How to optimize a polarization imager for target detection?

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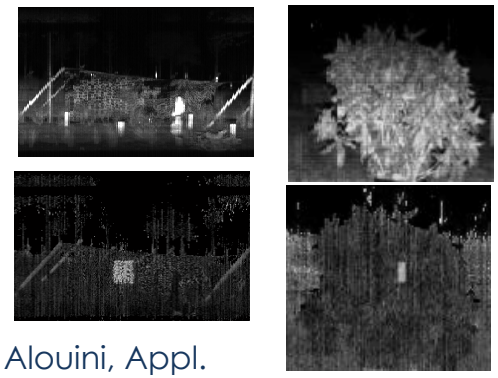
Our approach of polarimetric imaging

Objective: to **reveal contrasts** that do not appear in classical images by using **polarization properties** of scenes

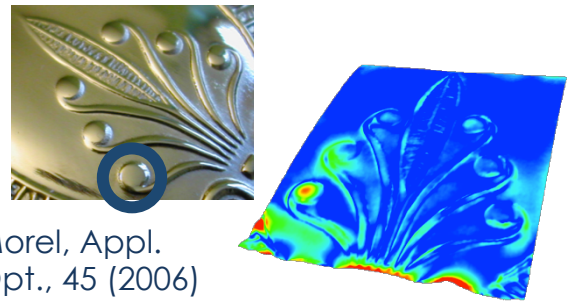
Transform **differences of polarimetric properties** into **differences of graylevel**

Decamouflaging



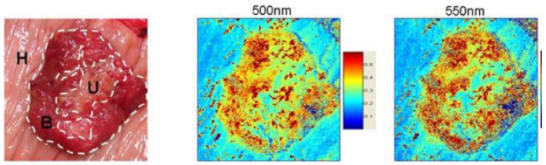
Alouini, Appl. Opt., 48 (2009)

Industrial inspection

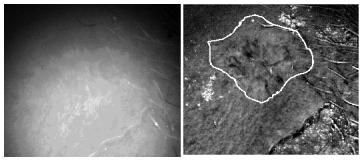


Morel, Appl. Opt., 45 (2006)

Tumor detection



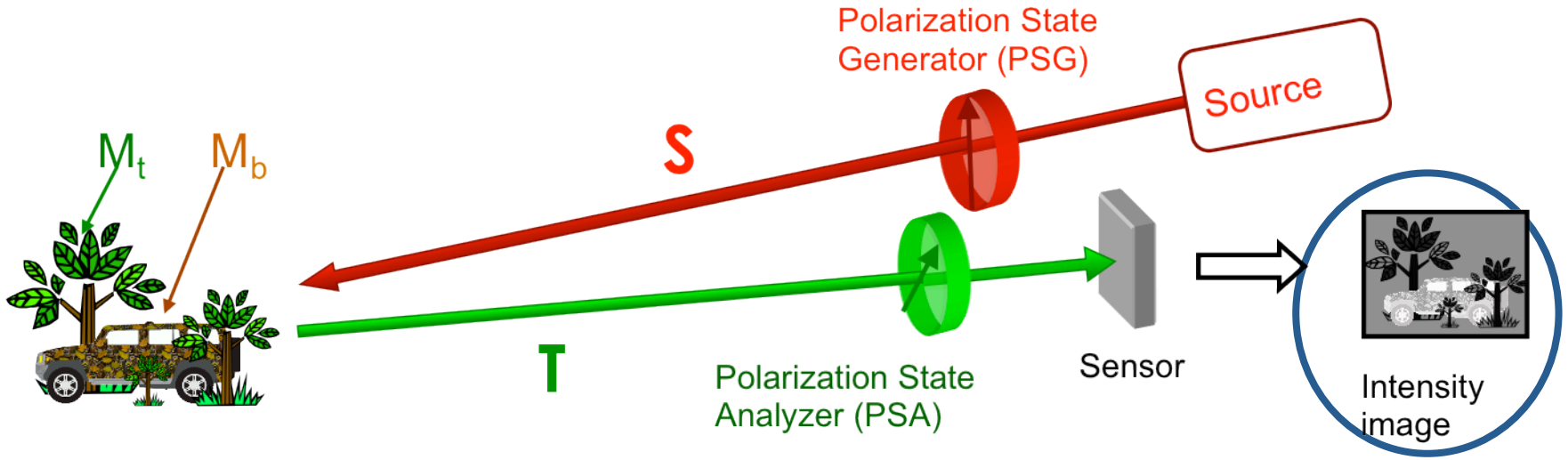
Pierangelo, Opt. Express, 19 (2011)



Jacques, J. Biomed. Opt., 7 (2002)

- our goal is not to measure polarimetric properties but to **optimize a contrast**
- **Adaptive polarimetric imaging:** adapt the polarization states to the observed scene and its variations

