Tradeoffs in Polarimeter Design

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Standard Form 298 (Rev. 8-98)
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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

1-D Polarimetry

Contrast Enhancement in Photography
(e.g. Duntley, 1974; Gilbert, 1964)

2-D Polarization Difference

Scatter Mitigation,
Contrast Enhancement
(Tyo, *et al.*,1996;
Silverman and Strange, 1996)

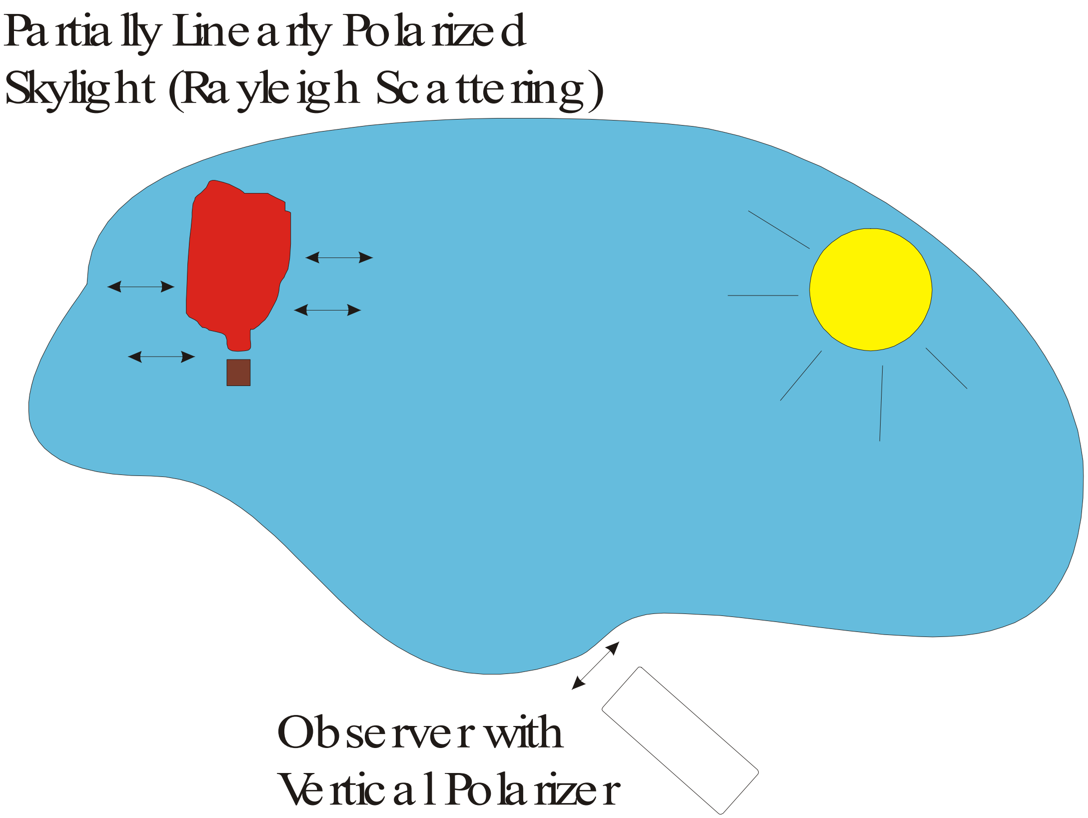
3-D Linear Polarimetry

Target Identification
(Halaijan and Hallock, 1972;
Walraven, 1977; Duggin 2002;
Wolff, *et al.*, 1994; etc.)

4-D Stokes Vector Imaging

Target Identification
(Soloman, 1981;
Chipman, *et al.*, 1997; etc.)

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

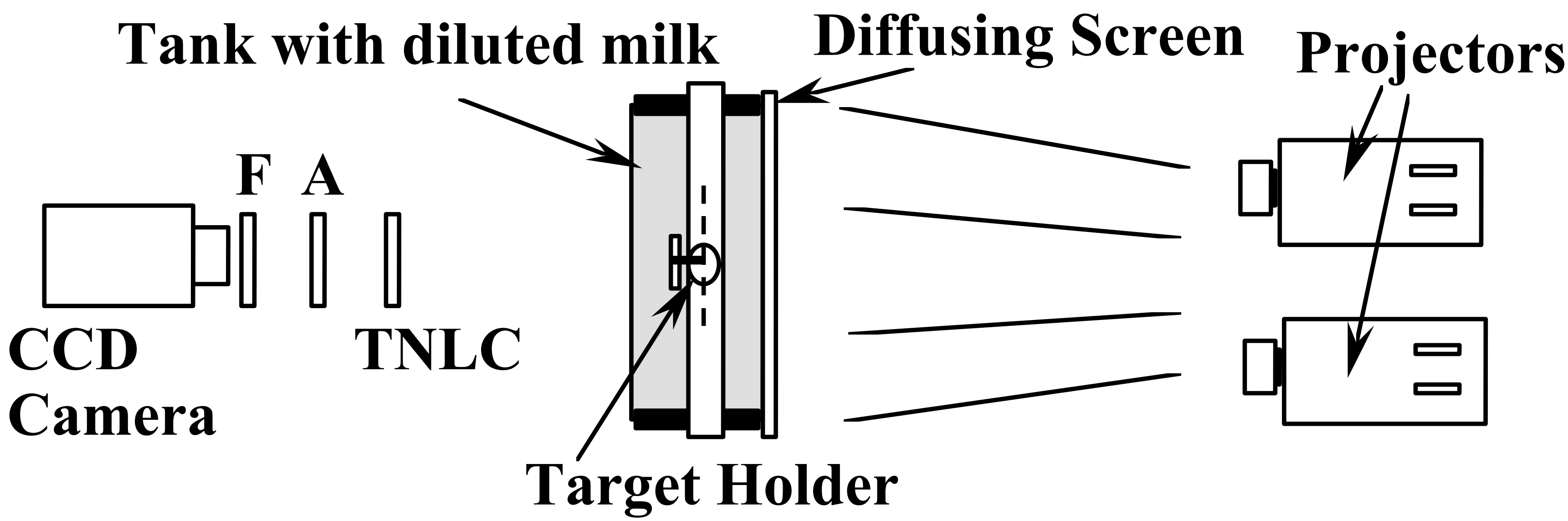
pros

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

cons

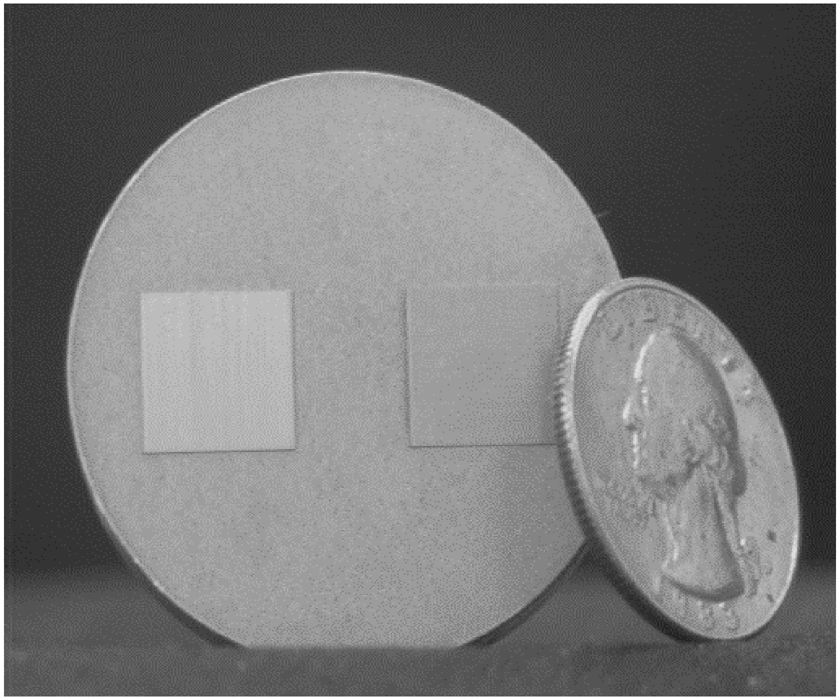
- 3 dimensions of polarization blindness
- Image features vary as system is tuned
- No quantitative polarization result

