SALSA: Full Stokes Polarization camera - Spatial inhomogeneity and field calibration

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Bossa Nova Tech

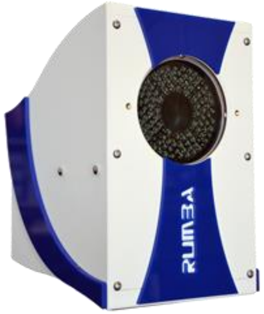
Company Overview

- Located in Los Angeles (Culver City), CA, USA
- Founded in 2002
- Small business of 7 people specialized in optics, electronics, imaging and software development
- Manufacturer of scientific and testing equipment : laser ultrasonic inspection equipment, polarization cameras and systems for the cosmetic testing
- Provides research for NASA, NSF, DoD and corporate clients

Bossa Nova Tech

Polarization imaging products

Bossa Nova Technologies provides *products* and *services* for non-destructive testing.

3 lines of products:

- **Polarization Imaging**
  SAMBA, SALSA, RUMBA & POLKA
- **Cosmetic Testing Equipment (Hair & Face)**
- **Laser Ultrasonics**
  TEMPO, QUARTET
  LU Systems


Our Objective was to develop a camera that is:

- COMPACT!

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- Uses off the shelf components

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- COMPACT!

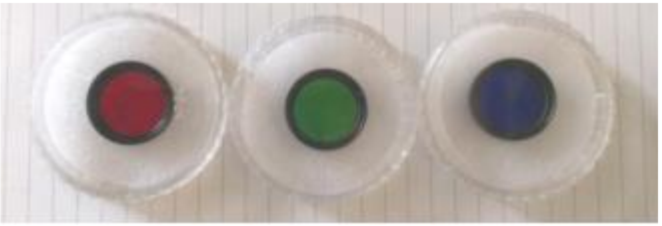
- Uses off the shelf components
- Turn-key system

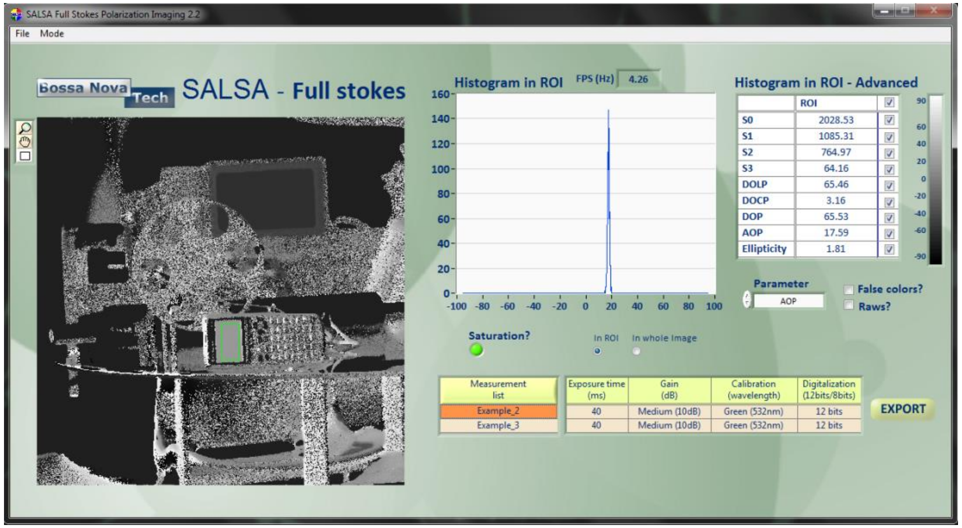
- At reasonable cost AND profitable!

SALSA: Full Stokes Polarization camera

Complete turn-key system:

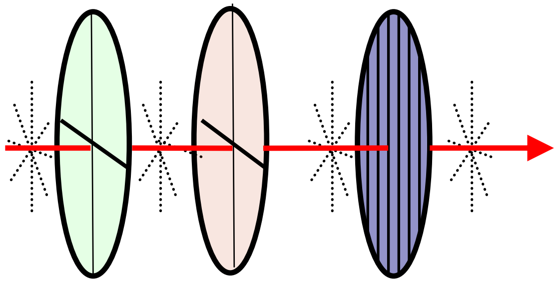
- Camera
- C-mount lens ready
- Controller
- Laptop
- Software
- SDK (LabVIEW)





