Full Polarimetric Measurements in 3D Integral Imaging

Artur Carnicer,[1] Thaddée delebarre,[1, 2] Salvador Bosch,[1] and Bahram Javidi [3]

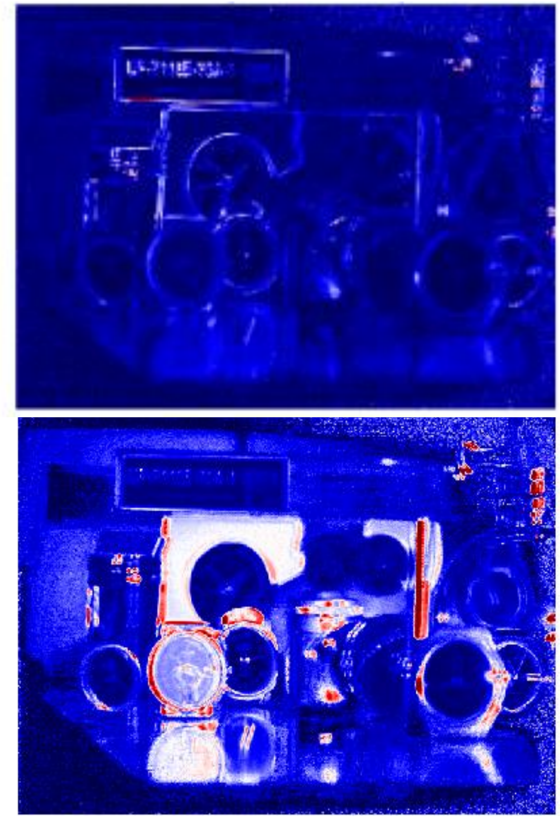
[1]Universitat de Barcelona (UB), Facultat de Física, Departament de Física Aplicada, Martí i Franquès 1, 08028 Barcelona

[2]Institut d'Optique Graduate School, ParisTech, 2 Avenue Augustin Fresnel, 91120 Palaiseau (France)

[3]Electrical and Computer Engineering Department, University of Connecticut, 371 Fairfield Road, Storrs, Connecticut 06269 (USA)

- Most of the light information is missing when the intensity is recorded. In particular, the vector of character of light.
- Information associated to the direction of the electric field can be measured using polarimetric techniques.
- When using natural light, polarimetric signals can be week.

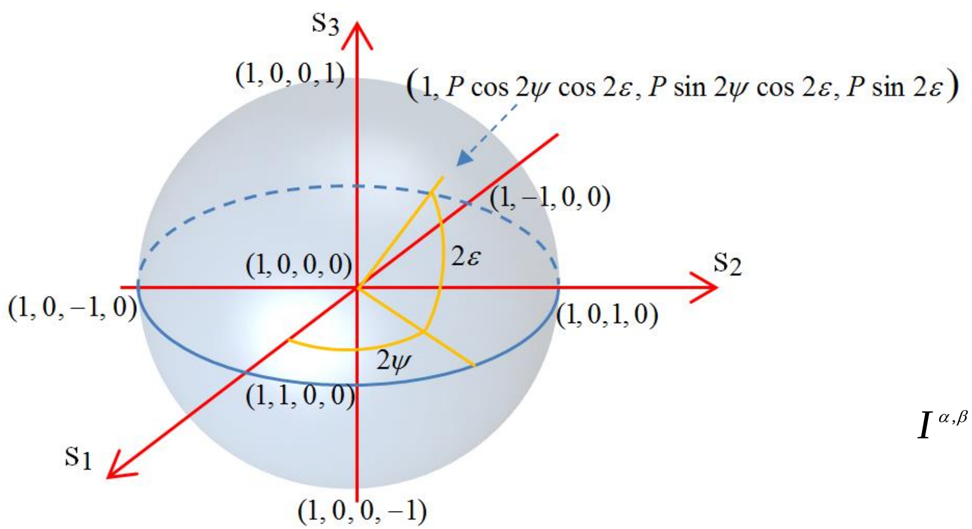
- Goal: to extend Mueller matrix measurements to 3D integral imaging



Outline

1. Degree of polarization measurements in 3D integral imaging
2. 3D Mueller Matrix Integral Image estimation
3. Comparison between experimental measurements and estimated DOP
4. Comparison between 3D and 2D polarimetric images
5. Use of synthetic light
6. Fusion of DOP maps
7. Conclusions