Experimental Setup for 2-D PDI



Prepared Targets

A



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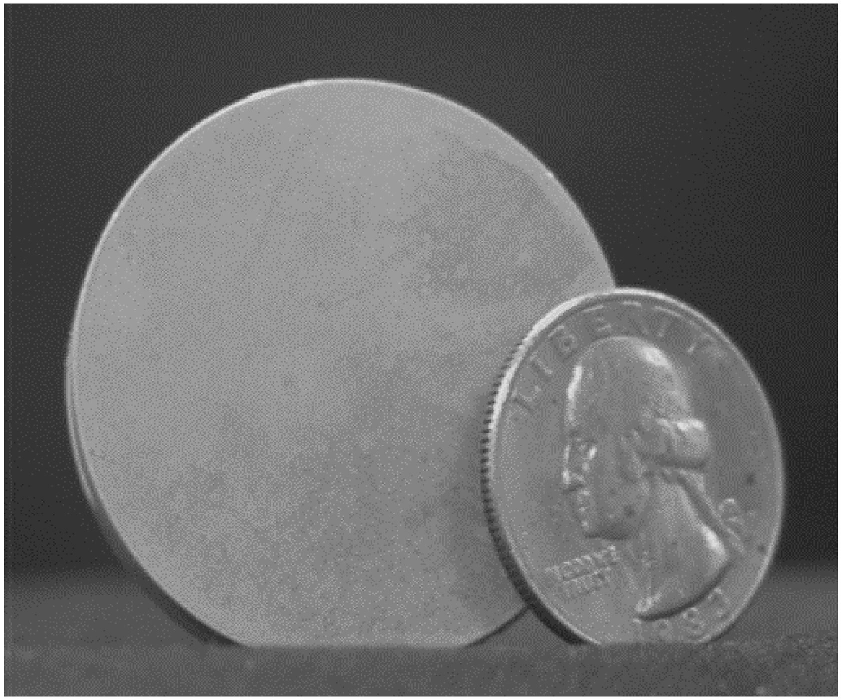
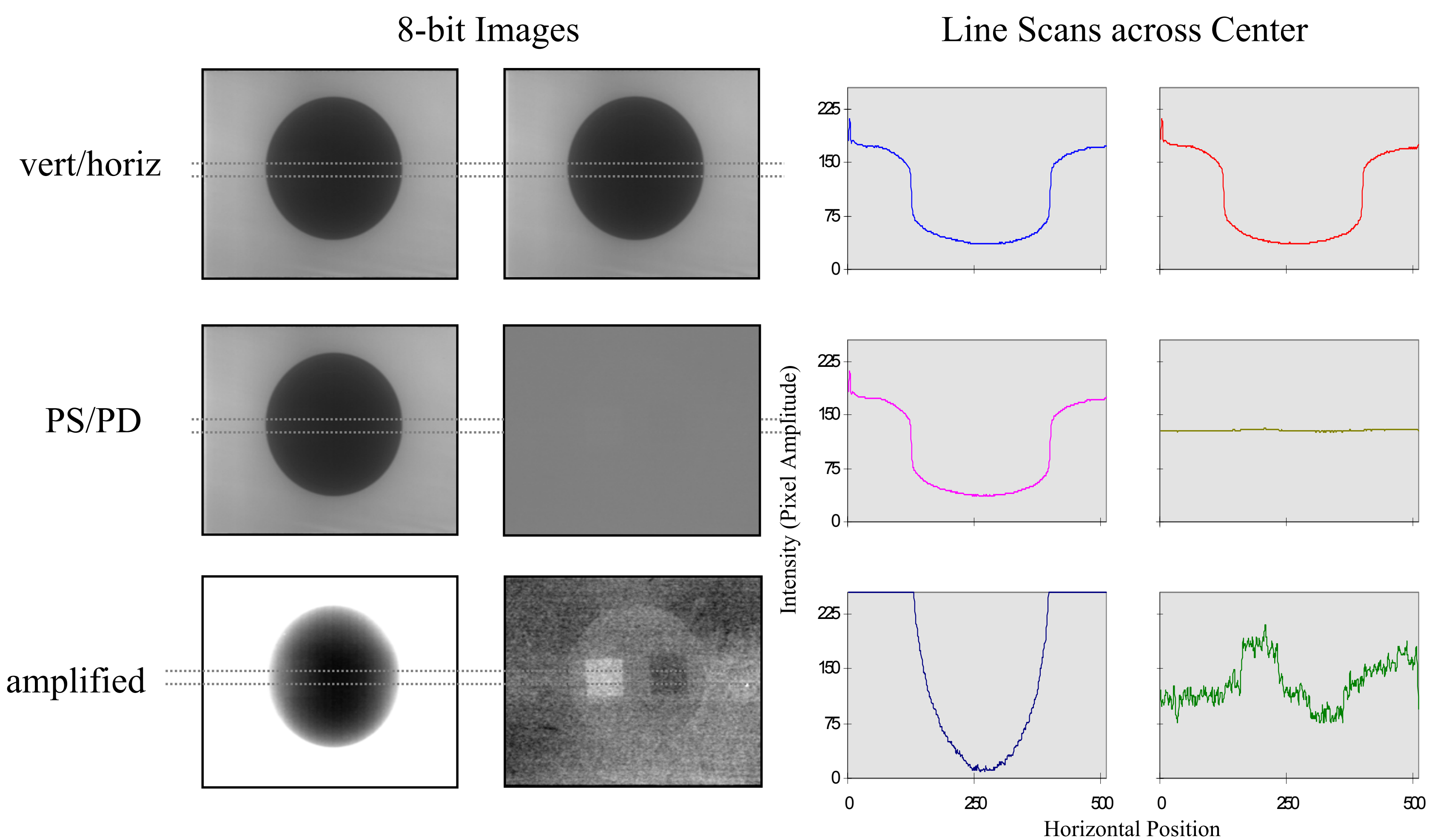


Step-by-Step PDI (2-D)



Tradeoffs for 2-D Polarimetry

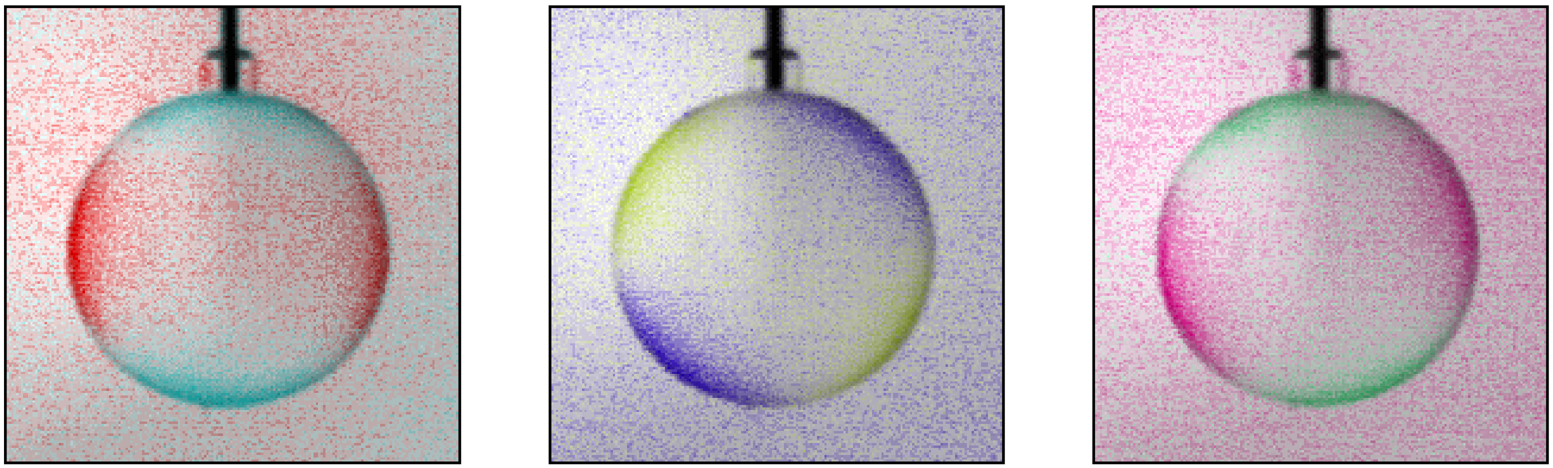
pros

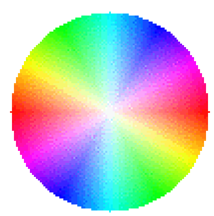
- 2 images to register
- Can be optimized in near-real time
- Linear polarization (can be used with circular too)
- Projects noise into orthogonal dimension, suppresses biases

cons

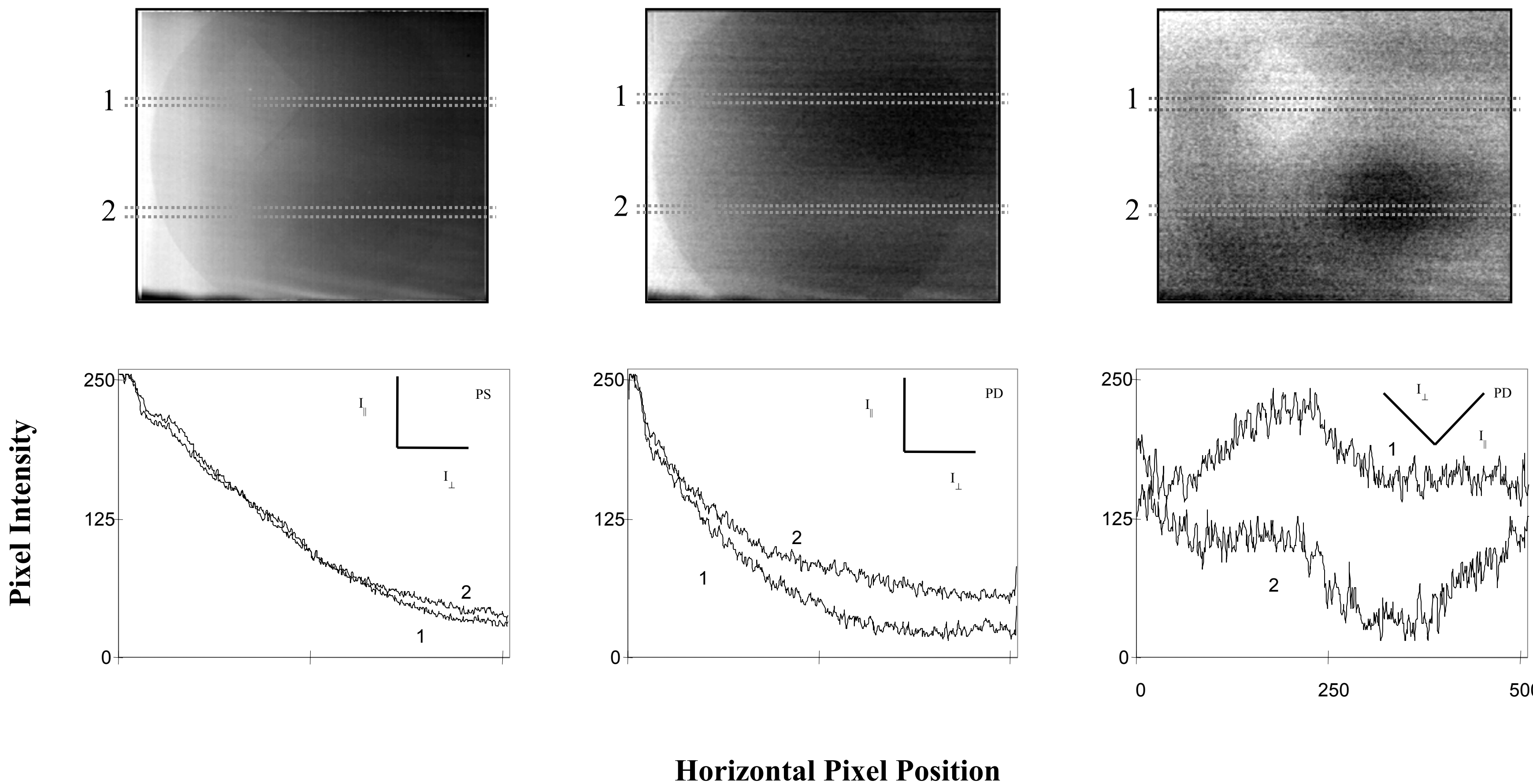
- 2 dimension of polarization blindness
- Image Registration
- Image features vary as system is tuned

