Tradeoffs in Polarimeter Design

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**Report Documentation Page**

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<td>See also ADM201529., The original document contains color images.</td>
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Presentation Outline

• System Dimensionality
  – Example Applications and Methods

• Data Collection Strategies
  – Serial -vs- Parallel
  – Rotating -vs- Non-Rotating Optics
  – Active -vs- Passive

• System Optimization
## Multi-Dimensional Stokes Polarimetry

<table>
<thead>
<tr>
<th>1-D Polarimetry</th>
<th>2-D Polarization Difference</th>
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<tr>
<td>Contrast Enhancement in Photography (e.g. Duntley, 1974; Gilbert, 1964)</td>
<td>Scatter Mitigation, Contrast Enhancement (Tyo, <em>et al.</em>, 1996; Silverman and Strange, 1996)</td>
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<tr>
<th>3-D Linear Polarimetry</th>
<th>4-D Stokes Vector Imaging</th>
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<tr>
<td>Target Identification (Halaijan and Hallock, 1972; Walraven, 1977; Duggin 2002; Wolff, <em>et al.</em>, 1994; etc.)</td>
<td>Target Identification (Soloman, 1981; Chipman, <em>et al.</em>, 1997; etc.)</td>
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1-D Polarimetry - Photography

• Linear polarization filters are used extensively in photography to maximize the contrast between the subject and the background.

• Maximum utility when the scattering background provides a high degree of linear polarization, as when a scattering medium is illuminated at right-angles to the direction of observation.

• Beneficial with sky-background, underwater, in fog or dust, etc.
Tradeoffs for 1-D Polarimetry

**pros**
- No images to register
- Can be optimized in near-real time
- Linear or circular

**cons**
- 3 dimensions of polarization blindness
- Image features vary as system is tuned
- No quantitative polarization result
Experimental Setup for 2-D PDI

- Tank with diluted milk
- Target Holder
- CCD Camera
- TNLC
- Diffusing Screen
- Projectors
Prepared Targets
Step-by-Step PDI (2-D)

8-bit Images

Line Scans across Center

vert/horiz

PS/PD

amplified
# Tradeoffs for 2-D Polarimetry

<table>
<thead>
<tr>
<th><strong>pros</strong></th>
<th><strong>cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>2 images to register</td>
<td>2 dimension of polarization blindness</td>
</tr>
<tr>
<td>Can be optimized in near-real time</td>
<td>Image Registration</td>
</tr>
<tr>
<td>Linear polarization (can be used with circular too)</td>
<td>Image features vary as system is tuned</td>
</tr>
<tr>
<td>Projects noise into orthogonal dimension, suppresses biases</td>
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2-D Polarization Images
Polarization Bias

Horizontal Pixel Position

Pixel Intensity
3-D Linear Polarimetry

- Measures the first three Stokes parameters
- Needs 3 or more measurements
- Can physically or electro-optically rotate
3-D Polarimetric Images

Back-Illuminated dielectric sphere with full 3-D colorimetric representation

Revisiting the earlier scene (Note – color axis reversed)
## Tradeoffs for 3-D Polarimetry

**Pros**

- Linear polarization (can be used with circular as $s_0, s_1, s_3$)
- Provides angle of polarization, DOLP

**Cons**

- 1 dimension of polarization blindness
- Image Registration
- Image features vary as system is tuned
- 3-D noise can corrupt data presentation
Benefits of 2-D vs 3-D

Robust Representations in Scattering Media
Full Stokes Vector Polarimeter Design

- Analyzer - Fixed
- $\alpha$-wave plate, Various angles
- Detector
- Rotating Compensator (up to 4-D)
- Variable Retardance (up to 4-D)
- Variable Retarders (fixed angles, variable retardance pairs)

Data Collection can be either SERIAL or PARALLEL
Polarimetric images of sphere and cylinder

Variable Retardance Polarimetry
# Tradeoffs for 4-D Polarimetry

<table>
<thead>
<tr>
<th><strong>pros</strong></th>
<th><strong>cons</strong></th>
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</thead>
<tbody>
<tr>
<td>Provides full Stokes Vector Information</td>
<td>Must collect at least 4 images (registration, spatiotemporal resolution)</td>
</tr>
<tr>
<td>No polarization blindness</td>
<td>Requires circular polarization optics (expensive, difficult)</td>
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</tbody>
</table>
And What About Spectropolarimetry?

