focal plane array.

Reconstruction is equivalent to the problem of limited-angle computed tomography.



### The principle of Channelled Spectropolarimetry (CHSP)







# CTIS + CHSP = CTICS





Insert the thick retarders and analyzer into the CTIS collimated path. The resulting spectra are modulated with the polarization information.





# **Prism Polarimeter Principle**





- Two prisms made of birefringent crystal (such as quartz) can be combined with their optical axes orthogonal.
- An Electric field incident in the center of the structure experiences no phase delay.
- A field incident on the top of the structure has its y-component retarded more than its x-component.
- Conversely, a field incident on the bottom of the structure has its x-component retarded more than its y-component.
- Phase retardance varies as a function of y position.





### Snapshot Imaging Prism Polarimeter Implementation



- Combining a second pair of prisms with their axes 45° to the first pair and an analyzer enables interference fringes to be recorded on a detector array.
- These fringes are proportional to the incident state of polarization of the light.
- Reconstruction and calibration can be completed by Fourier filtering.



![](_page_55_Picture_0.jpeg)

### Savart Plate Polarimeter Concept

![](_page_55_Picture_2.jpeg)

- Prism method relies on image-plane interference to generate the polarization data. This method accomplishes the same task not on the image plane, but in a collimated space before the detector array.
- In this case, the plates take a collimated wavefront and shears them laterally. After re-imaging, the interference pattern generated will be nearly identical to that of the aforementioned prism polarimeter, meaning reconstruction is the same.

![](_page_55_Figure_5.jpeg)

## Snapshot Savart Plate Polarimeter

![](_page_56_Picture_1.jpeg)

![](_page_56_Figure_2.jpeg)

- TE and TM states separate into four components upon transmission through the plates. An optical path difference (OPD) is setup and interference between the components occurs on the FPA.
- This OPD is proportional to the angle of incidence on the plates.
- Can be thought of as a shearing interferometer.

![](_page_57_Picture_0.jpeg)

## Interference Pattern

![](_page_57_Picture_2.jpeg)

![](_page_57_Picture_3.jpeg)

$$I(x, y) = \frac{1}{2} S_0(x, y) + \frac{1}{2} S_1(x, y) \cos[2\pi Ux] + \frac{1}{4} |S_{23}(x, y)| \cos\{2\pi U[x - y] + \arg[S_{23}(x, y)]\} - \frac{1}{4} |S_{23}(x, y)| \cos\{2\pi U[x + y] - \arg[S_{23}(x, y)]\}$$
  
where  $U = \frac{2(n_e - n_o) \tan \alpha}{\lambda}$ ,  $S_{23}(x, y) = S_2(x, y) + iS_3(x, y)$   
 $\alpha = \text{prism dihedral angle}$ 

![](_page_57_Figure_5.jpeg)

![](_page_57_Figure_6.jpeg)

![](_page_57_Picture_7.jpeg)

![](_page_57_Picture_8.jpeg)

![](_page_58_Picture_0.jpeg)

### **Fourier Transform for Reconstruction**

![](_page_58_Picture_2.jpeg)

![](_page_58_Figure_3.jpeg)

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![](_page_59_Figure_0.jpeg)

![](_page_60_Picture_0.jpeg)

# **Example Reconstruction**

![](_page_60_Picture_2.jpeg)

![](_page_60_Figure_3.jpeg)

![](_page_61_Picture_0.jpeg)

# New CTICS Grating Designs

![](_page_61_Picture_2.jpeg)

![](_page_61_Figure_3.jpeg)

- New CGH and volume phase hologram designs may be able to double the spatial and spectral resolution of current snapshot hyperspectral imaging techniques.
- Use of volume phase holograms for windowing datacubes is new.
- Construct a snapshot hyperspectral imager with improved performance.
- Develop a technique for doing hyperspectral imaging which can simplify the hardware, and make systems easier to deploy, without sacrificing measurement quality.

![](_page_62_Picture_0.jpeg)

### Fourier Transform Spectrometer Approach

![](_page_62_Picture_2.jpeg)

- Idea is based on using the channeled spectropolarimetry technique in the Infrared.
- Using an FTS is beneficial for these wavelengths.
- The FTS system has an added benefit of enabling the spectropolarimetric data to be extracted directly from the interferogram.
- Method can be combined with imaging interferometers to give it more of a snapshot capability.

![](_page_62_Figure_7.jpeg)

![](_page_62_Figure_8.jpeg)