Active polarimetric imaging system



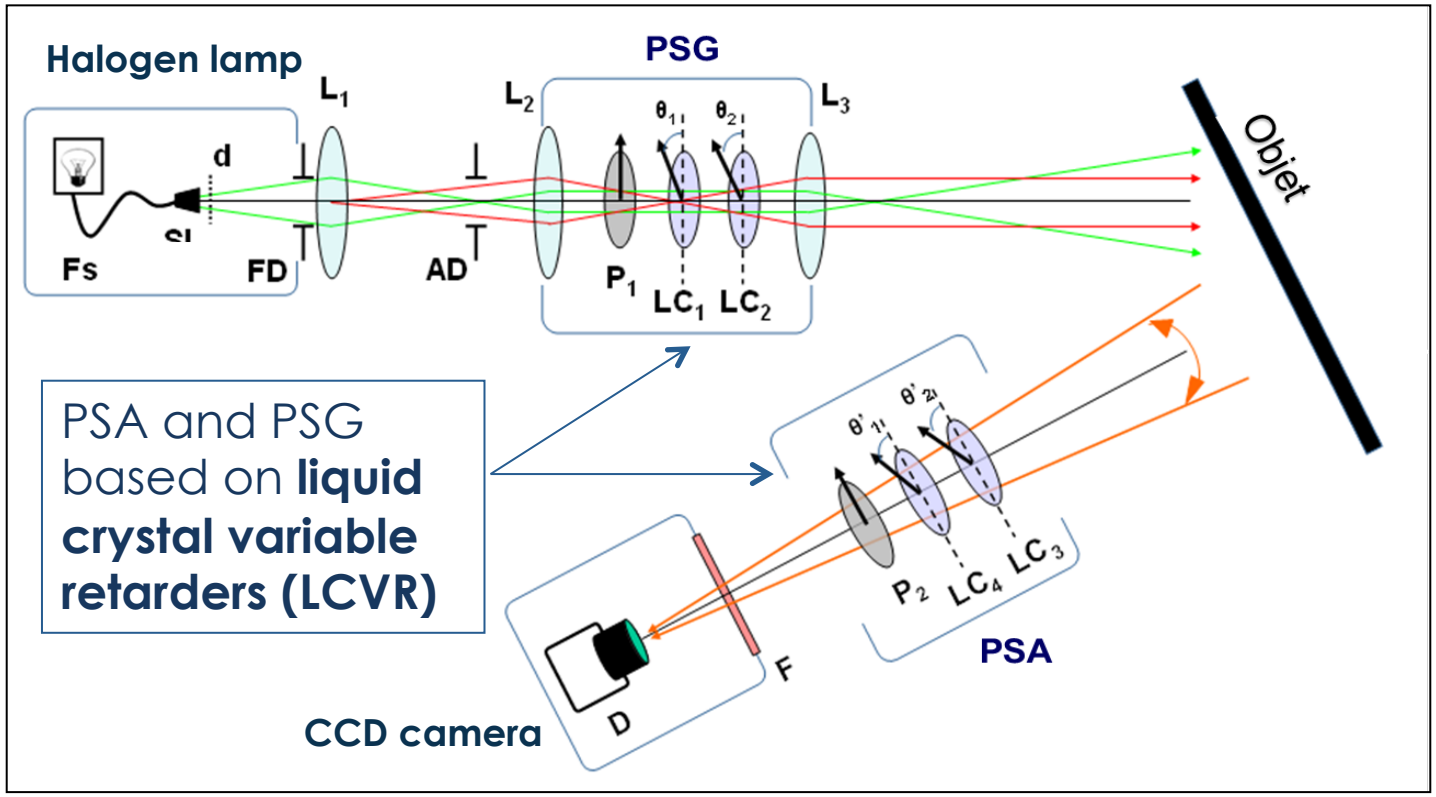
Intensity collected by one pixel seeing **Mueller matrix M_u**: $i_u \propto \mathbf{T}^t \mathbf{M}_u \mathbf{S}$

Objective: optimize the contrast by adjusting PSA and PSG

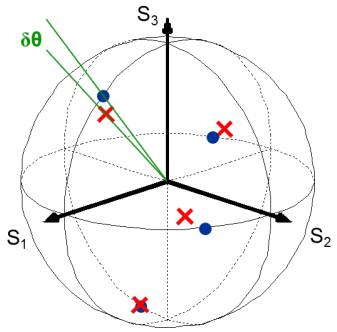
- How to build such an adaptive polarization imager?
- How to find the optimal states of PSG and PSA?
- What if nothing is known about the scene?

How to build a adaptive polarization imager?