Technology: *2 FLCs, 1 Analyser*

PSA: State 1

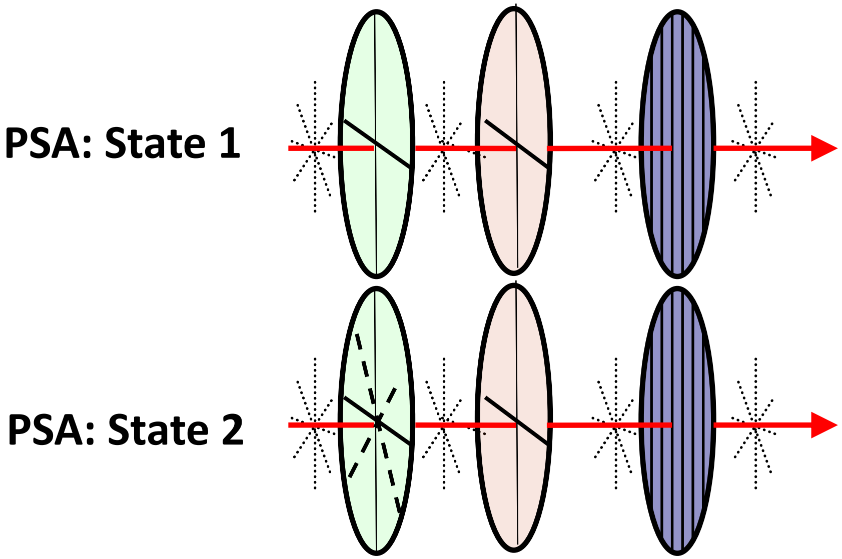


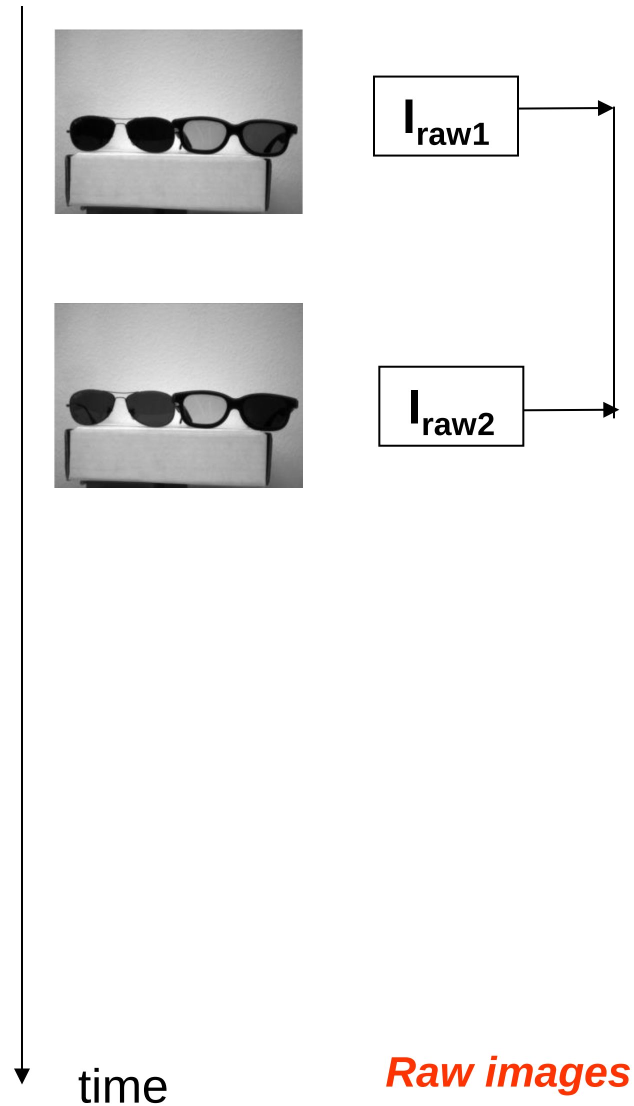
I_{raw1}

Raw images

time

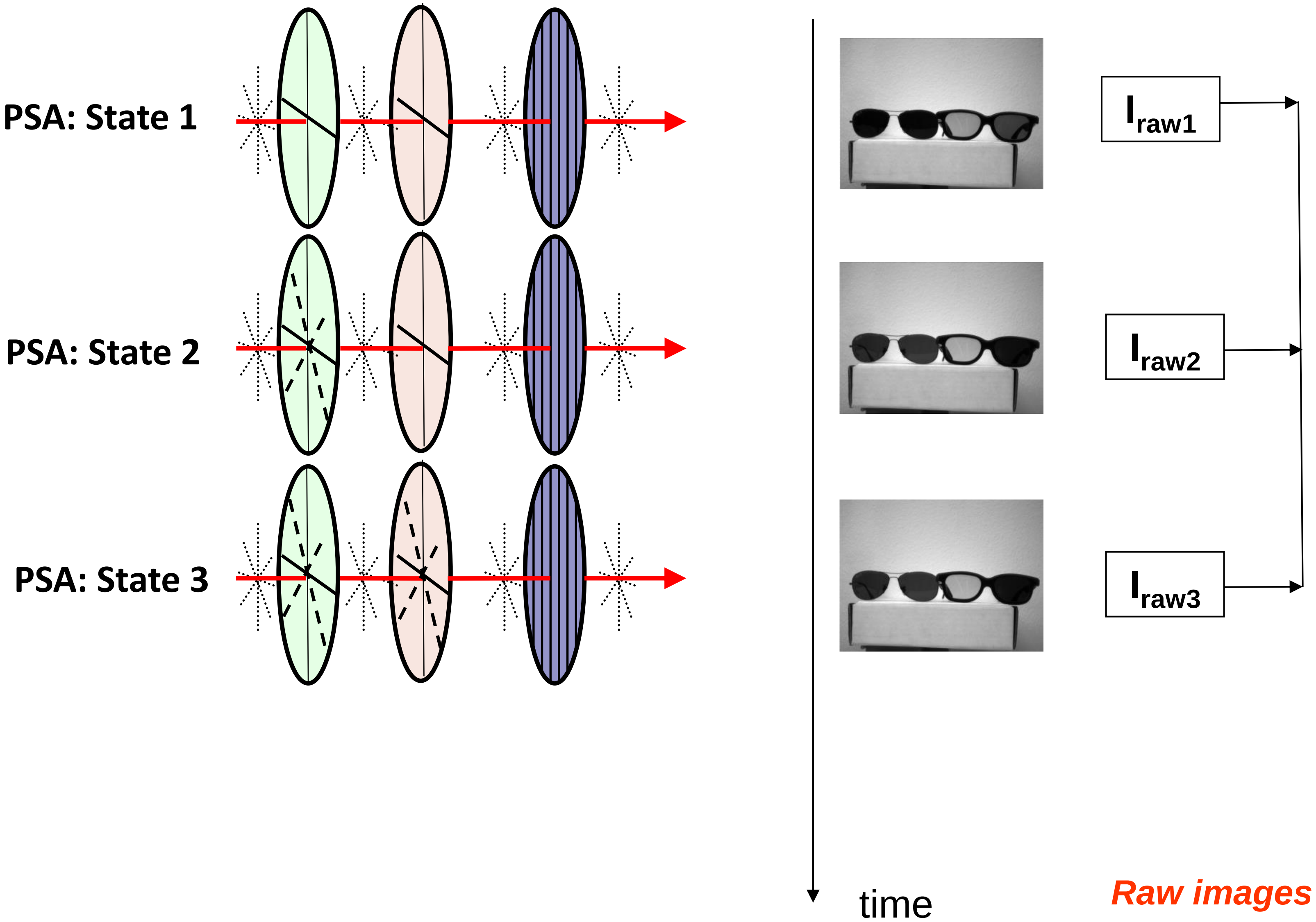
Technology: *2 FLCs, 1 Analyser*





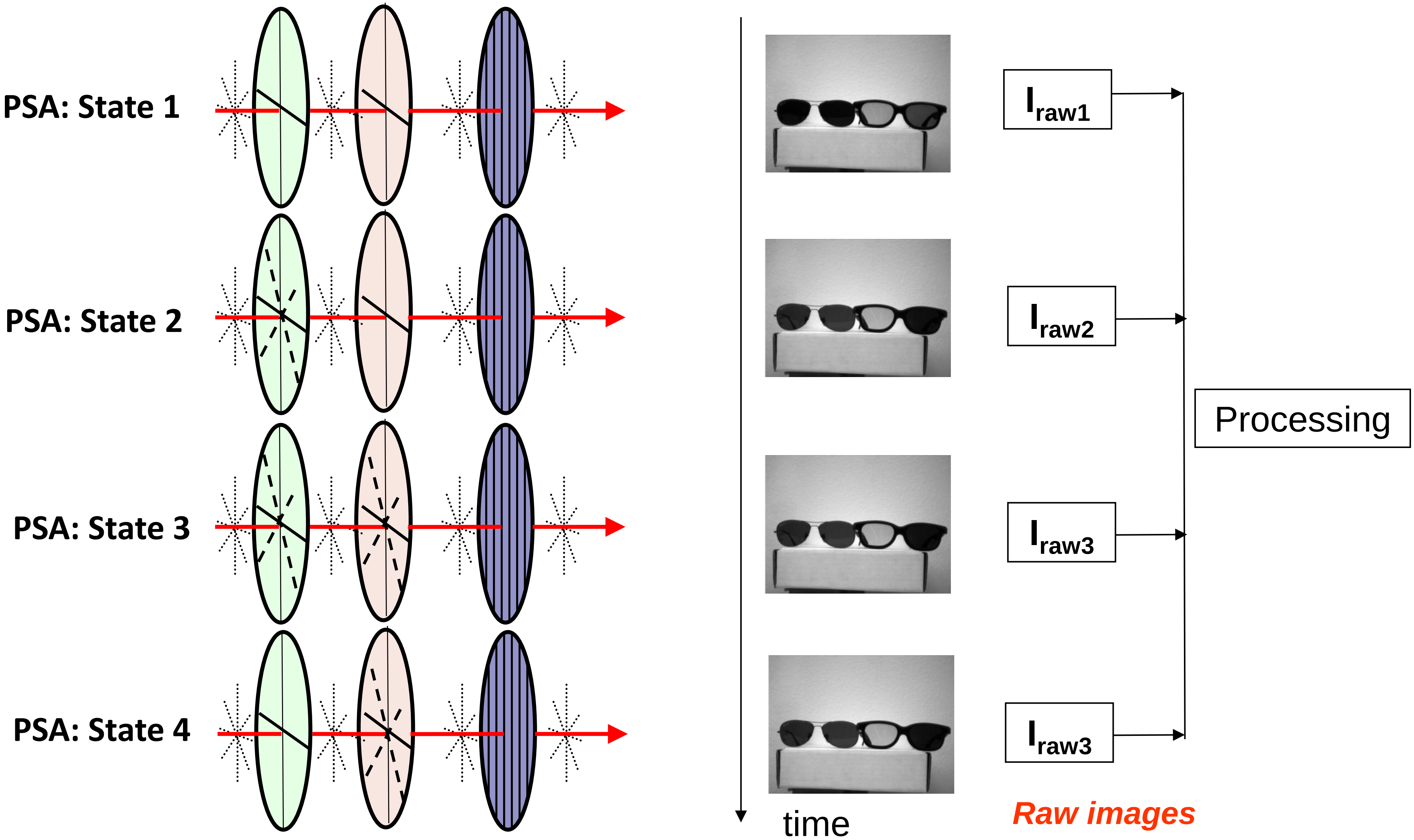
SALSA Technology

Technology: *2 FLCs, 1 Analyser*



SALSA Technology

Technology: *2 FLCs, 1 Analyser*



Technology -2

$$\mathbf{X} = \begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix} = \mathbf{C} \cdot \begin{bmatrix} S_{0,in} \\ S_{1,in} \\ S_{2,in} \\ S_{3,in} \end{bmatrix}$$

Images acquired

Incident Stokes vector

Technology -2

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Images acquired

Incident Stokes vector

Incident Stokes vector estimate

Calibration

SALSA Technology

Technology -2

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Incident Stokes vector estimate

Calibration

S_0 S_1 S_2 S_3

Deduction of the 4 Stokes parameters!

Mathematical model

*Data Reduction Matrix (DRM) **

$$\mathbf{X} = \begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix} = \mathbf{C} \cdot \begin{bmatrix} S_{0,in} \\ S_{1,in} \\ S_{2,in} \\ S_{3,in} \end{bmatrix} \quad \Rightarrow \quad \widehat{S_{in}} = C^{-1} \cdot \begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix}$$

Images acquired

Incident Stokes vector

Incident Stokes vector estimate

DRM

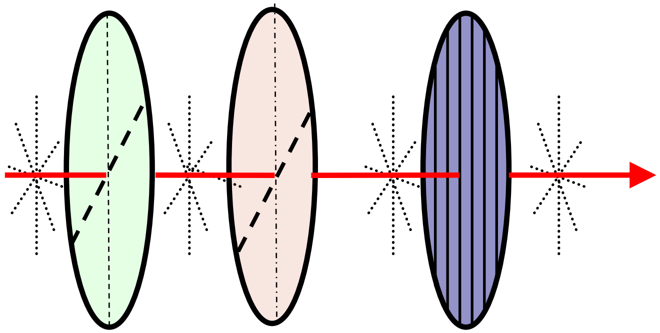