2-D Polarization Images





Polarization Bias

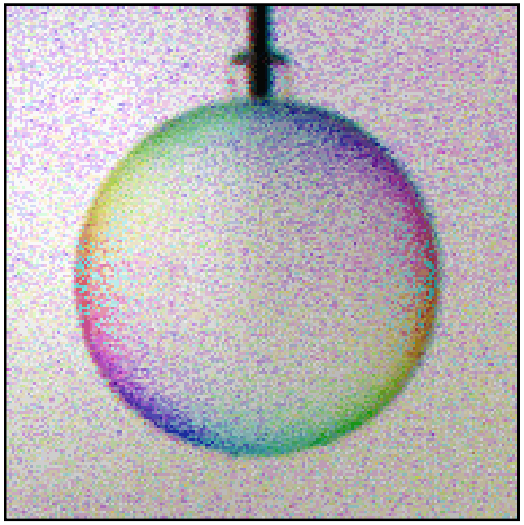


3-D Linear Polarimetry

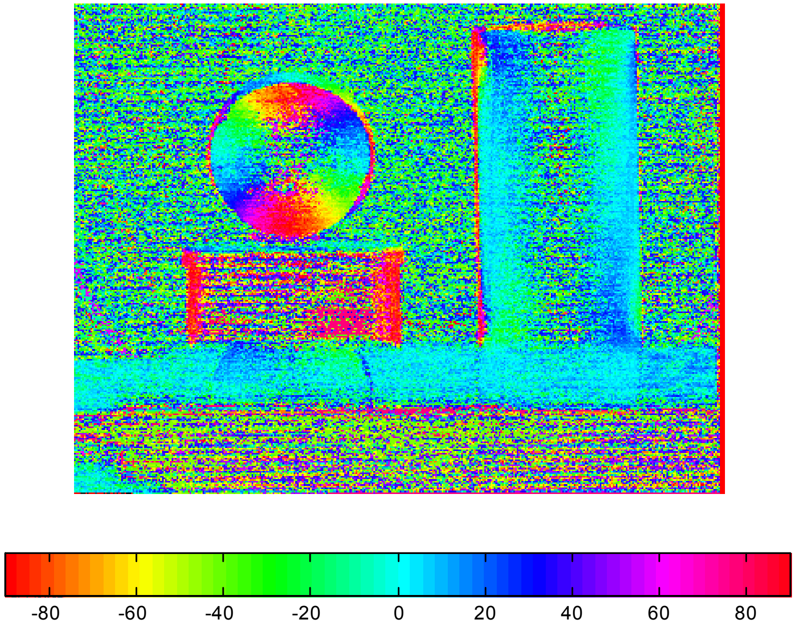
Rotating Analyzer
(2- or 3-D Linear)

- 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

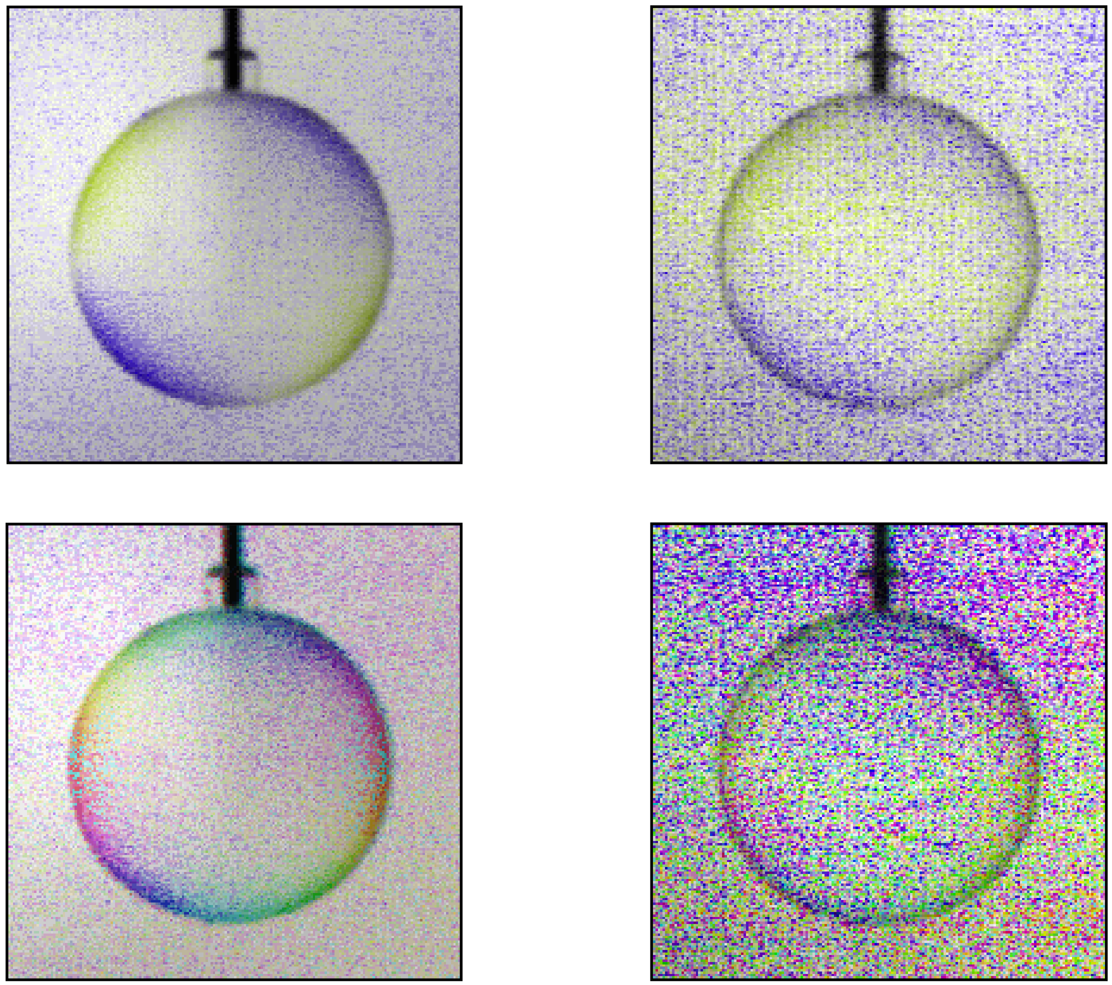
- 1 dimension of polarization blindness
- Image Registration
- Image features vary as system is tuned
- 3-D noise can corrupt data presentation

Benefits of 2-D -vs- 3-D

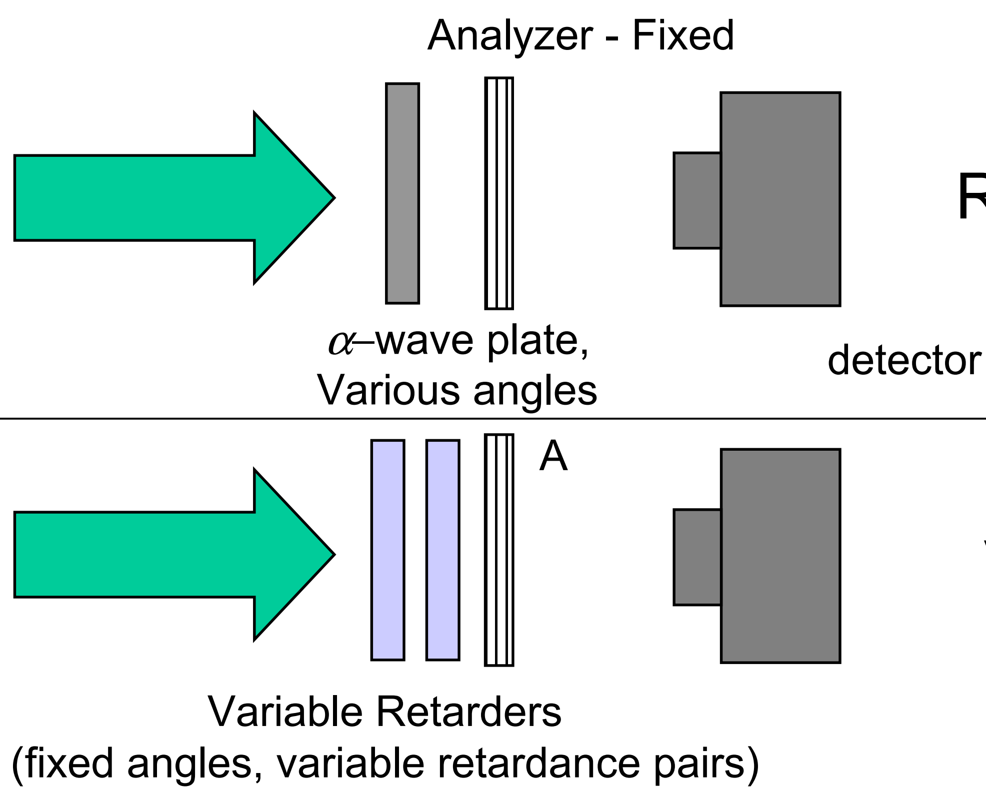
Robust Representations in Scattering Media