Matlab+Labview



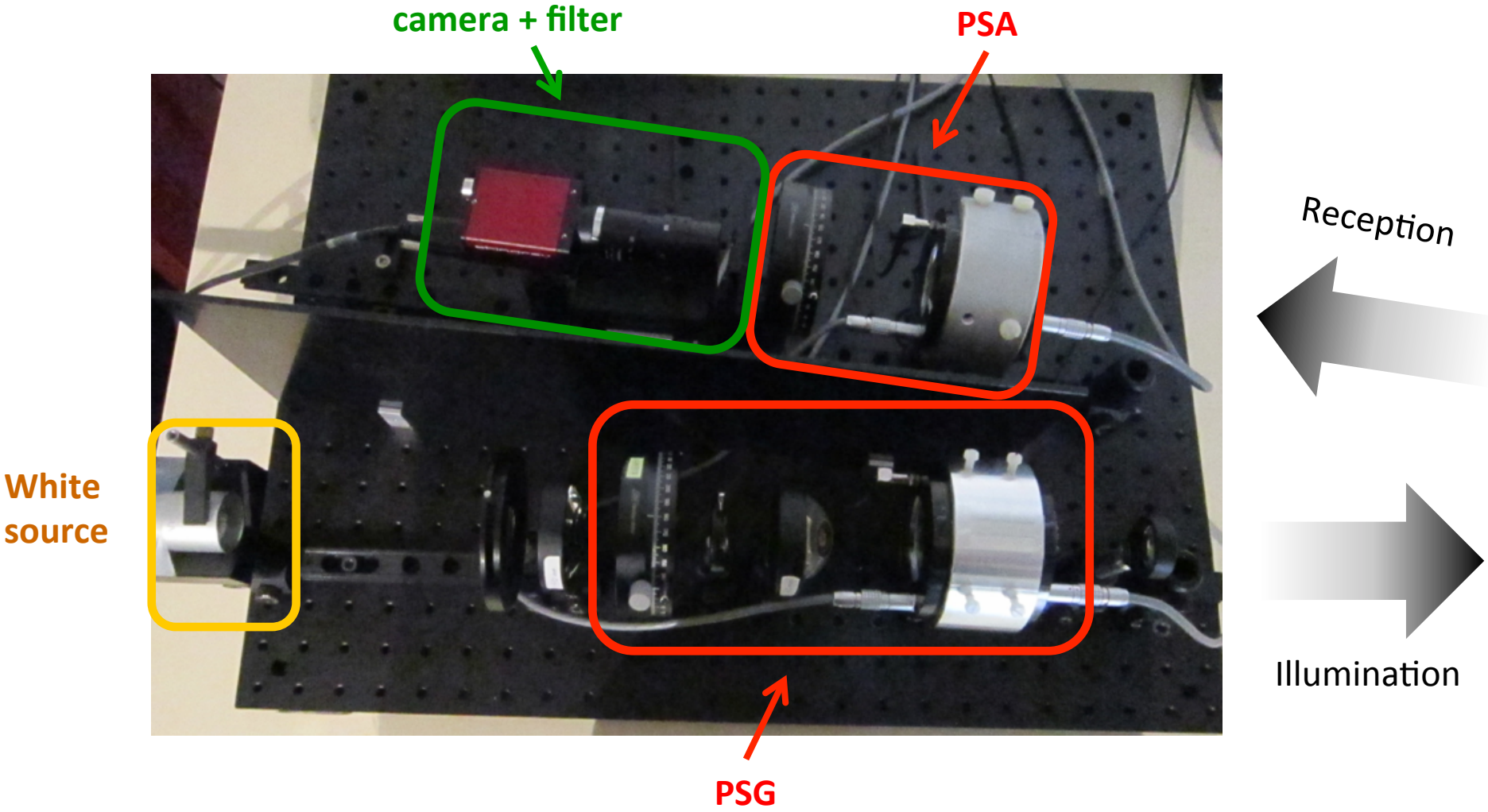
Accuracy: 2° on Poincaré sphere



Response time: 100ms

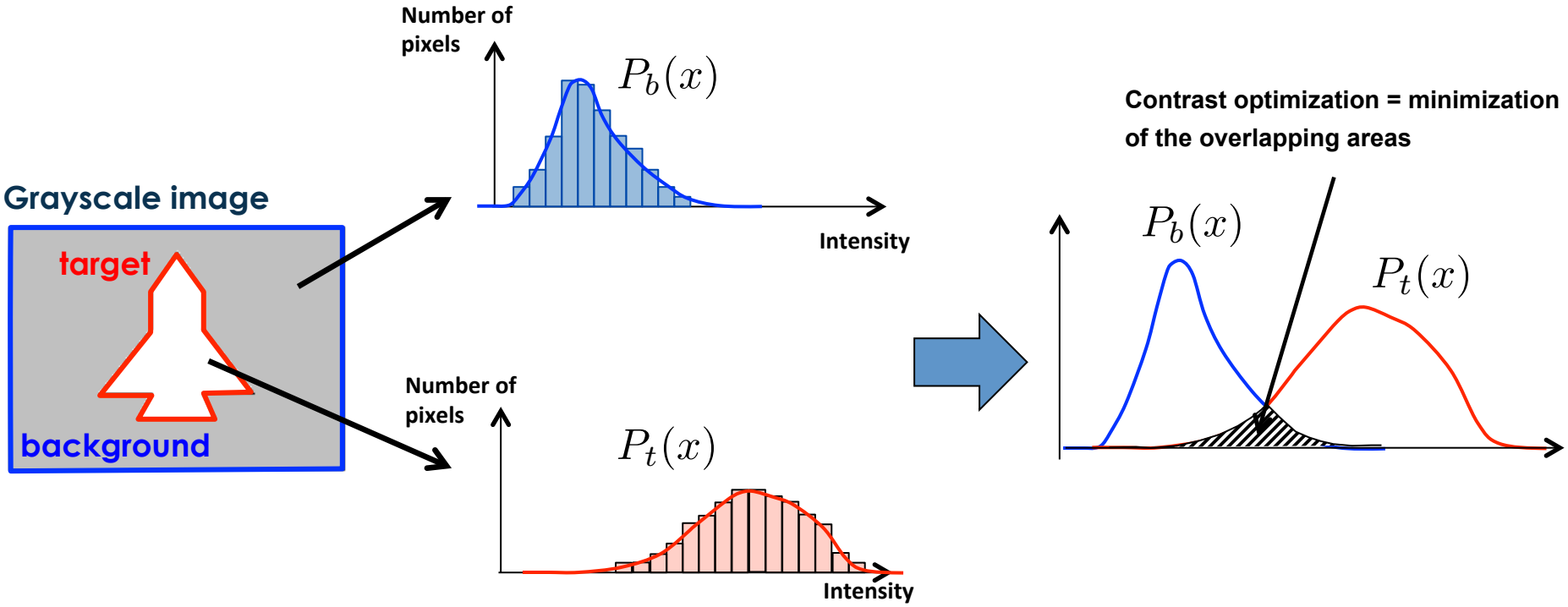
Appl. Opt. 51, 5302-5309 (2012)

How to build a adaptive polarization imaging?