➢ Experimental determination of the DRM

*R. A. Chipman, “Polarimetry,” in Handbook of Optics, Vol. 2, Chap. 22.

Schott Tyo J. *et al*, "Review of passive imaging polarimetry for remote sensing applications", Applied Optics, Vol. 45, N22.

Mathematical model

PSA Mueller matrices



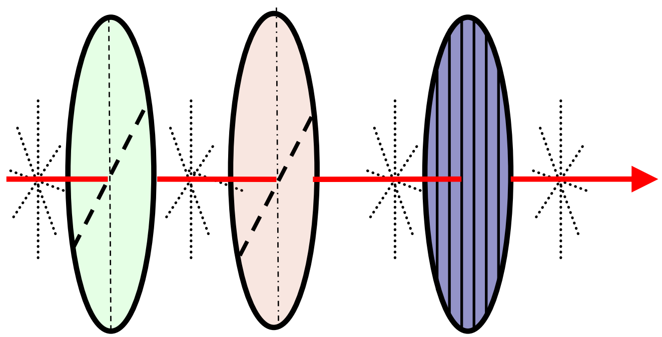
$$S_{out}^{state\ i} = \begin{bmatrix} S_{0,out}^{i} \\ S_{1,out}^{i} \\ S_{2,out}^{i} \\ S_{3,out}^{i} \end{bmatrix} = \begin{bmatrix} m_{00}^{state\ i} & m_{01}^{state\ i} & m_{02}^{state\ i} & m_{03}^{state\ i} \\ m_{10}^{state\ i} & m_{11}^{state\ i} & m_{12}^{state\ i} & m_{13}^{state\ i} \\ m_{20}^{state\ i} & m_{21}^{state\ i} & m_{22}^{state\ i} & m_{23}^{state\ i} \\ m_{30}^{state\ i} & m_{31}^{state\ i} & m_{32}^{state\ i} & m_{33}^{state\ i} \end{bmatrix} \cdot \begin{bmatrix} S_{0,in} \\ S_{1,in} \\ S_{2,in} \\ S_{3,in} \end{bmatrix}$$

Polarization State Analyzer in position **i**, **i**={0;1;2;3}

Mueller matrix for the i*th* state of the PSA

Mathematical model

PSA Mueller matrices



Polarization State Analyzer in position **i**, **i**={0;1;2;3}

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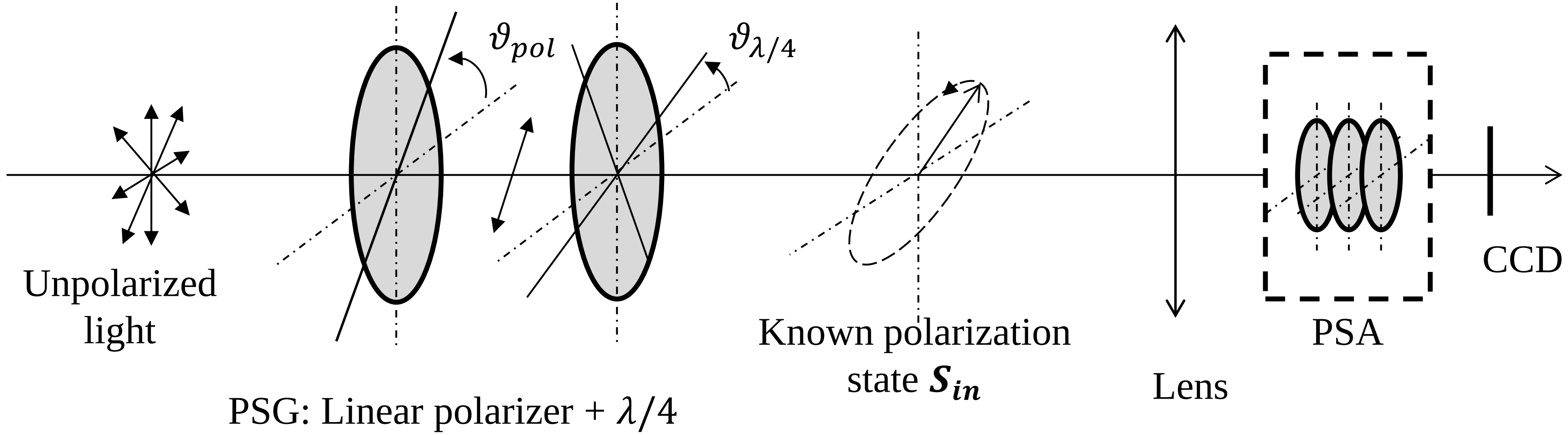
Mueller matrix for the **i***th* state of the PSA

Detectors are only sensitive to the intensity of light

$$S_{0,out}^{PSAi} = m_{00}^{i}.S_{0,in} + m_{01}^{i}.S_{1,in} + m_{02}^{i}.S_{2,in} + m_{03}^{i}.S_{3,in}$$