2-D

3-D



Full Stokes Vector Polarimeter Design



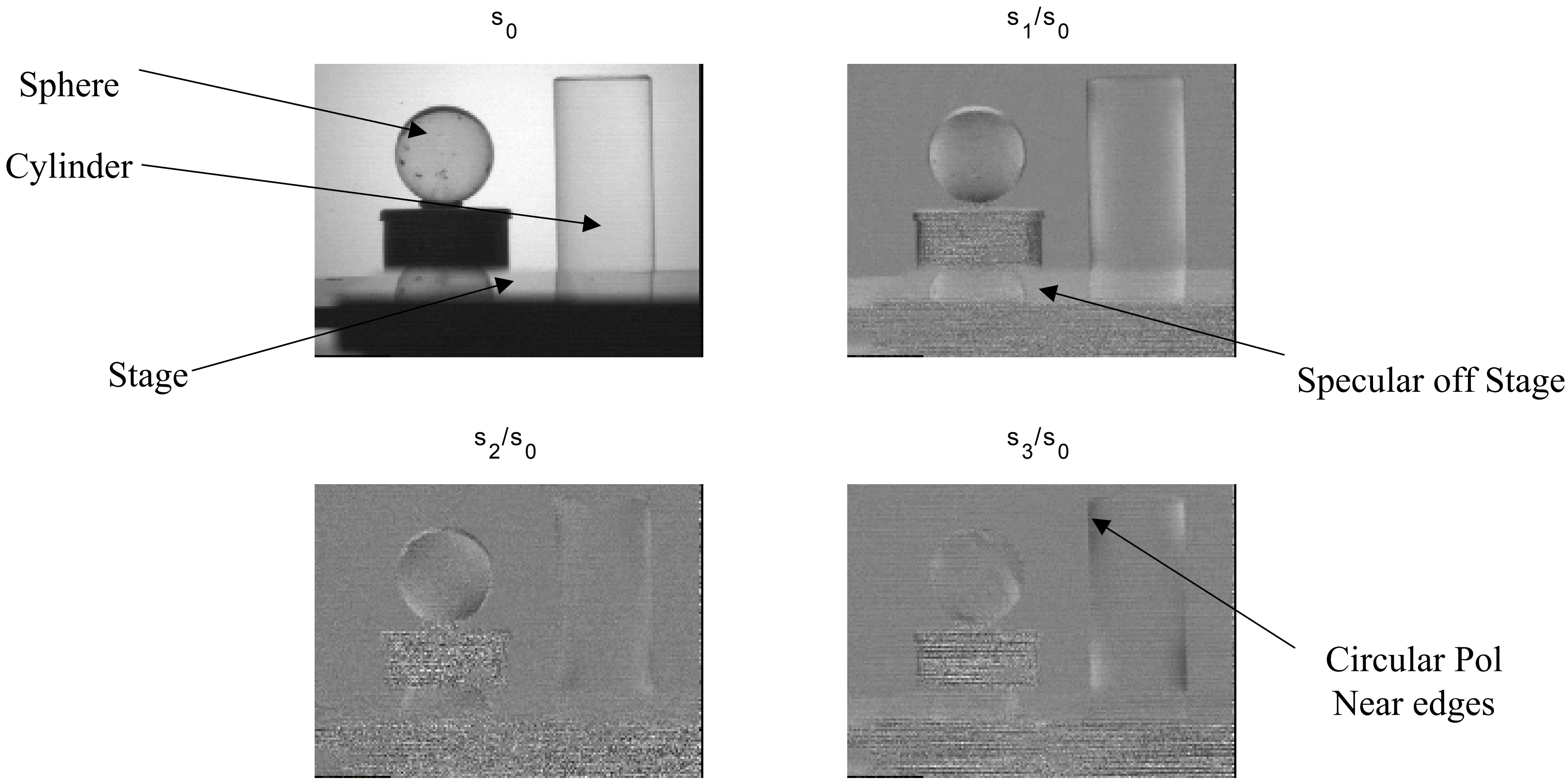
Rotating Compensator
(up to 4-D)

Variable Retardance
(up to 4-D)

Data Collection can be either SERIAL or PARALLEL

Polarimetric images of sphere and cylinder

Variable Retardance Polarimetry



Tradeoffs for 4-D Polarimetry

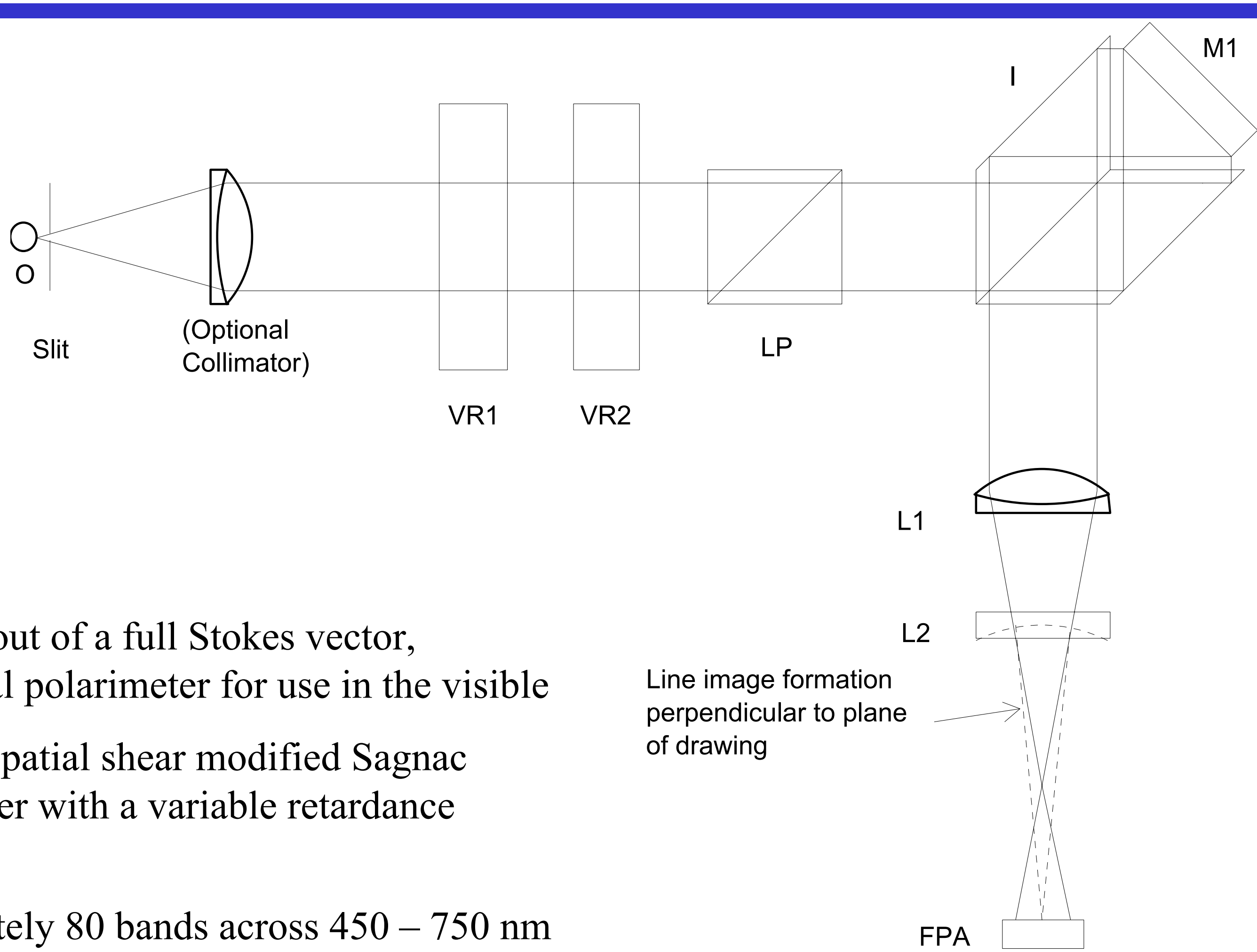
pros

- Provides full Stokes Vector Information
- No polarization blindness

cons

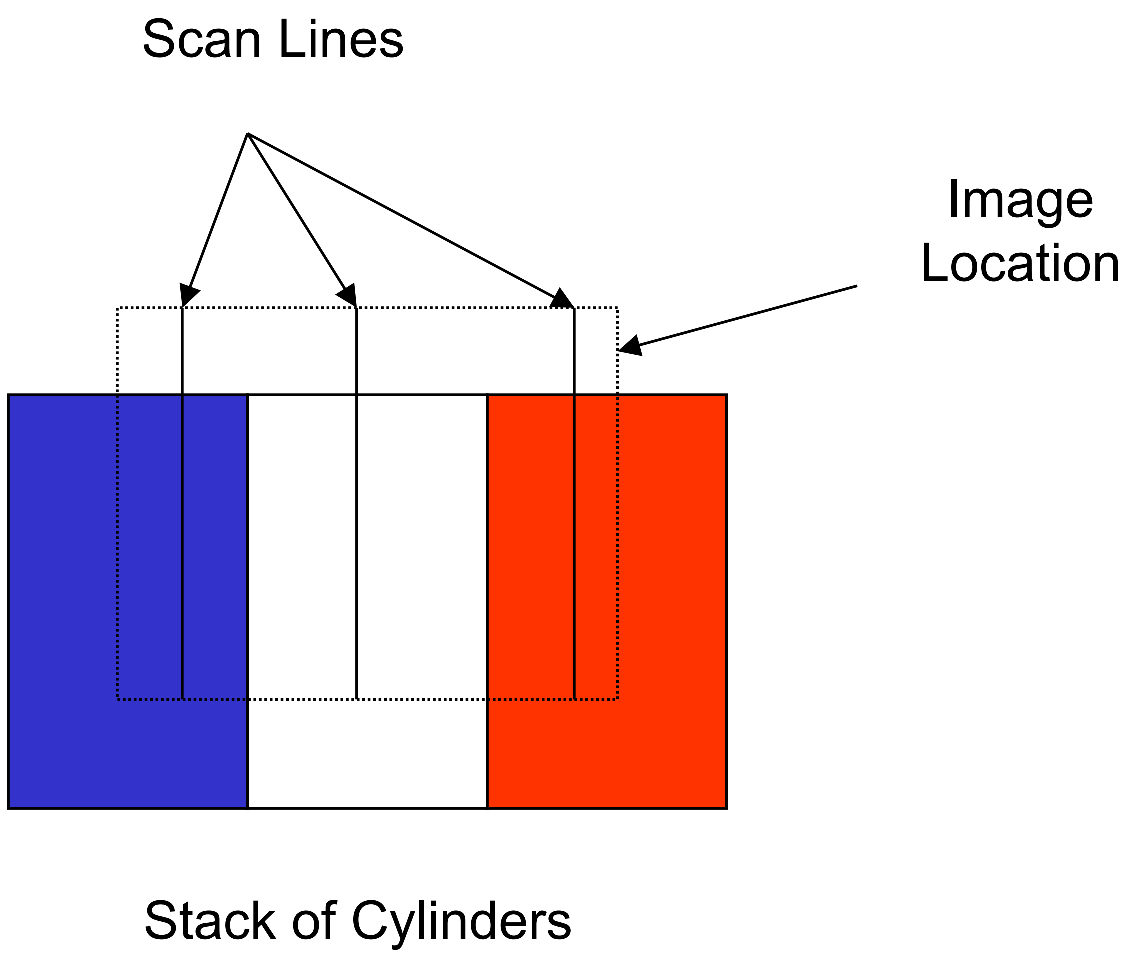
- Must collect at least 4 images (registration, spatiotemporal resolution)
- Requires circular polarization optics (expensive, difficult)

And What About Spectropolarimetry?