How to define the contrast of a image?

Statistical definition of the contrast:

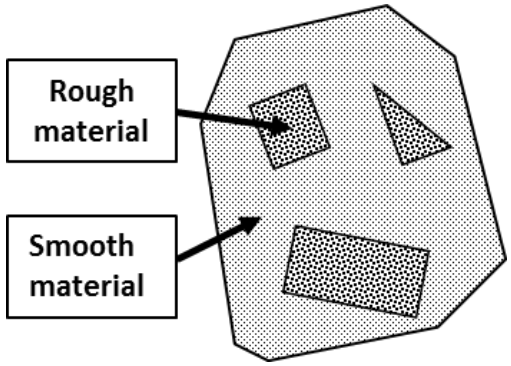


Bhattacharyya distance: optimizing the contrast = maximizing the distance

$$\mathcal{B}_{t,b} = -\log\left[\int_{\mathcal{D}} \left[P_t(x)P_b(x)\right]^{1/2} dx\right] = \mathcal{B}_{t,b}(\mathbf{S},\mathbf{T},\mathbf{M})$$

How to find the optimal polarization states?

Scheme of the scene



Painted with the same paint

Same painting

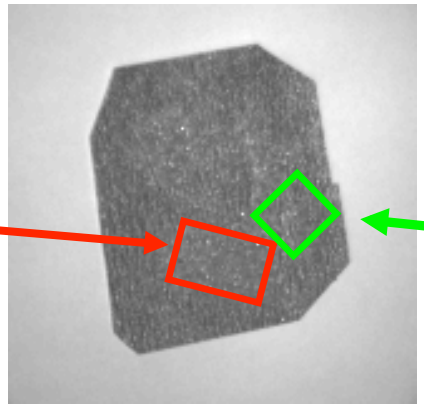
↳ **No contrast on intensity images**

Different roughness

↳ **Different Mueller matrix**

Intensity image

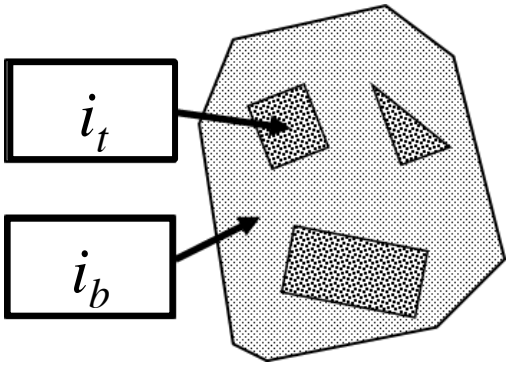
$$M_a = \begin{bmatrix} 1 & -0.01 & 0.01 & -0.00 \\ -0.03 & 0.25 & -0.04 & 0.03 \\ 0.04 & -0.02 & -0.27 & 0.01 \\ 0.02 & 0.01 & 0.03 & -0.19 \end{bmatrix}$$



$$M_b = \begin{bmatrix} 1 & -0.02 & 0.01 & -0.00 \\ -0.02 & 0.56 & -0.10 & 0.05 \\ 0.05 & -0.03 & -0.61 & 0.02 \\ 0.00 & 0.00 & 0.10 & -0.53 \end{bmatrix}$$

How to find the optimal polarization states?

Scheme of the scene



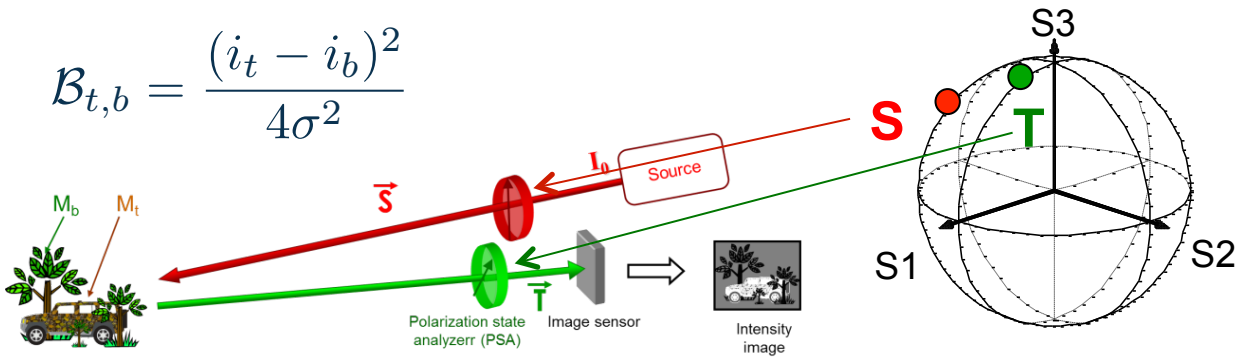
Optimal PSA and PSG states

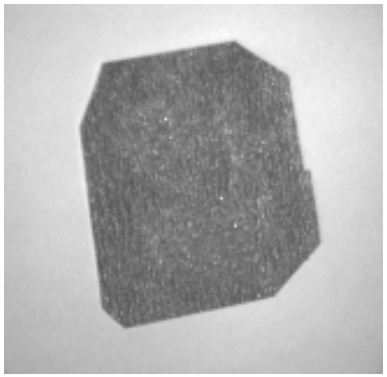
under hypothesis of **additive Gaussian noise**

$$\mathcal{B}_{t,b} = \frac{(i_t - i_b)^2}{4\sigma^2}$$

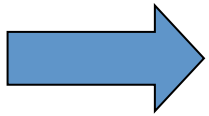
$(\alpha_S , \varepsilon_S) = (-35°,15°)$