Experimental setup



$$\Rightarrow \begin{bmatrix} S_{0,out}^{0} \\ S_{0,out}^{1} \\ \vdots \\ S_{0,out}^{N} \end{bmatrix}_i = \begin{bmatrix} S_{0,in}^{0} & S_{1,in}^{0} & S_{2,in}^{0} & S_{3,in}^{0} \\ S_{0,in}^{1} & S_{1,in}^{1} & S_{2,in}^{1} & S_{3,in}^{1} \\ \vdots & \vdots & \vdots & \vdots \\ S_{0,in}^{N} & S_{1,in}^{N} & S_{2,in}^{N} & S_{3,in}^{N} \end{bmatrix} . \begin{bmatrix} m_{00}^{state\ i} \\ m_{01}^{state\ i} \\ m_{02}^{state\ i} \\ m_{03}^{state\ i} \end{bmatrix}$$

N Linear equations: possible estimation of the $m_{0,l}^{i}$ parameters

Data Reduction Matrix

State i={0;1;2;3}

$$\begin{bmatrix} m_{00}^{state\ i} \\ m_{01}^{state\ i} \\ m_{02}^{state\ i} \\ m_{03}^{state\ i} \end{bmatrix} = [(S_{in})^T]^+ \cdot \begin{bmatrix} S_{0,out}^{0} \\ S_{0,out}^{1} \\ \vdots \\ S_{0,out}^{N} \end{bmatrix}$$

Pseudo inversion

Global

$$\begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix} = \begin{bmatrix} m_{00}^{state\ 1} & m_{01}^{state\ 1} & m_{02}^{state\ 1} & m_{03}^{state\ 1} \\ m_{00}^{state\ 2} & m_{01}^{state\ 2} & m_{02}^{state\ 2} & m_{03}^{state\ 2} \\ m_{00}^{state\ 3} & m_{01}^{state\ 3} & m_{02}^{state\ 3} & m_{03}^{state\ 3} \\ m_{00}^{state\ 4} & m_{01}^{state\ 4} & m_{02}^{state\ 4} & m_{03}^{state\ 4} \end{bmatrix} \cdot S_{in}$$

PSA matrix

Data Reduction Matrix

$$\begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix} = \begin{bmatrix} m_{00}^{state\ 1} & m_{01}^{state\ 1} & m_{02}^{state\ 1} & m_{03}^{state\ 1} \\ m_{00}^{state\ 2} & m_{01}^{state\ 2} & m_{02}^{state\ 2} & m_{03}^{state\ 2} \\ m_{00}^{state\ 3} & m_{01}^{state\ 3} & m_{02}^{state\ 3} & m_{03}^{state\ 3} \\ m_{00}^{state\ 4} & m_{01}^{state\ 4} & m_{02}^{state\ 4} & m_{03}^{state\ 4} \end{bmatrix} \cdot S_{in}$$

Numerical inversion

$$\widehat{S_{in}} = C^{-1} \cdot \begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix}$$

Incident Stokes vector estimate

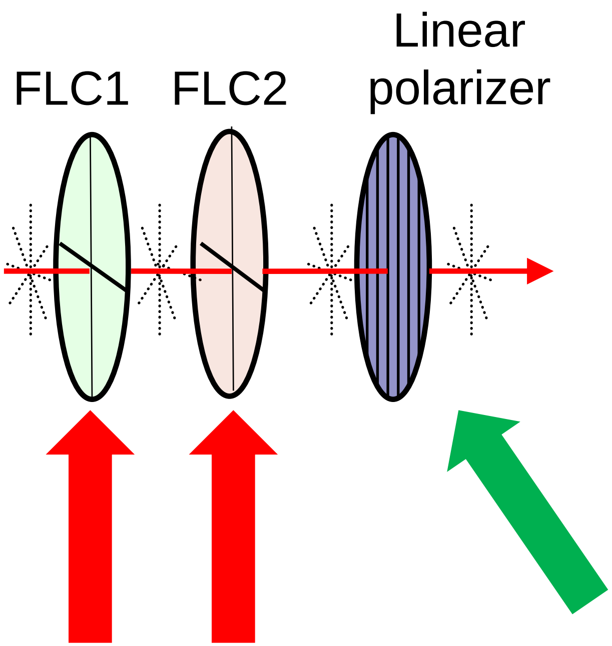
DRM

Measured intensities

Optimization of Condition Number?

$$\widehat{S_{in}} = C^{-1} \cdot \begin{bmatrix} I_{raw1} \\ I_{raw2} \\ I_{raw3} \\ I_{raw4} \end{bmatrix}$$

CN needs to be minimal

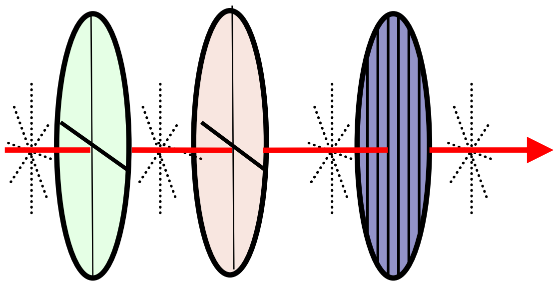


- Fixed Retardance
- Fixed Orientations

Adjustable orientation!

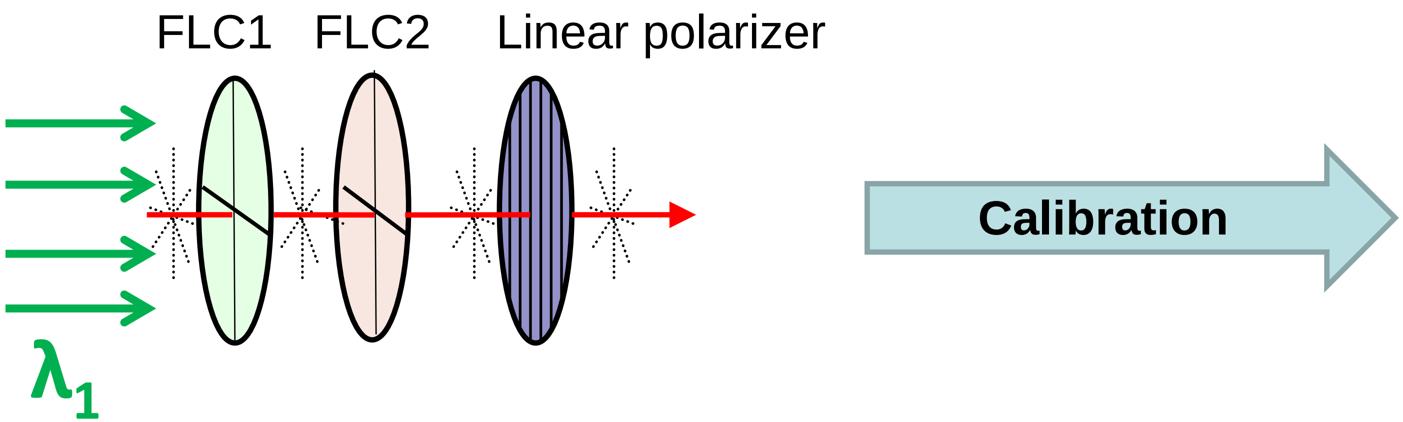
Optimization possible by adjusting the polarizer's orientation => α

Optimization of Condition Number?