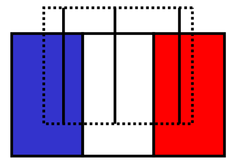


- Optical layout of a full Stokes vector, hyperspectral polarimeter for use in the visible
- Coupled a spatial shear modified Sagnac interferometer with a variable retardance polarimeter
- Approximately 80 bands across 450 – 750 nm

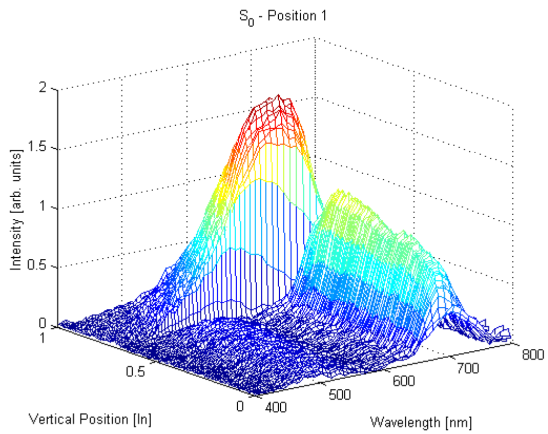
Experimental Images

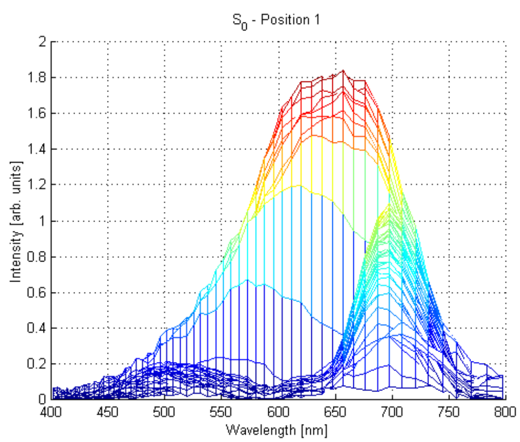


Spatio-Spectral s_0 "Images"
Stack of Cylinders

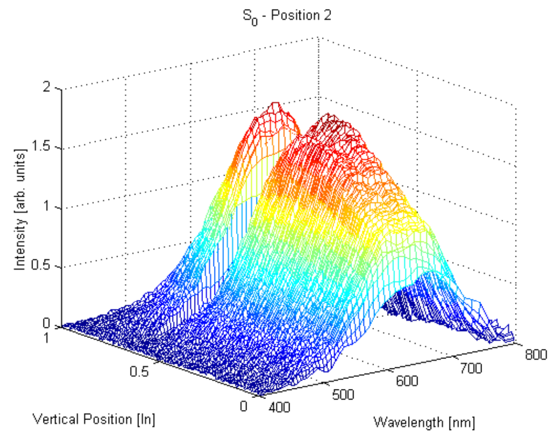


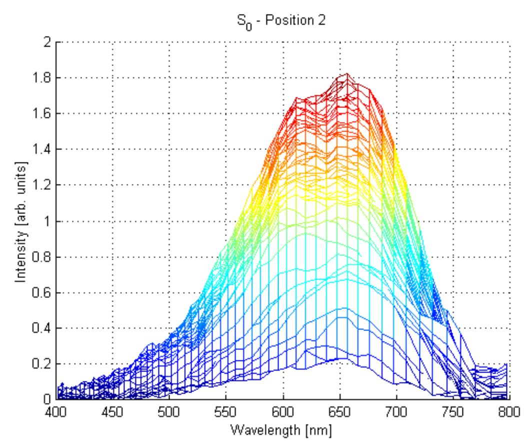
Blue



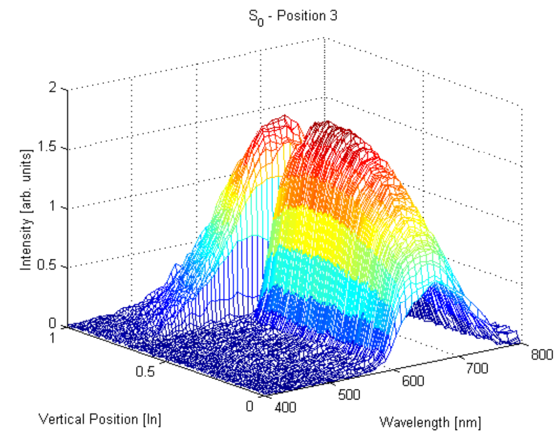


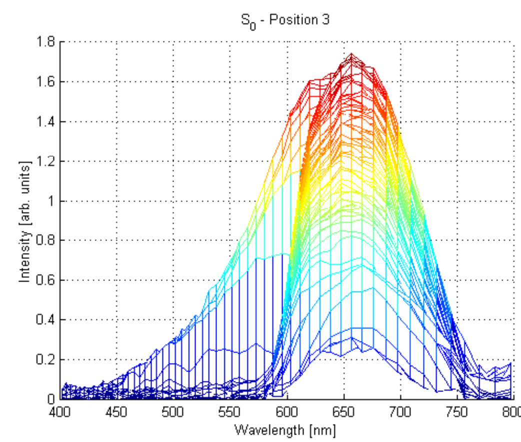
Clear



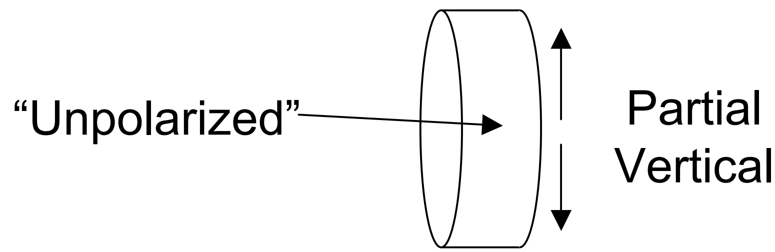


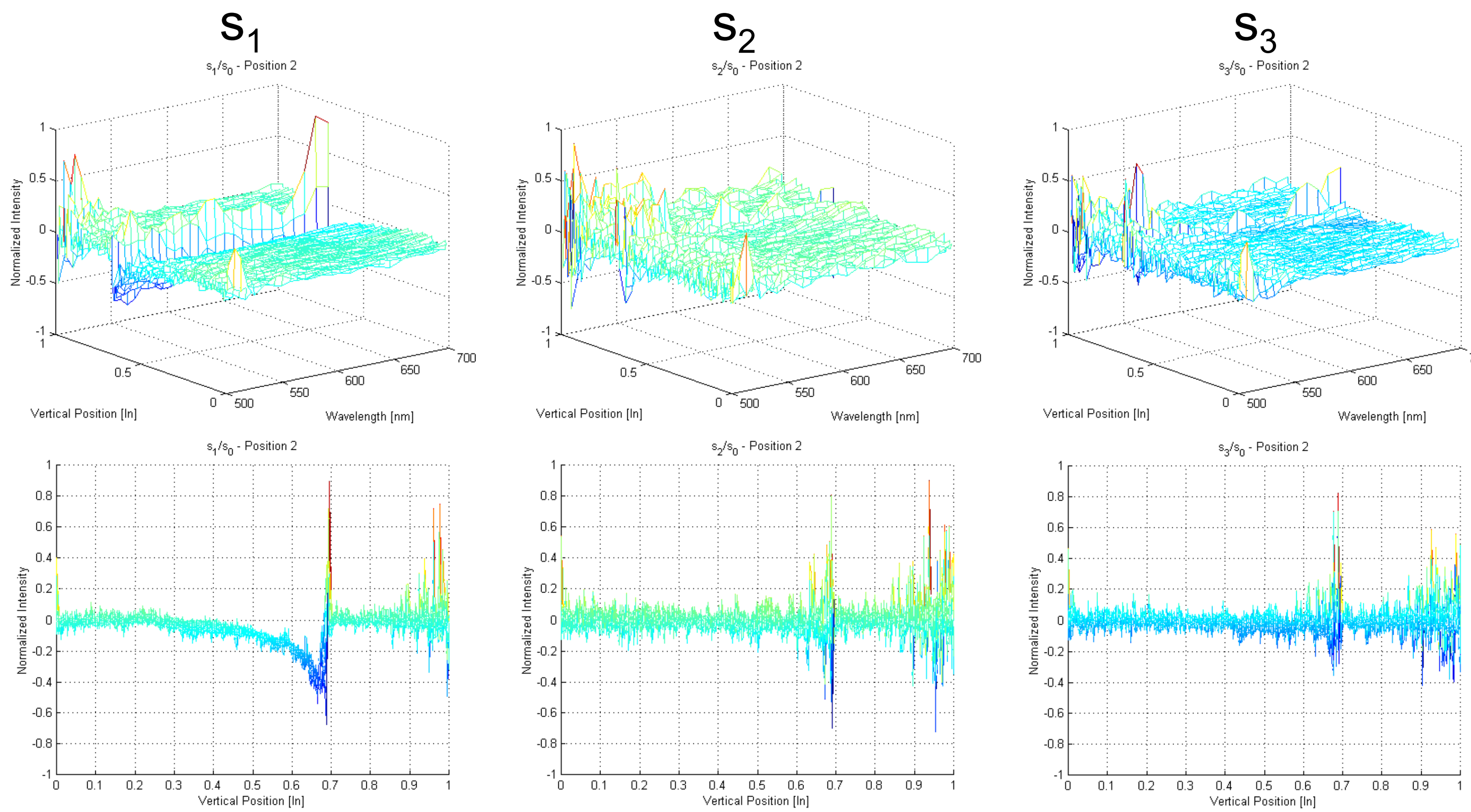
Red





Spatio-Spectral Stokes "Images"
Clear Cylinder





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

$$\mathbf{S}_o = \mathbf{M}_{LP}(\theta)\,\mathbf{M}_{VR}(\phi_2, \delta_2)\,\mathbf{M}_{VR}(\phi_1, \delta_1)\,\mathbf{S}_i$$

With Intensity $I = \mathbf{M}_1{}^T \cdot \mathbf{S}_i$

Vary parameters to form a linear system:

$$\mathbf{I} = \mathbf{A} \cdot \mathbf{S}_i$$

Polarimetric analysis (cont.)