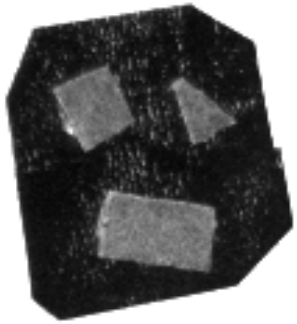
$(\alpha_T , \varepsilon_T) = (-60°,15°)$





Standard intensity image



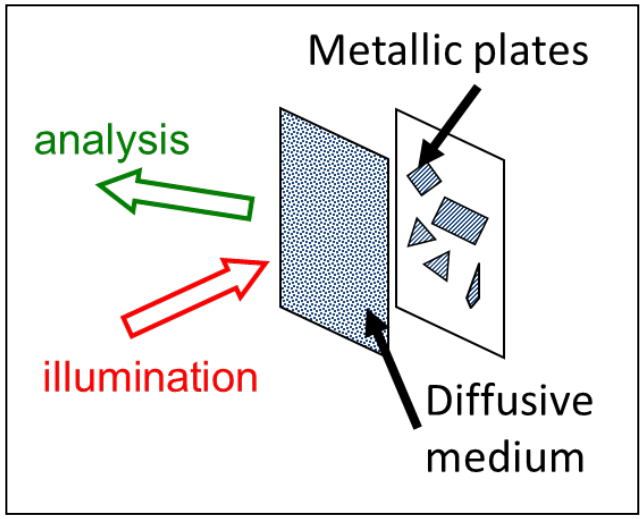


Polarimetric image with optimal states

Opt. Lett., 34(9), 1471-1473 (2009) *J. Opt. Soc. Am. A 28, 46-53 (2011)*

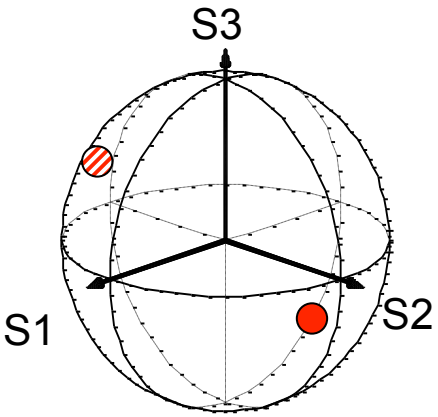
Impact of the noise model

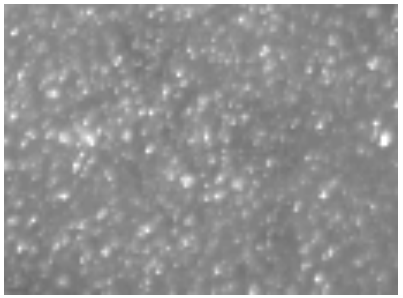
Scheme of the scene



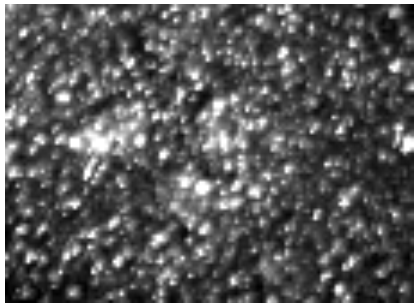
Optimal PSA and PSG state

under hypothesis of **additive Gaussian noise**





Standard Intensity image



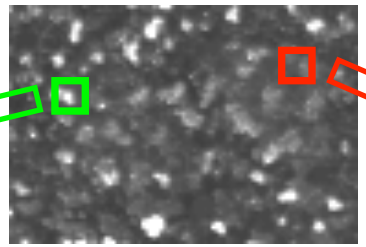
Polarimetric image

The noise model is **not adapted**

Spatial fluctuations of the Mueller matrix

Noise is due to **spatial fluctuations of polarimetric properties!**

$$\begin{bmatrix} 1 & -0.14 & 0.00 & 0.14 \\ -0.03 & -0.05 & -0.03 & -0.53 \\ 0.07 & 0.09 & -0.89 & -0.02 \\ 0.11 & -0.59 & 0.05 & 0.21 \end{bmatrix}$$



$$\begin{bmatrix} 1 & -0.24 & -0.07 & 0.22 \\ -0.07 & 0.09 & 0.02 & -0.10 \\ 0.13 & -0.07 & -0.40 & 0.10 \\ 0.15 & -0.12 & -0.02 & 0.07 \end{bmatrix}$$

The Mueller matrix of each pixel is modeled as a Gaussian random vector

$$\mathbf{V}_M = [M_{00}\ M_{01} \cdots M_{33}]^t$$

defined by its:

Average $\mathbf{V}_{\langle M \rangle} = \langle \mathbf{V}_M \rangle$

Covariance matrix $G = \langle (\mathbf{V}_M - \mathbf{V}_{\langle M \rangle})(\mathbf{V}_M - \mathbf{V}_{\langle M \rangle})^t \rangle$

Expression of the contrast in the presence of spatial fluctuations of the Mueller matrix