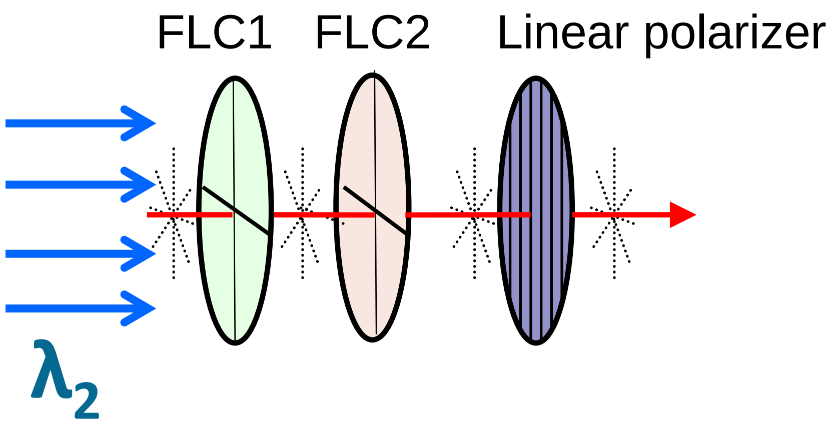
Calibration → $CN_{\alpha} \leq 2$

Optimization of Condition Number?

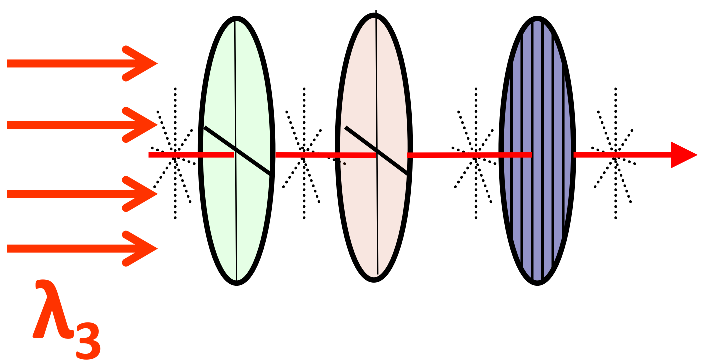


$CN_{\alpha} \leq 2$

Other wavelengths?



Calibration → CN_{α}>50!



Calibration → CN_{α} >50!

α is not optimum for all wavelengths

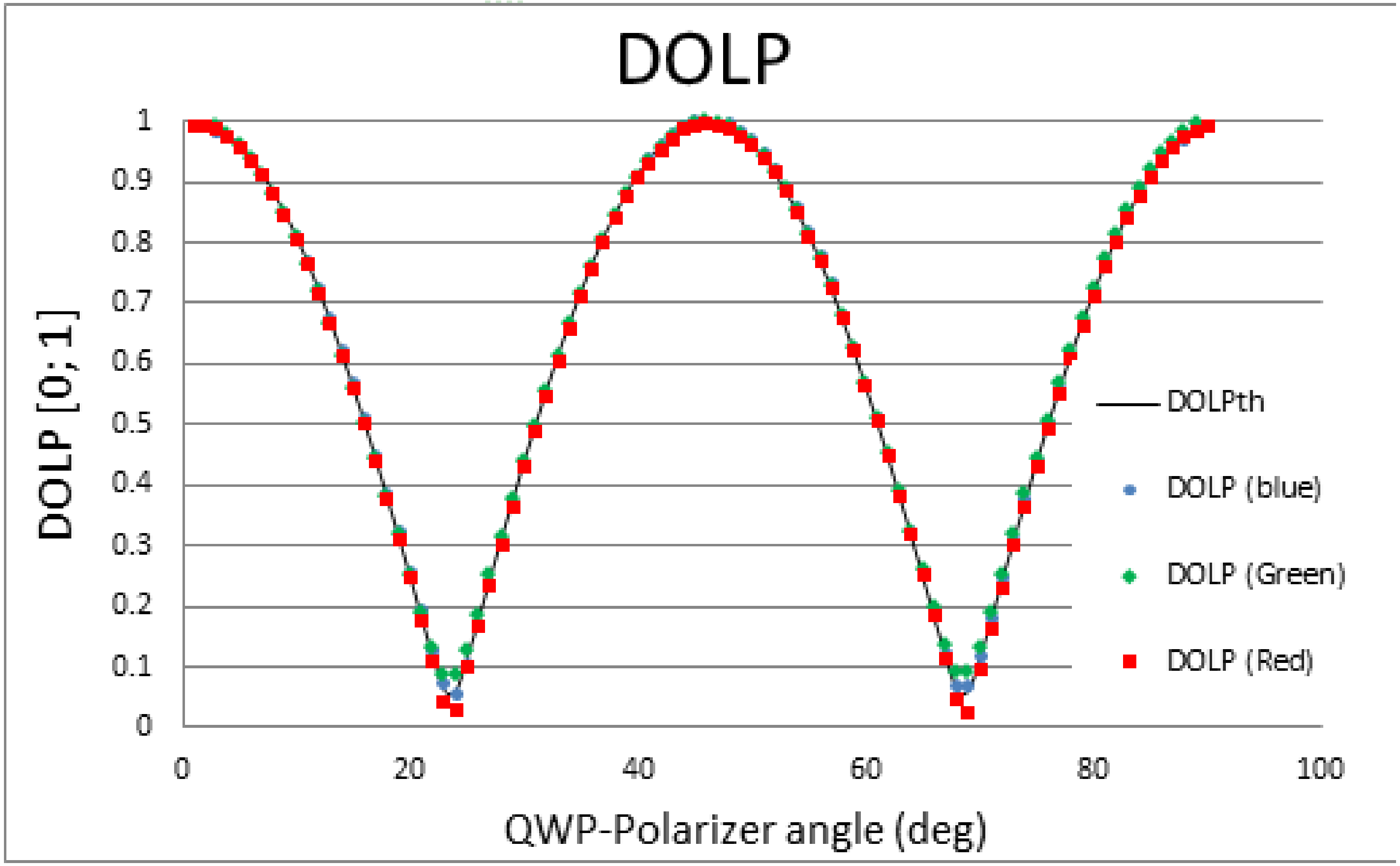
Multi-Optimization of Condition Number?

1. Characterization/model of our FLCs for each wavelength
2. Simulation of calibration procedure for each wavelength of interest
3. Optimization of polarizer orientation for each wavelength
4. Compromise angle $\alpha_{\lambda 1,\ \lambda 2,}$ …!
5. Actual calibration at $\alpha_{\lambda 1,\ \lambda 2,}$ …
6. Testing