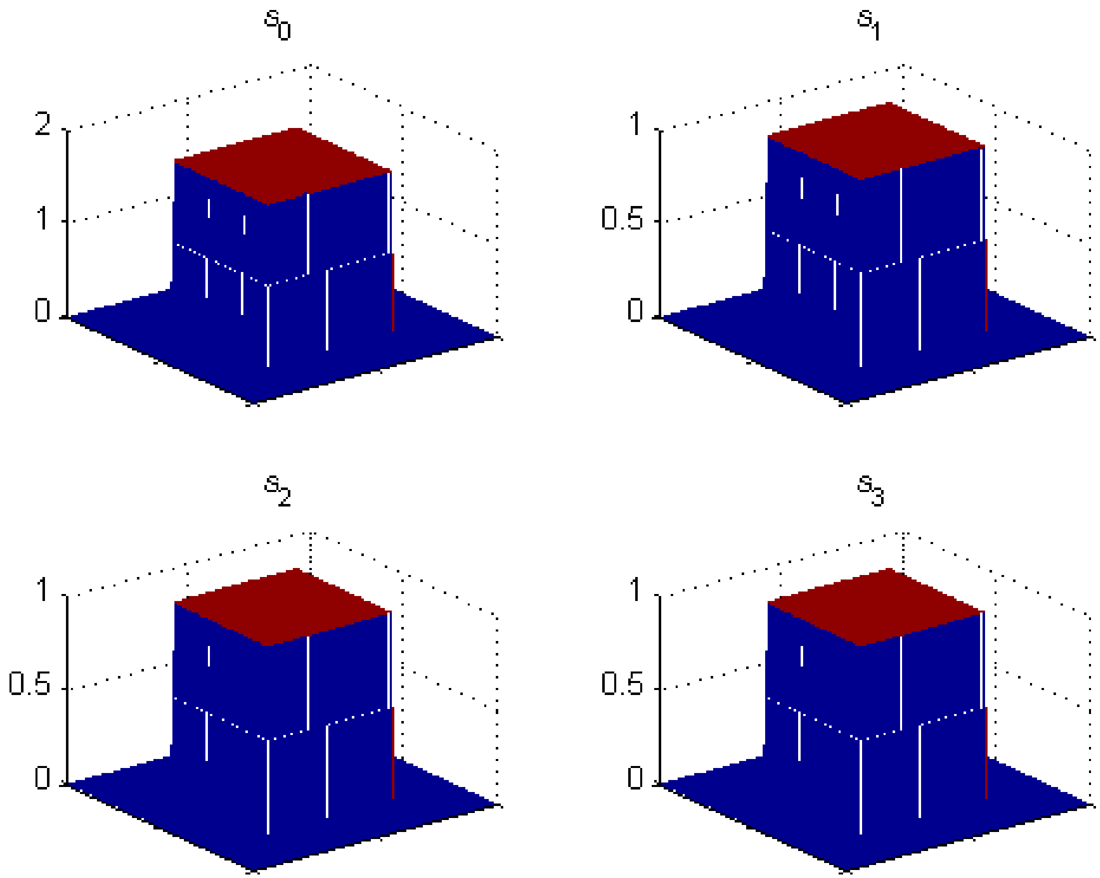
The input Stokes vector is obtained by inversion:

$$\mathbf{S}_i = \mathbf{A}^{-1} \cdot \mathbf{I} = \mathbf{B} \cdot \mathbf{I}$$

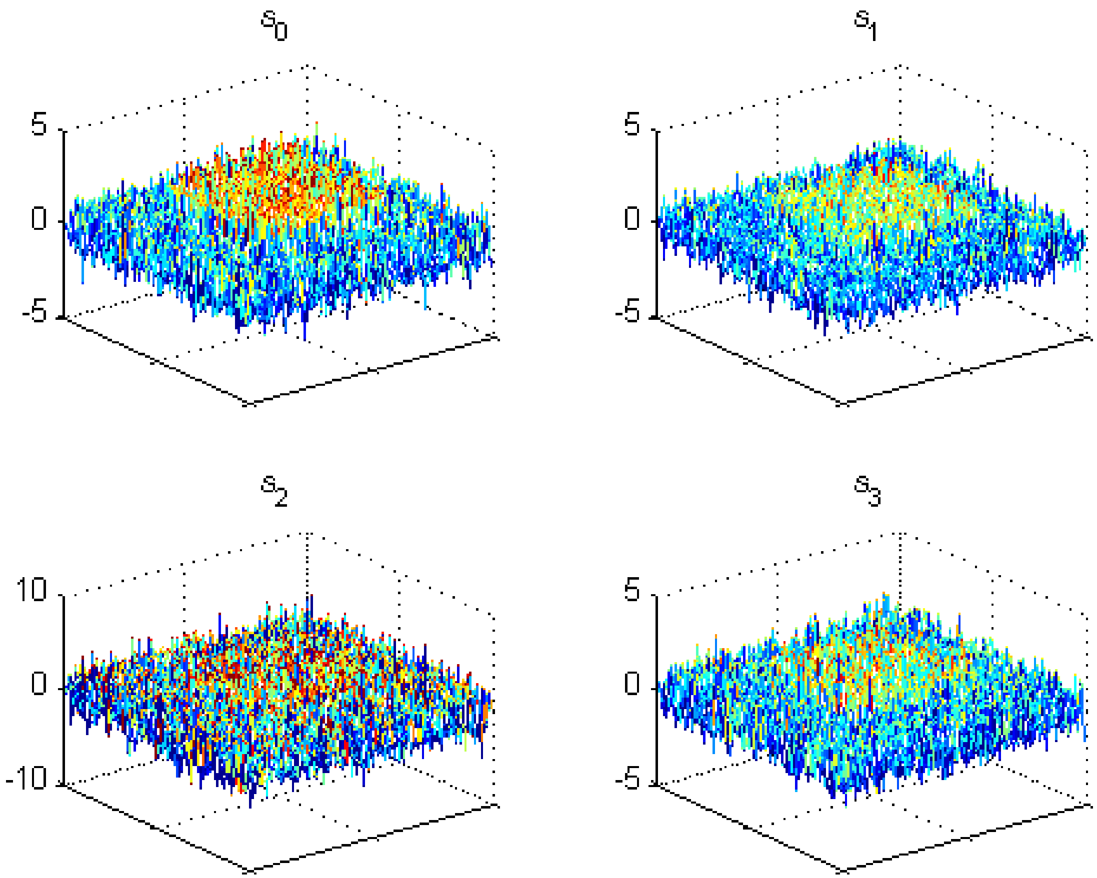
B is termed the "Synthesis Matrix" as it is used to reconstruct the Stokes Parameters

Simulated Images

$$\mathbf{S} = \begin{bmatrix} \sqrt{3} \\ 1 \\ 1 \\ 1 \end{bmatrix}$$



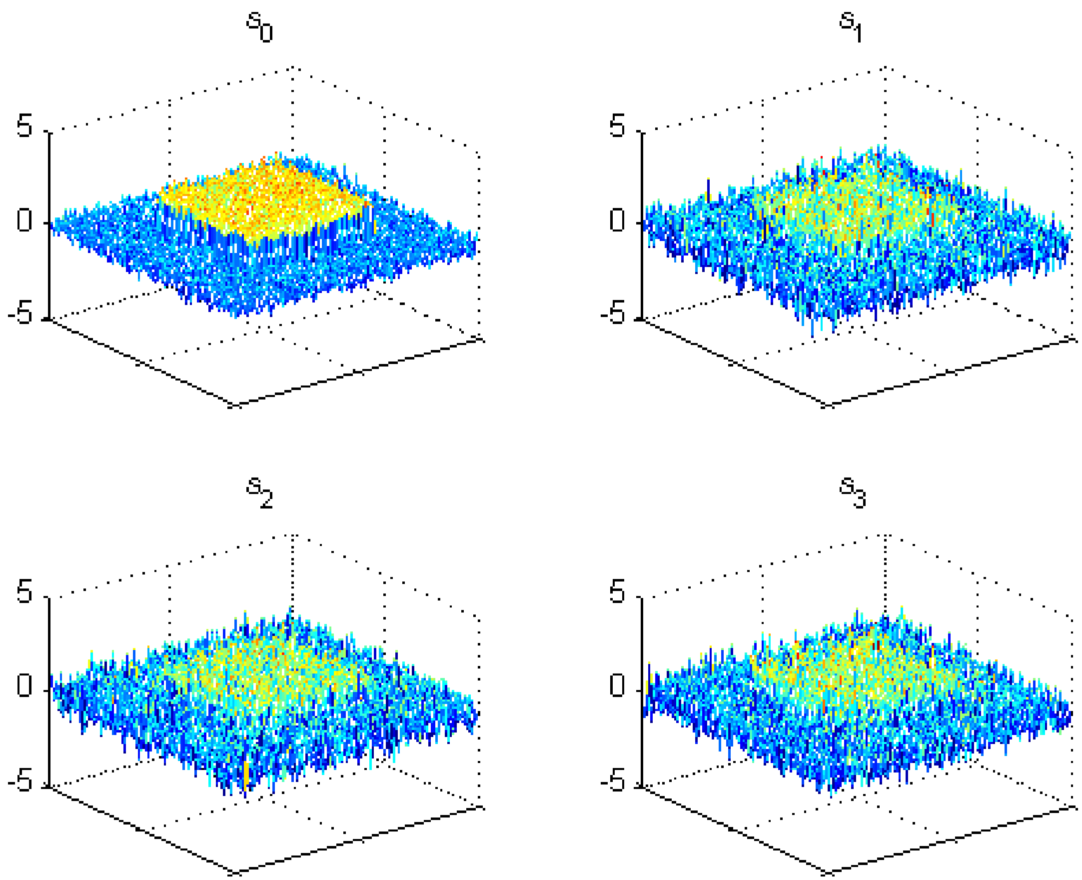
Simulated Images - Original Parameters



$$\langle \mathbf{S} \rangle = \begin{bmatrix} 1.74 \\ 0.99 \\ 0.98 \\ 1.00 \end{bmatrix}$$

$$\mathrm{var}(\mathbf{S}) = \begin{bmatrix} 0.59 \\ 0.43 \\ 1.93 \\ 0.60 \end{bmatrix}$$