Statistics of the intensity image: Gaussian random variables defined by

Average $i_u = I_0[\mathbf{T} \otimes \mathbf{S}]^t \mathbf{V}_{\langle M_u \rangle}$

Variance: $\sigma_u^2 = I_0^2[\mathbf{T} \otimes \mathbf{S}]^t G_u [\mathbf{T} \otimes \mathbf{S}]$

$\otimes$: Kronecker product

Bhattacharyya distance:

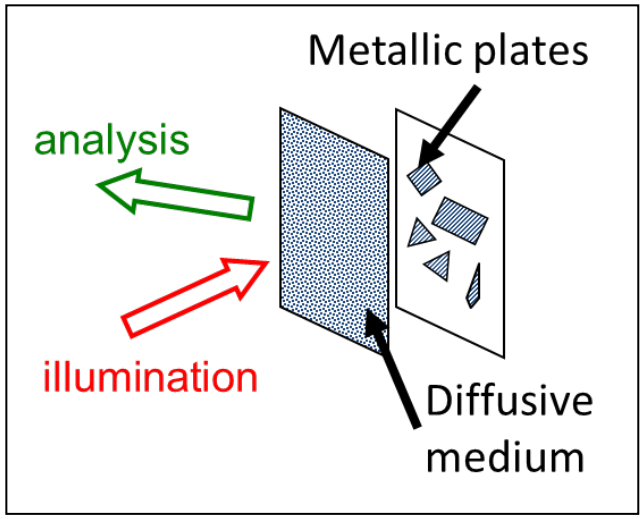
$$B_{t,b} = \frac{(i_t - i_b)^2}{\sigma_t^2 + \sigma_b^2 + \sigma^2} = \frac{(\mathbf{T}\Delta M \mathbf{S})^2}{[\mathbf{T} \otimes \mathbf{S}]^t G_{\text{fluct}} [\mathbf{T} \otimes \mathbf{S}] + SNR^{-1}}$$

Spatial fluctuations Additive noise

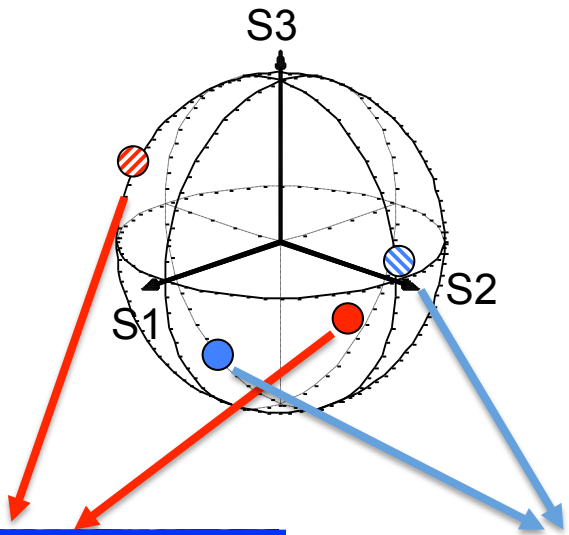
with $\Delta M = M_t - M_b$ $G_{\text{fluct}} = G_t - G_b$ $\text{SNR} = I_0^2/\sigma^2$

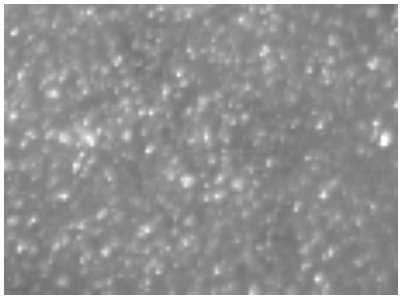
Optimal states

Scheme of the scene



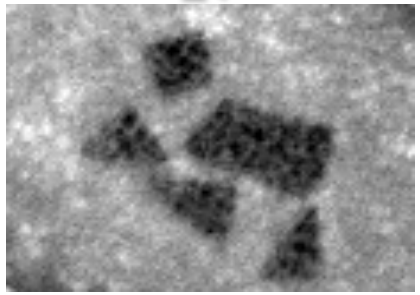
Optimal PSA and PSG states
under hypothesis of **spatial**
fluctuations of polarimetric properties





Standard
Intensity image

Importance of **accurate** physical modeling of the scene



Polarimetric image
with optimal states

Optics Letters, 36, pp. 4590-4592 (2011) *Applied Optics, 51, 1178-1187 (2012)*

Limitations of this approach

To **optimize the contrast**, one needs **to know** the ***polarimetric properties*** of the two regions of interest.

What if we do not know this information?

Proposed solution:

Combining the capabilities of adaptive polarimetric system with **image processing algorithms**

