Tradeoffs in Polarimeter Design

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---|---
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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>
</tr>
</thead>
</table>
| Contrast Enhancement in Photography  
(e.g. Duntley, 1974; Gilbert, 1964) | Scatter Mitigation, Contrast Enhancement  
(Tyo, et al., 1996; Silverman and Strange, 1996) |

<table>
<thead>
<tr>
<th>3-D Linear Polarimetry</th>
<th>4-D Stokes Vector Imaging</th>
</tr>
</thead>
</table>
| Target Identification  
(Halaijan and Hallock, 1972; Walraven, 1977; Duggin 2002; Wolff, et al., 1994; etc.) | Target Identification  
(Soloman, 1981; Chipman, et al., 1997; etc.) |
1-D Polarimetry - Photography

Partially Linearly Polarized Skylight (Rayleigh Scattering)

- 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

<table>
<thead>
<tr>
<th><strong>pros</strong></th>
<th><strong>cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- No images to register</td>
<td>- 3 dimensions of polarization blindness</td>
</tr>
<tr>
<td>- Can be optimized in</td>
<td>- Image features vary as</td>
</tr>
<tr>
<td>near-real time</td>
<td>system is tuned</td>
</tr>
<tr>
<td>- Linear or circular</td>
<td>- No quantitative polarization result</td>
</tr>
</tbody>
</table>
Experimental Setup for 2-D PDI

- Tank with diluted milk
- Diffusing Screen
- Projectors
- Target Holder
- TNLC
- CCD Camera
Prepared Targets

A

B
Step-by-Step PDI (2-D)

8-bit Images

vert/horiz

PS/PD

amplified

Line Scans across Center

8-bit Images

vert/horiz

PS/PD

amplified

Line Scans across Center
# Tradeoffs for 2-D Polarimetry

## Pros

- 2 images to register
- Can be optimized in near-real time
- Linear polarization (can be used with circular too)
- Projects noise into orthogonal dimension, suppresses biases

## Cons

- 2 dimension of polarization blindness
- Image Registration
- Image features vary as system is tuned
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

<table>
<thead>
<tr>
<th><strong>pros</strong></th>
<th><strong>cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Linear polarization</td>
<td>• 1 dimension of polarization blindness</td>
</tr>
<tr>
<td>(can be used with</td>
<td>• Image Registration</td>
</tr>
<tr>
<td>circular as $s_0, s_1, s_3$)</td>
<td></td>
</tr>
<tr>
<td>• Provides angle of</td>
<td>• Image features vary as system is tuned</td>
</tr>
<tr>
<td>polarization, DOLP</td>
<td>• 3-D noise can corrupt data presentation</td>
</tr>
</tbody>
</table>
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 Retarders
(fixed angles, variable retardance pairs)

Variable Retardance
(up to 4-D)

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

Variable Retardance Polarimetry

Sphere

Cylinder

Stage

Specular off Stage

Circular Pol
Near edges
## Tradeoffs for 4-D Polarimetry

### pros

- Provides full Stokes Vector Information
- No polarization blindness

### cons

- Must collect at least 4 images (registration, spatiotemporal resolution)
- Requires circular polarization optics (expensive, difficult)
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

<table>
<thead>
<tr>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides Stokes vector information <em>at all wavelengths</em></td>
<td>Huge data storage and alignment issues</td>
</tr>
<tr>
<td>Can calibrate out spectral dependence of optics</td>
<td>Requires circular polarization optics (expensive, difficult)</td>
</tr>
<tr>
<td>Can be used as a spectrometer</td>
<td>Major spatio-temporal resolution bottleneck</td>
</tr>
<tr>
<td></td>
<td>Extremely low optical throughput</td>
</tr>
<tr>
<td></td>
<td>Little or no evidence for highly spectrally resolved polarization information</td>
</tr>
</tbody>
</table>
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 measurements 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

\[
\begin{bmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3 \\
\end{bmatrix}
= \begin{bmatrix}
0.1 \\
98.0 \\
99.0 \\
74.1 \\
\end{bmatrix}
\]

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

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

\[
\begin{bmatrix}
0.10 \\
0.29 \\
0.31 \\
0.30
\end{bmatrix}
\]

\[
\begin{bmatrix}
1.73 \\
1.00 \\
1.00 \\
1.00
\end{bmatrix}
\]
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

120° Linear

60° Linear

0° Linear
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

5. @ARTICLE{sabatke_ol,
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)