7…

λ=[450nm…650nm] → CN ≤ 6

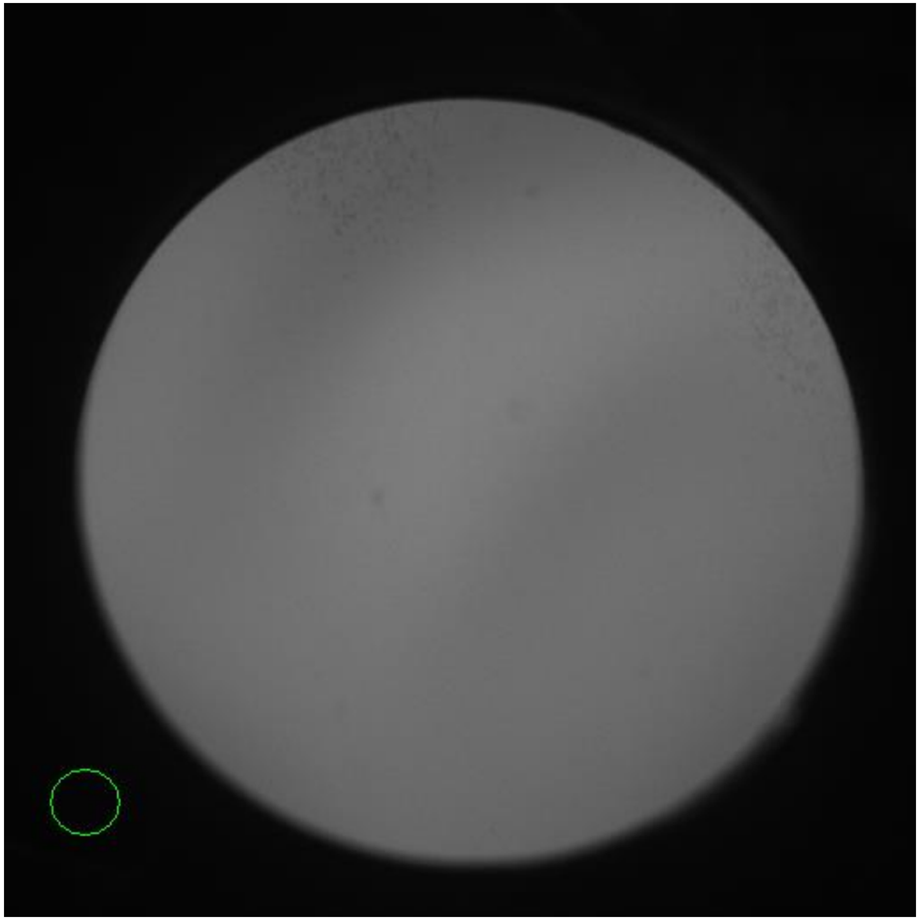
Typical Calibration accuracy



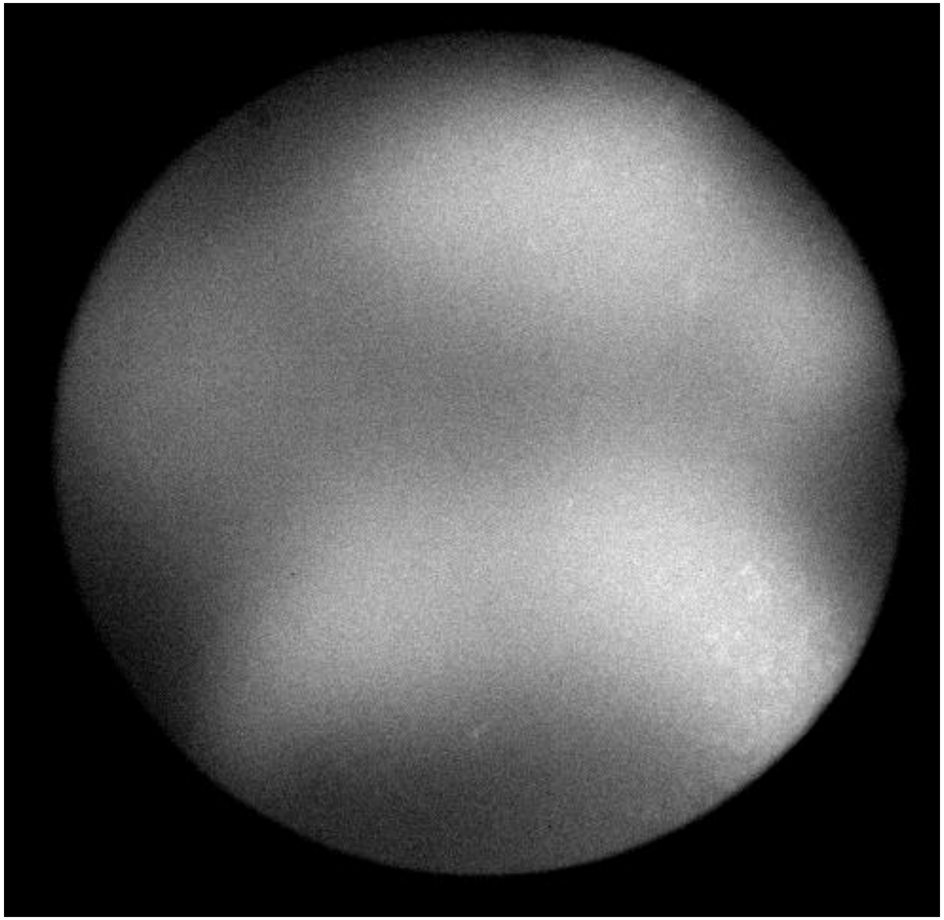
$$DOLP = \frac{\sqrt{{S_1}^2 + {S_2}^2}}{S_0}$$

Error peak-to-valley (PV): 3%

FLCs spatial inhomogeneity

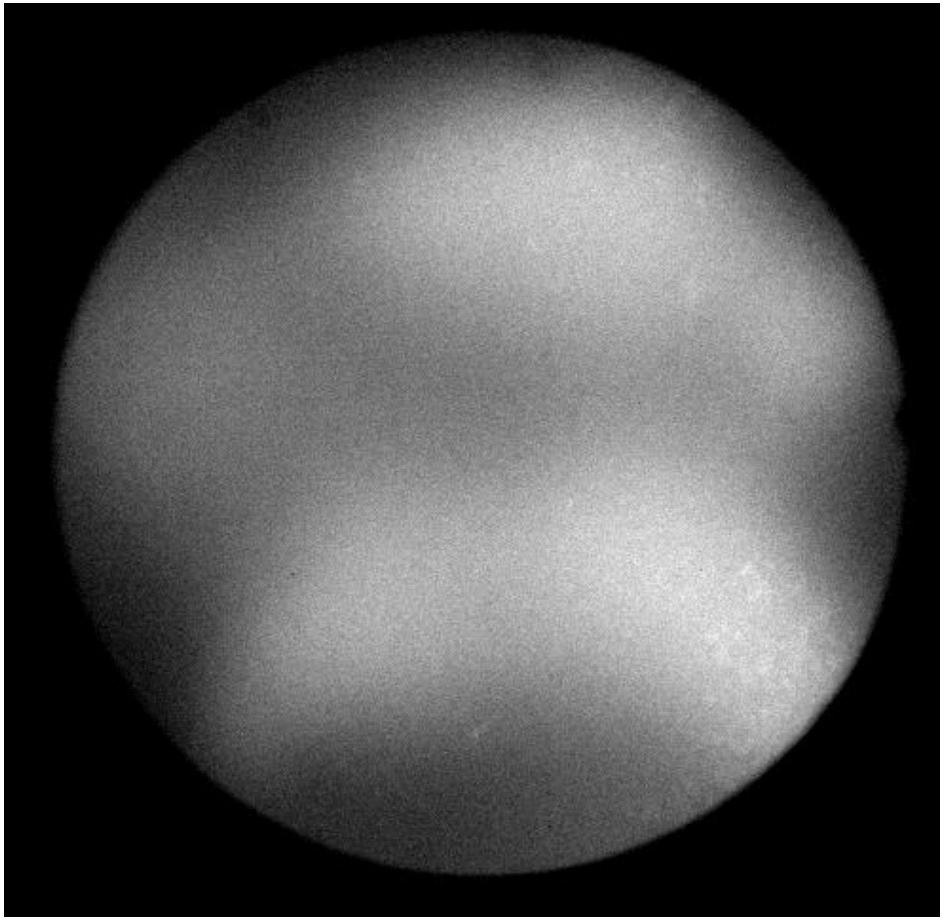


FLC between crossed polarizers



Contrast +50%

FLCs spatial inhomogeneity



Contrast +50%

- Very little data from manufacturers
- Variations up to 2% from one area to another accounts for up to +/-5% variation of DOP
- Pixel/pixel calibration not realistic for live measurement/display of polarization parameters
- Need to develop a field calibration of the FLCs
- Several approaches are being considered from basic grid decomposition to "smarter" segmentation