Automation of the method

1. **Acquisition of the Mueller image of the scene (16D)**

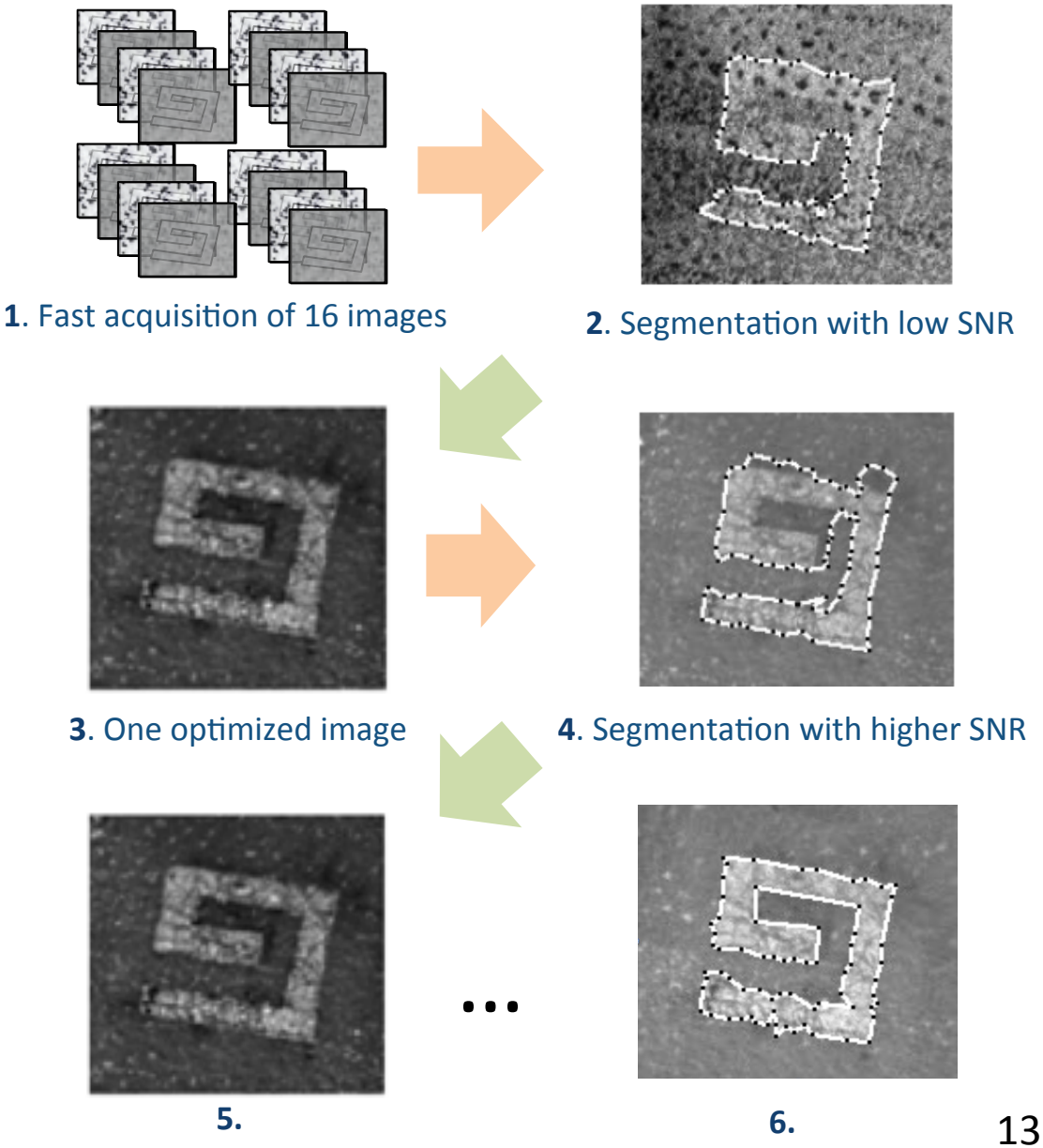
2. **Segmentation:** separate an object from the background

3. **Estimation of the optimal T and S and acquisition of the optimized image**

4. **Segmentation of the optimized image**

5. **Re-iteration of steps 3 and 4**

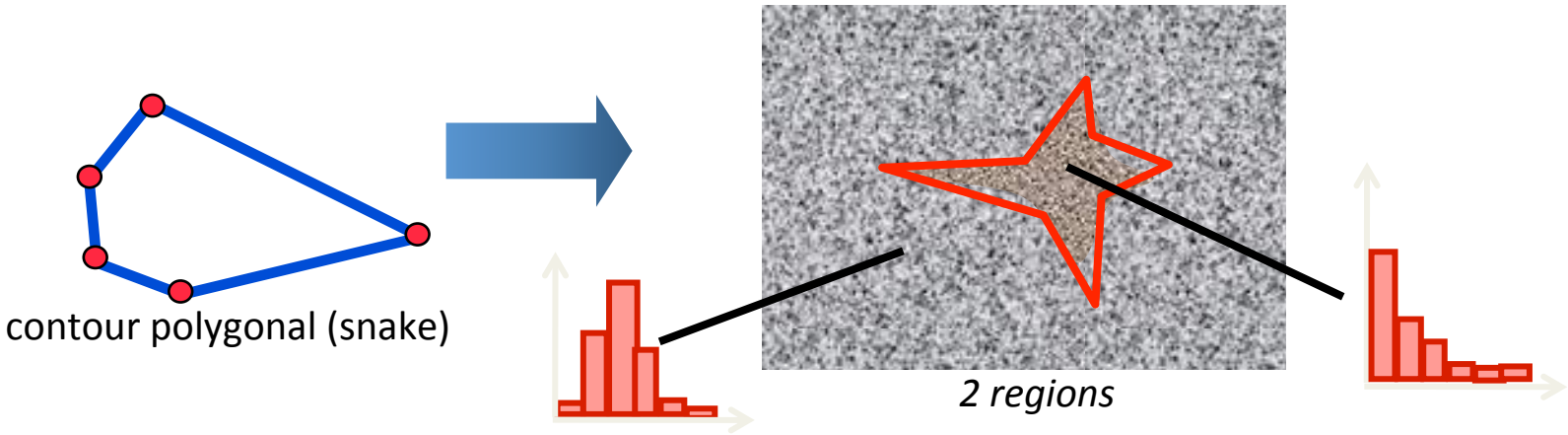
6. **Final image**



Optics Letters 37, pp. 3321-3323 (2012)