- Optical layout of a full Stokes vector, hyperspectral polarimeter for use in the visible
- Coupled a spatial shear modified Sagnac interferometer with a variable retardance polarimeter
- Approximately 80 bands across 450 – 750 nm
Experimental Images

Scan Lines

Image Location

Stack of Cylinders
Spatio-Spectral $s_0$ “Images”
Stack of Cylinders

Blue

Clear

Red
Spatio-Spectral Stokes “Images”
Clear Cylinder

“Unpolarized” Partial Vertical

$S_1$ $S_2$ $S_3$
Tradeoffs for Spectropolarimetry

**pros**
- Provides Stokes vector information *at all wavelengths*
- Can calibrate out spectral dependence of optics
- Can be used as a spectrometer

**cons**
- Huge data storage and alignment issues
- Requires circular polarization optics (expensive, difficult)
- Major spatio-temporal resolution bottleneck
- Extremely low optical throughput
- Little or no evidence for highly spectrally resolved polarization information
Active Polarimetry

**pros**
- Can use polarization even when signature is depolarizing
- Can use in any wavelength regime (radar, lidar, etc.)
- Provides up to 16 dimensional information
- Can control illumination to maximize utility

**cons**
- System complexity
- Very low spatiotemporal resolution
- Difficult to do “broadband”
- Provides up to 16 dimensional information
Polarimeter Optimization

• There is an optimum configuration for every 2-D, 3-D, and 4-D polarimeter design, as well as active systems
• Depends on the strategy used and the number of measurement made
• Improper design of system can provide unnecessarily low SNR and oversensitivity to optical calibration issues
How Do We Detect Stokes Vector?

• Problem: Optical detectors are typically photon counters – Generally Pol-insensitive
  – We can only measure $s_0$!

• Solution: Design an optical system that modifies $s_0$ based on the input polarization
  – Infer $s_0 – s_3$ from intensity measurements
Polarimetric analysis – Variable Retardance

The Stokes vector of the emergent light is

\[ S_o = M_{LP}(\theta)M_{VR}(\phi_2, \delta_2)M_{VR}(\phi_1, \delta_1)S_i \]

With Intensity \( I = M_1^T \cdot S_i \)

Vary parameters to form a linear system:

\[ I = A \cdot S_i \]
The input Stokes vector is obtained by inversion:

\[ S_i = A^{-1} \cdot I = B \cdot I \]

\( B \) is termed the “Synthesis Matrix” as it is used to reconstruct the Stokes Parameters.
Simulated Images

\[
S = \begin{bmatrix}
\sqrt{3} \\
1 \\
1 \\
1
\end{bmatrix}
\]
Simulated Images - Original Parameters

\[ \langle S \rangle = \begin{bmatrix} 1.74 \\ 0.99 \\ 0.98 \\ 1.00 \end{bmatrix} \]

\[ \text{var}(S) = \begin{bmatrix} 0.59 \\ 0.43 \\ 1.93 \\ 0.60 \end{bmatrix} \]
Simulated Images - Optimized System

\[
\langle S \rangle = \begin{bmatrix}
1.73 \\
1.00 \\
1.00 \\
1.00 \\
\end{bmatrix}
\]

\[
\text{var}(S) = \begin{bmatrix}
0.10 \\
0.29 \\
0.31 \\
0.30 \\
\end{bmatrix}
\]
General Optimization

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere
2-D Linear Polarization

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere
3-D Linear

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere
3-D Linear, 4 Measurements

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere
4-D Stokes Vector

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere
References for Optimization

Design of Optimum Polarimeters

• The optimum set of parameters provides maximum information per measurement, i.e. these measurements are maximally decorrelated.
• For Variable Retardance Polarimetry, a non-unique optimum parameter set will equalize the noise in the three Stokes images.
• Rotating retarder systems - the optimum retardance is 132° - not 90°.
• Rotating retarder systems – the optimum angles are at ±15.1°,±51.7°.
• A new set of optimum settings must be computed for situations with a polarization bias (Tyo, et al., 1996).
• In principle, such a set of optimum parameters exists for any polarimetry strategy.
  – N-channel Linear Polarimetry (Tyo, 1998).
  – Variable Retardance Polarimetry (Tyo and Turner, 1999).