Simulated Images - Optimized System

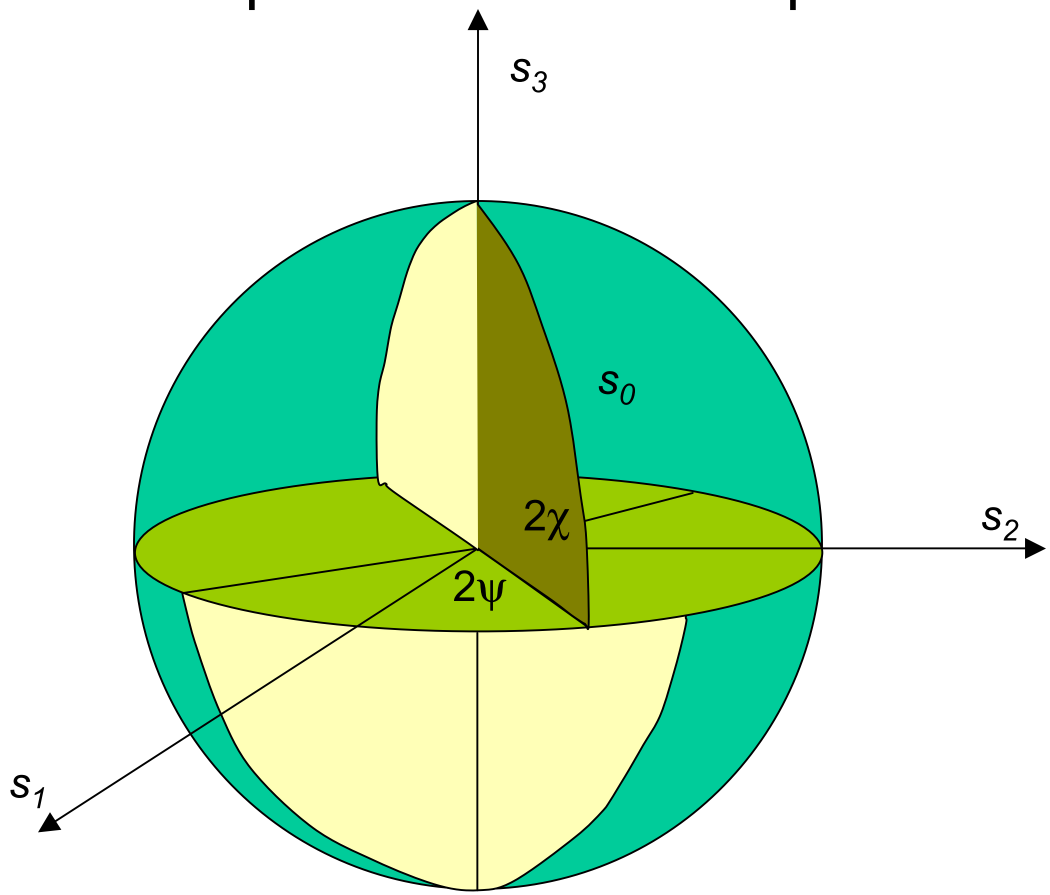


$$\langle \mathbf{S} \rangle = \begin{bmatrix} 1.73 \\ 1.00 \\ 1.00 \\ 1.00 \end{bmatrix}$$

$$\mathrm{var}(\mathbf{S}) = \begin{bmatrix} 0.10 \\ 0.29 \\ 0.31 \\ 0.30 \end{bmatrix}$$