Choice of the segmentation algorithm

Statistical polygonal active contour



- No parameter to adjust in the method
- Adapted to low SNR images
- Fast : computation time < 10 ms on 256 x 256 images

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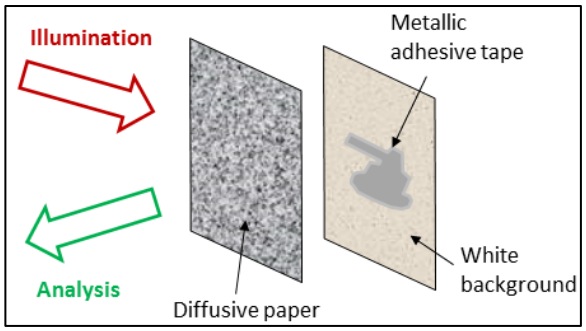
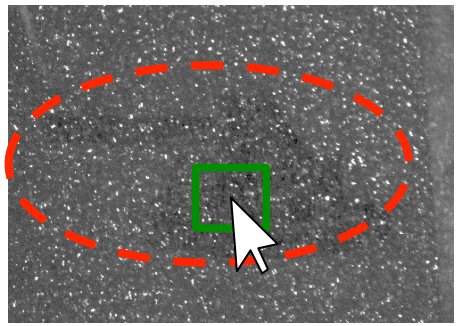
Bertaux et al., Electronics Letters, vol. 47 (2011)

Illustration of the complete procedure

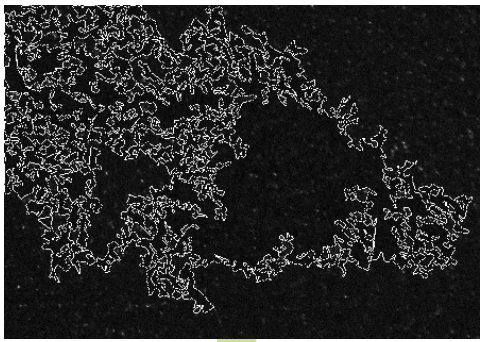
Scheme of the scene

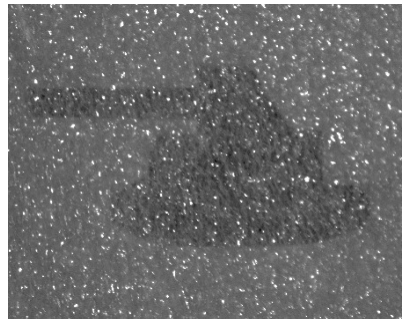


Intensity image

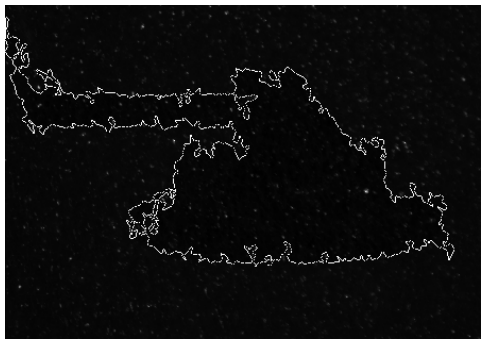


Segmentation based on the Mueller matrix

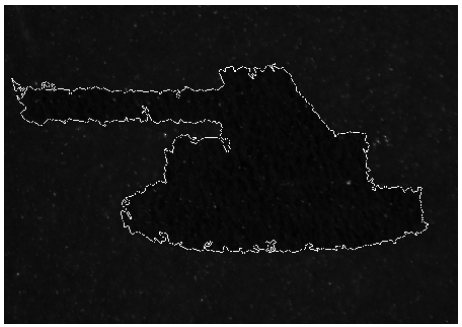




Optimized image

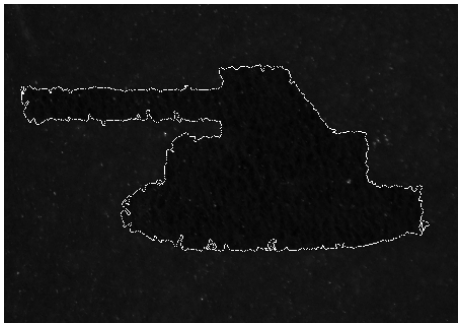


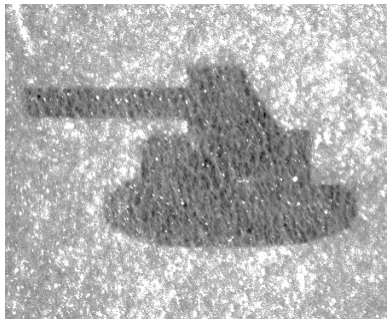
Segmentation on the optimized image



Iteration 2

Iteration 3





Final image

Conclusions & perspectives

- **Contrast optimization using adaptive imager**
  - Generation/analysis of any polarization state with **good accuracy** (~2°)
  - **video frame rate**
- **Polarimetric imaging controlled by image processing algorithm**
  - **(semi-)automation** of contrast optimization wihout ***a priori* knowledge** on target polarimetric properties

ONGOING/FUTURE WORKS

- **SWIR imager for decamouflaging applications**
- **Explore other applications**

THALES
RESEARCH & TECHNOLOGY

Thank you for your attention