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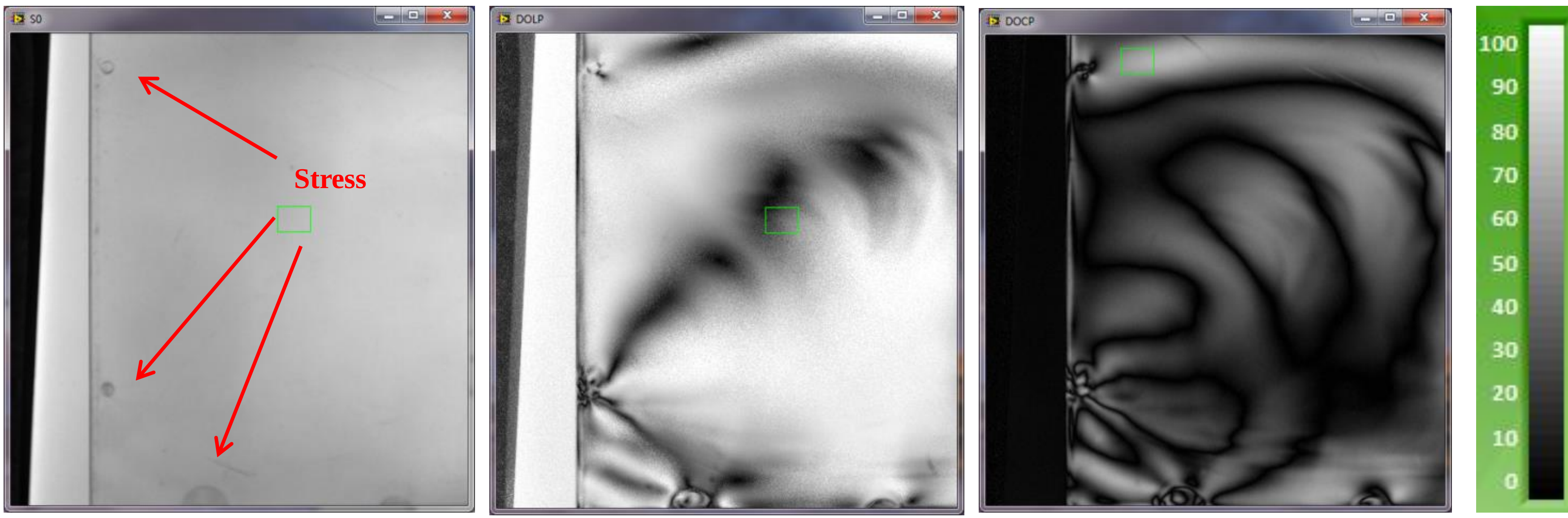
Full Stokes Polarization Imager