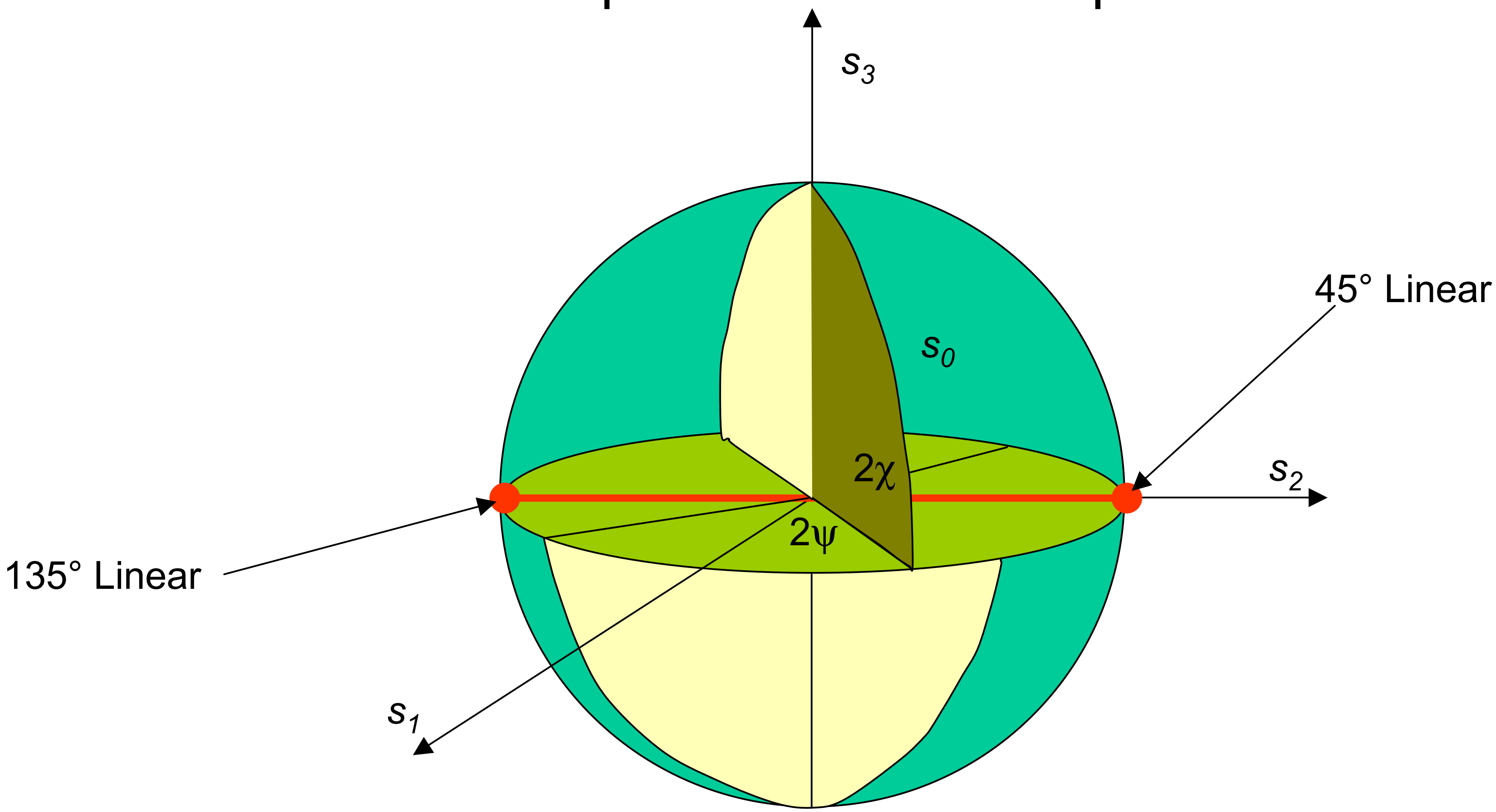
General Optimization

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere



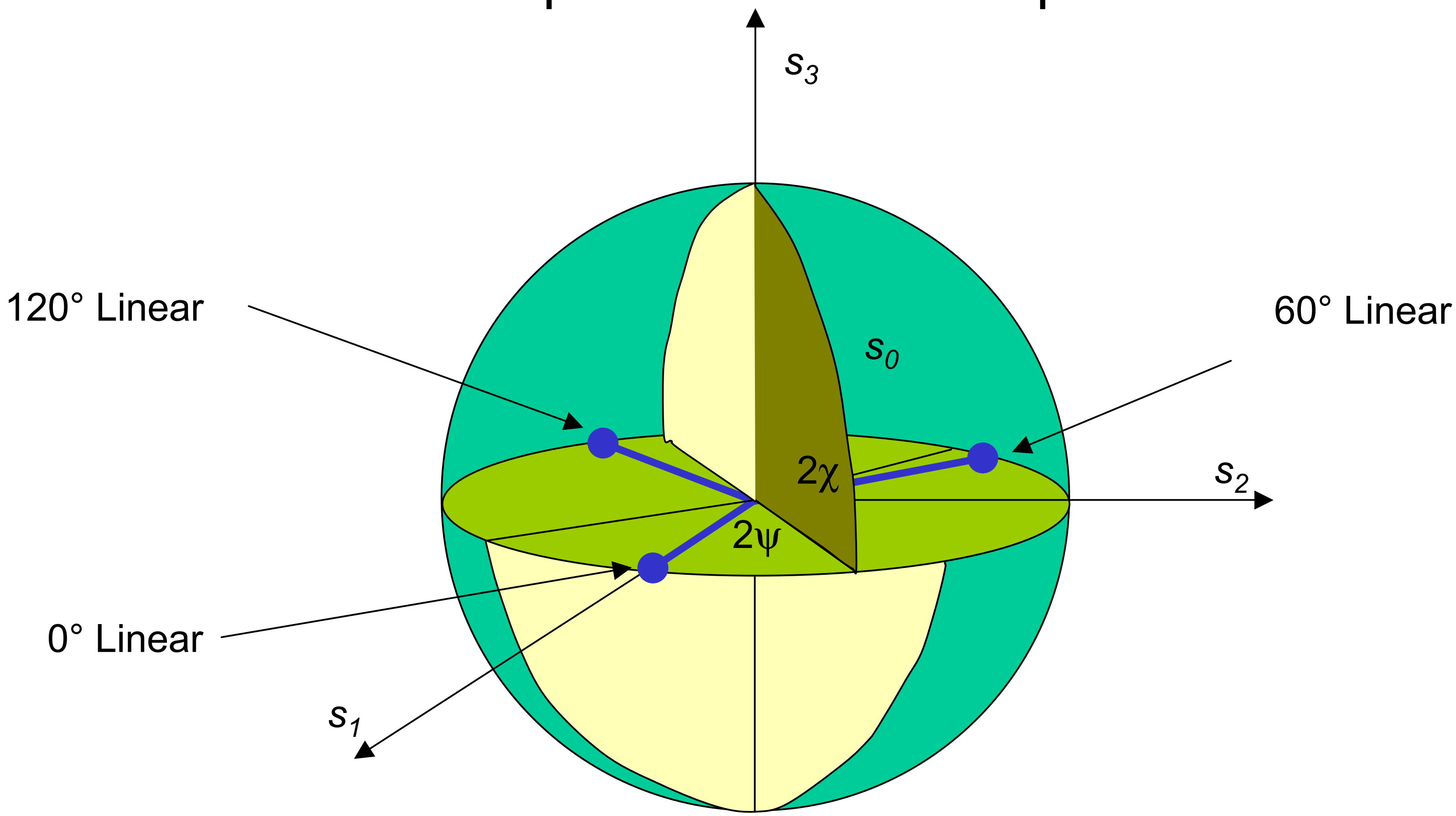
2-D Linear Polarization

Maximum Possible Separation of Measurements
in Subspace of Poincaré Sphere



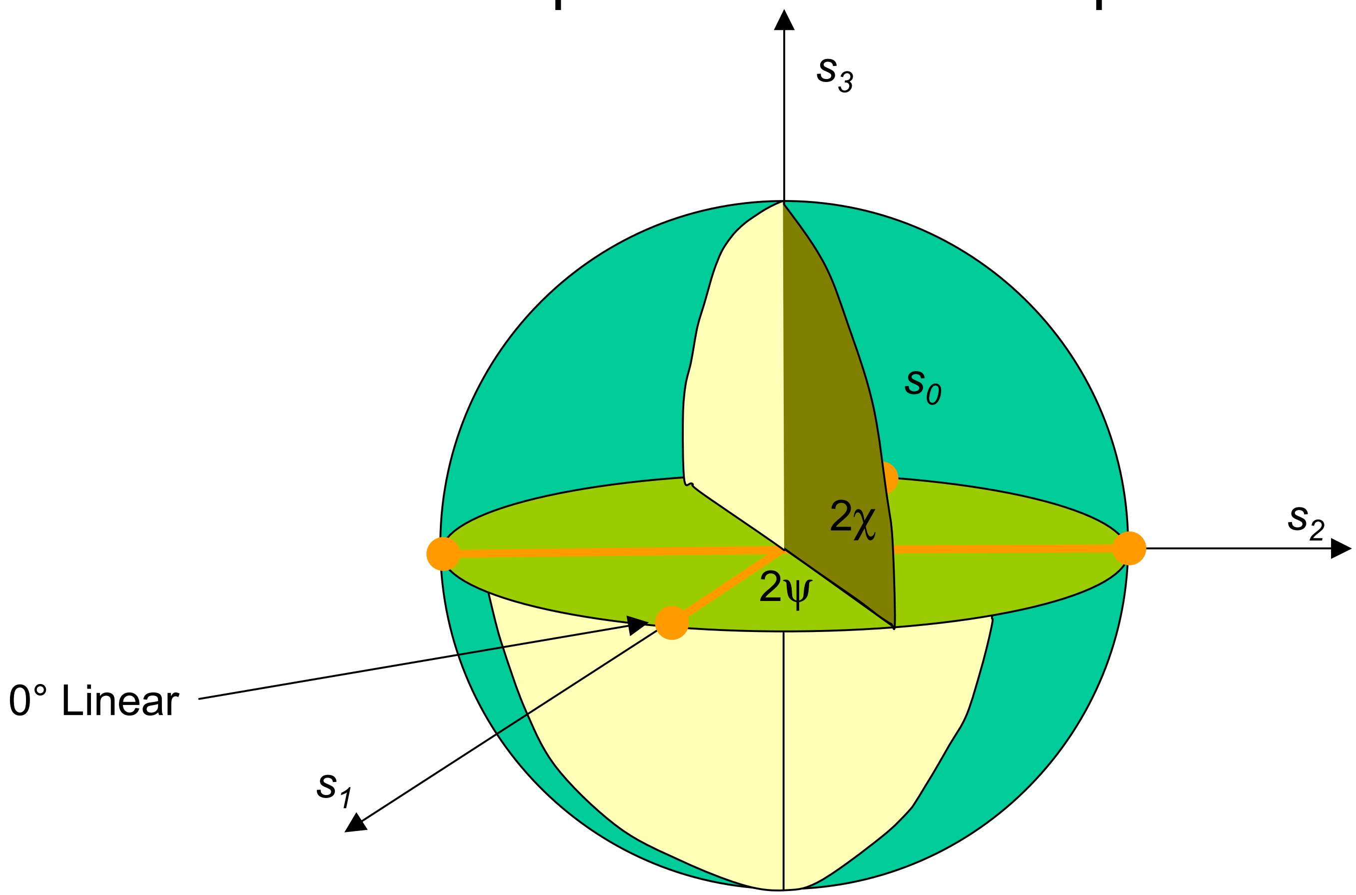
3-D Linear

Maximum Possible Separation of Measurements in Subspace of Poincaré Sphere



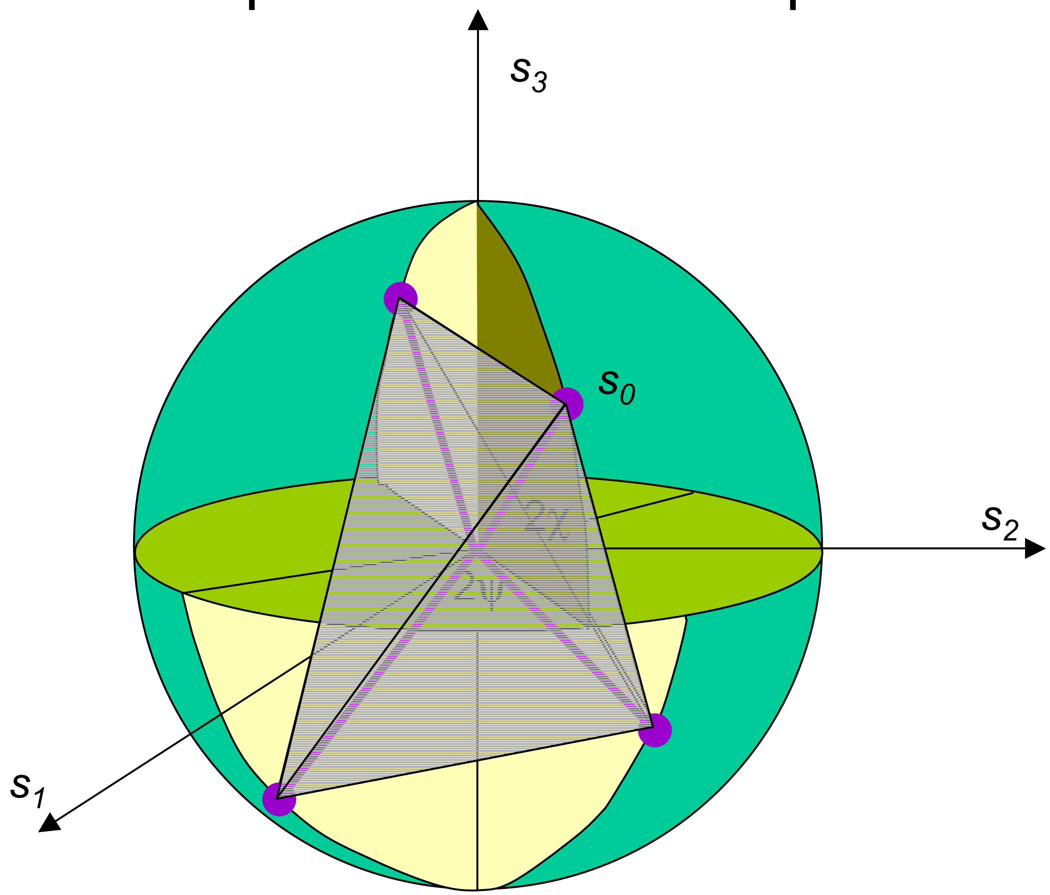
3-D Linear, 4 Measurements

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

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2. Ambirijan and Look "Optimum angles for a polarimeter: Part I," *Opt. Eng.* **34**: 1651 (1995)
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4. Tyo, "Optimum Linear Combination Strategy For A *N*-Channel Polarization Sensitive Vision Or Imaging System," *JOSA A* **15**:359 (1998)
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7. Polarimeter," *Opt. Lett.* **25**:802 (2000)
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9. Tyo, "Design of optimal polarimers: maximization of SNR and minimization of systematic errors," *Appl. Opt.* **41**:619 (2002)
10. Smith, "Optimization of a dual-rotating-retarder Mueller matrix polarimeter," *Appl. Opt.* **41**:2488 (2002)

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)
  - Rotating Compensator (Ambirajan and Look, 1995; Sweatt, *et al.*, 1999)