Example -1

Mechanical Stress on a plastic CD case

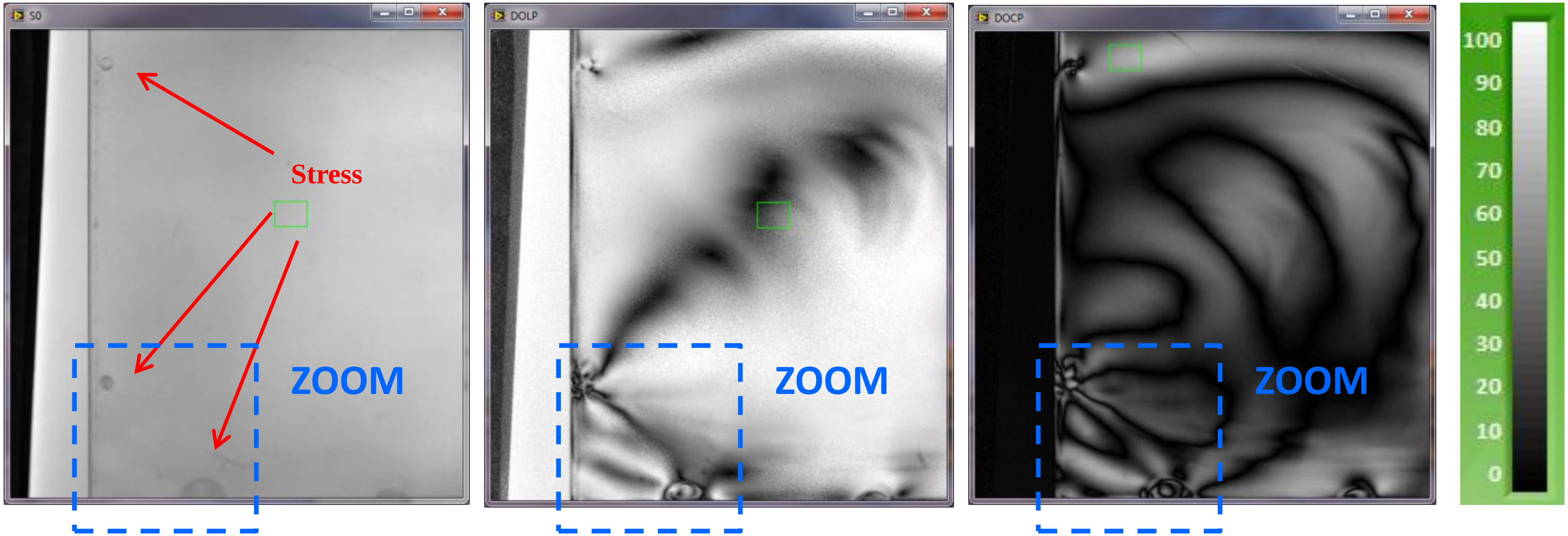


S_0 DOLP DOCP

Full Stokes Polarization Imager

Example -1

Mechanical Stress on a plastic CD case



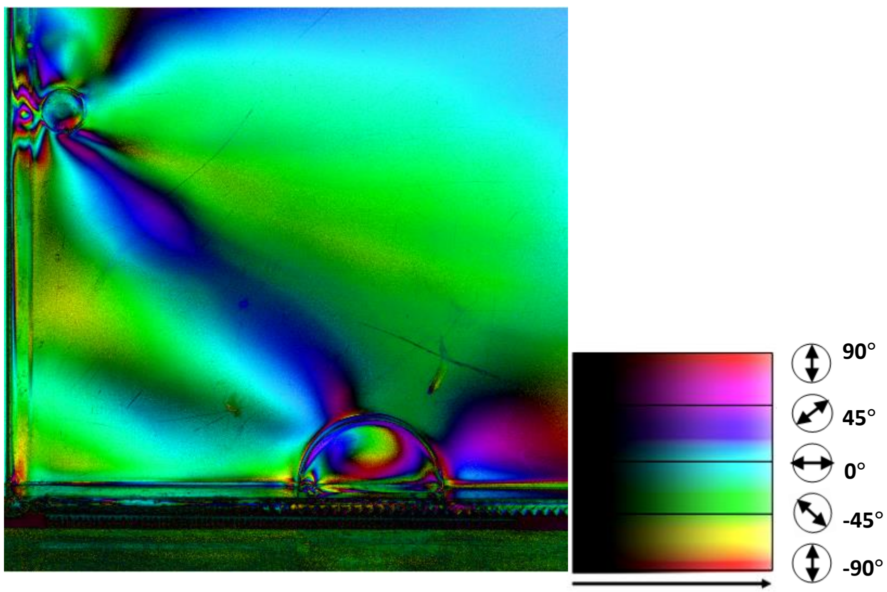
S_0 DOLP DOCP

Full Stokes Polarization Imager

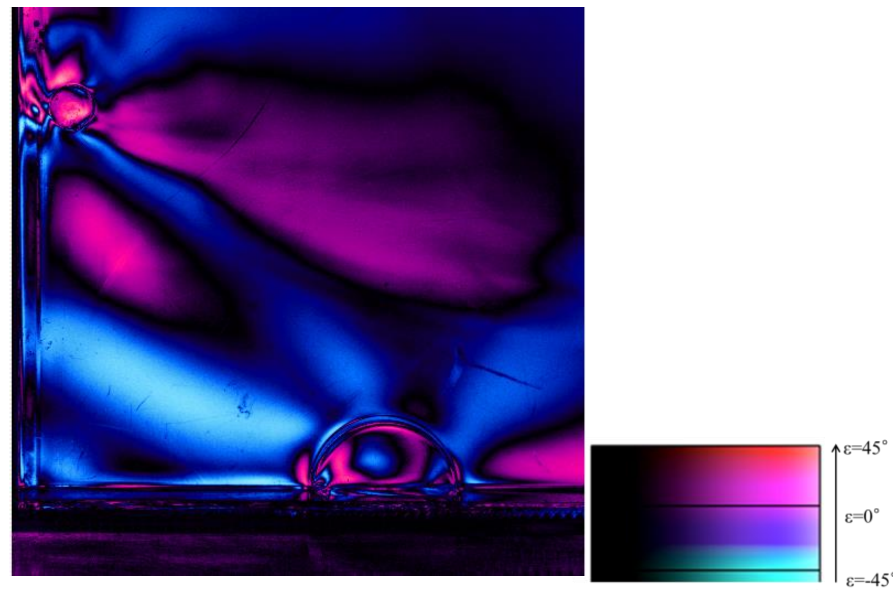
Example -1

Mechanical Stress on a plastic CD case

HSL Fusion Images



Linear polarization



Circular polarization

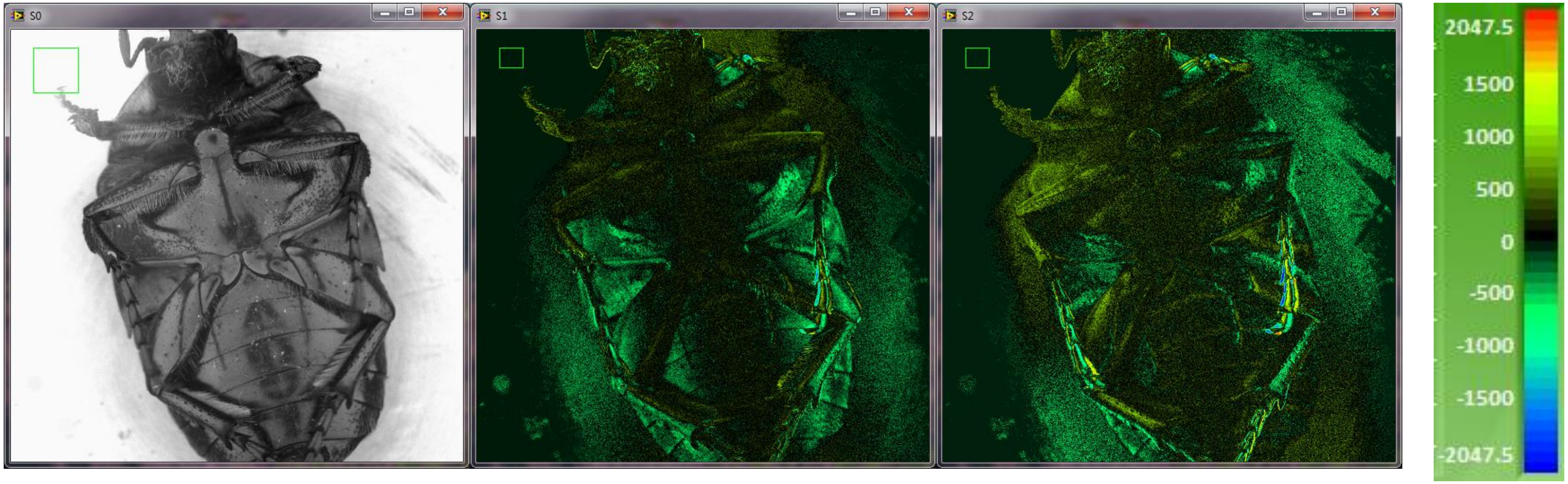
Possible to perform retardance/stress mapping!

Potential applications – Example -2

Biology measurements

Circular polarization reflected on a beetle scarab's carapace

Non polarized illumination (integrated sphere)



S_0 S_1 S_2

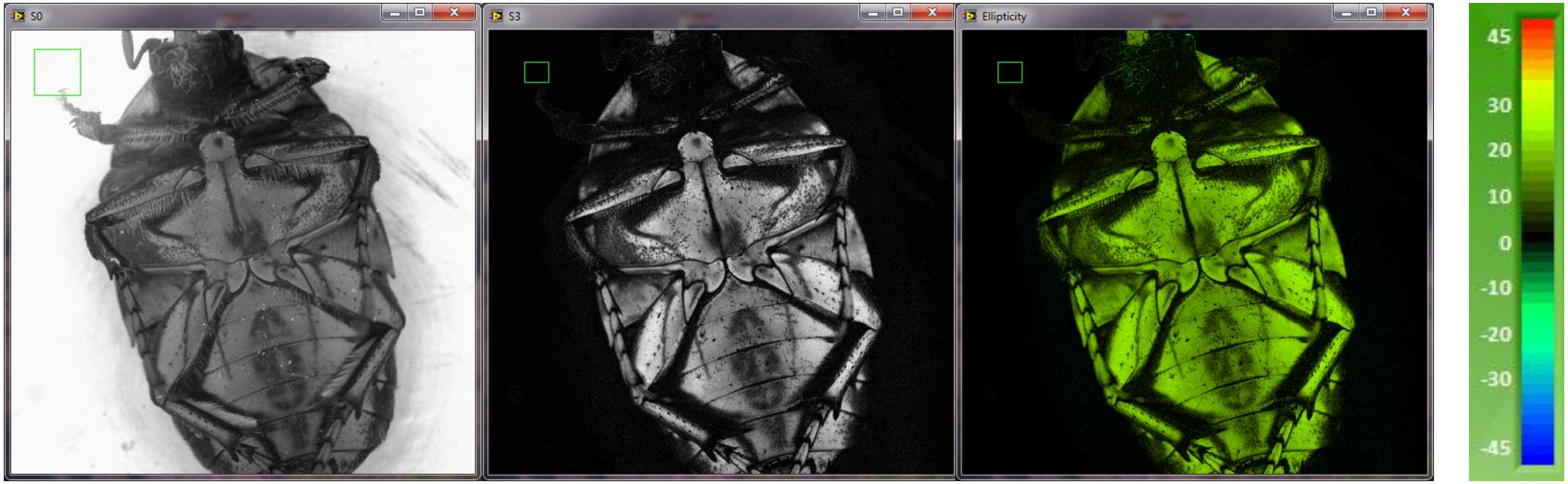
ALMOST NO <u>LINEAR</u> POLARIZATION REFLECTED

Potential applications – Example -2

Biology measurements

Circular polarization reflected on a beetle scarab's carapace

Non polarized illumination (integrated sphere)



S_0 S_3 Ellipticity

The specular reflection is elliptically polarized – left handed, DOCP≈40%, ε≈20°

Thank you!