Basic definitions



$$S_0 = I^{0°,0} + I^{90°,0}$$

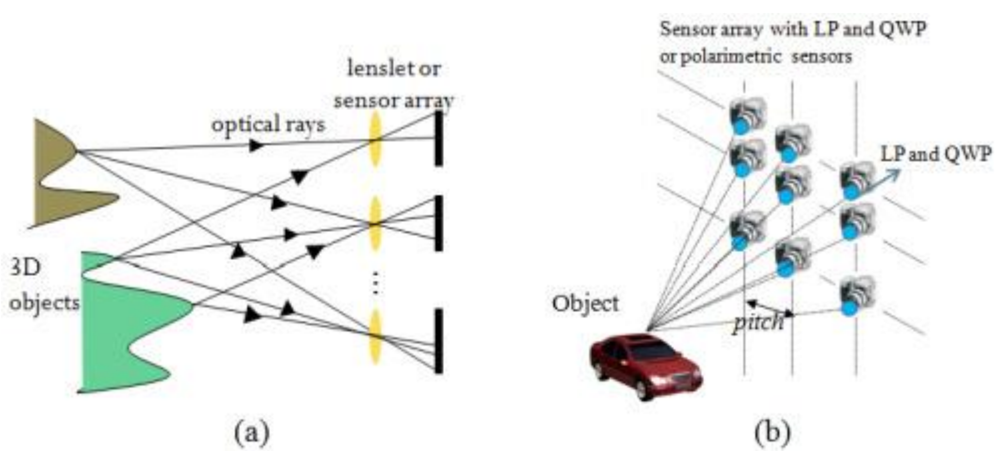
$$S_1 = I^{0°,0} - I^{90°,0}$$

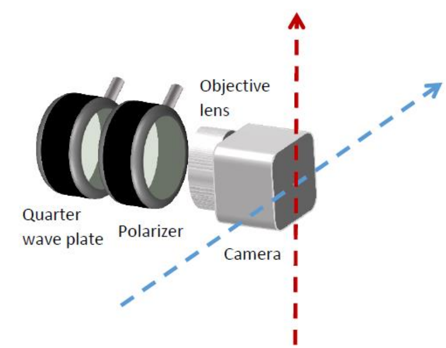
$$S_2 = I^{45°,0} - I^{135°,0}$$

$$S_3 = I^{45°,\pi/2} - I^{135°,\pi/2}$$

$$\mathrm{P} = \frac{1}{S_0}\sqrt{S_1^{\,2} + S_2^{\,2} + S_3^{\,2}},$$

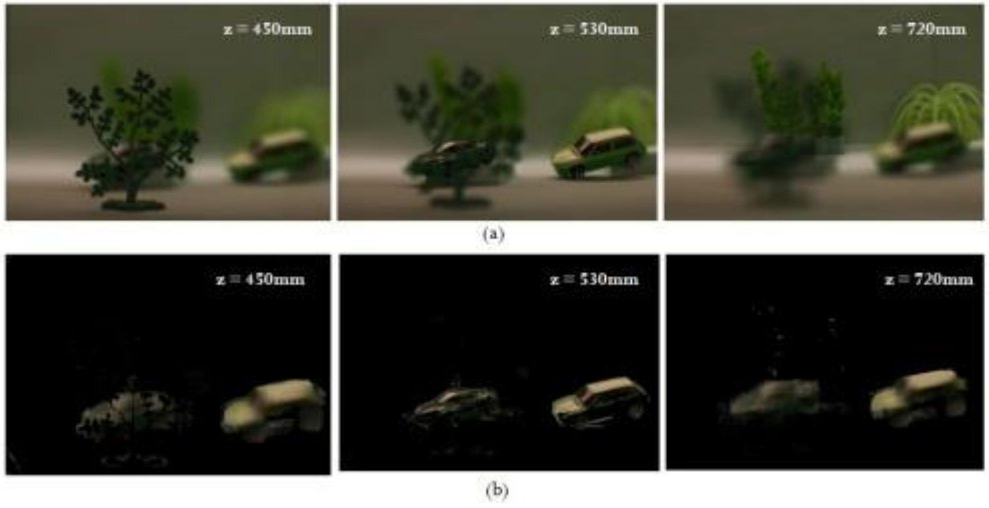
$$I^{\alpha,\beta}(x,y,z) = \sum_{k=0}^{N_x-1}\sum_{l=0}^{N_y-1} i_{k,l}^{\alpha,\beta}\left(x - k\frac{N_x p f}{c_x z}, y - l\frac{N_y p f}{c_y z}\right).$$



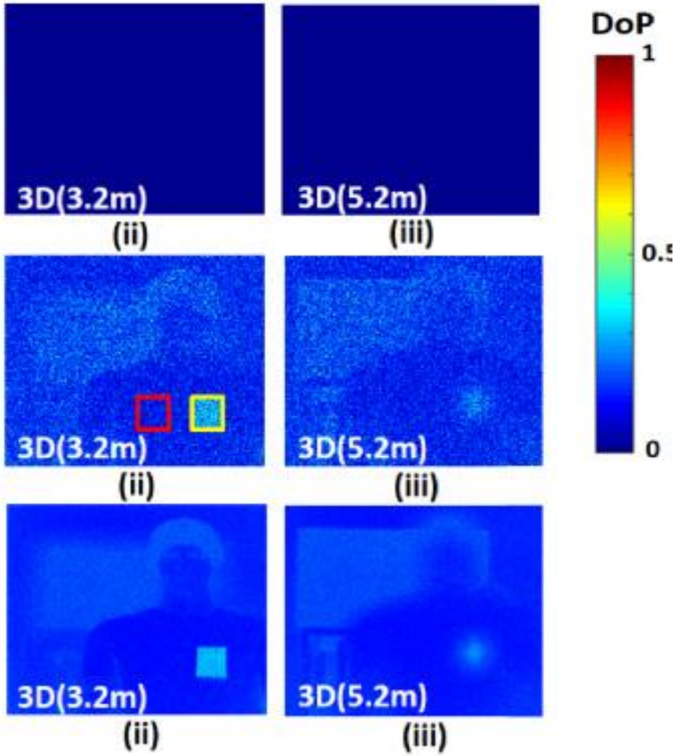


Degree of Polarization measurements 3D Integral Imaging

$$\mathrm{DoP}(i,j) = \frac{\sqrt{S_1(i,j)^2 + S_2(i,j)^2 + S_3(i,j)^2}}{S_0(i,j)}.$$

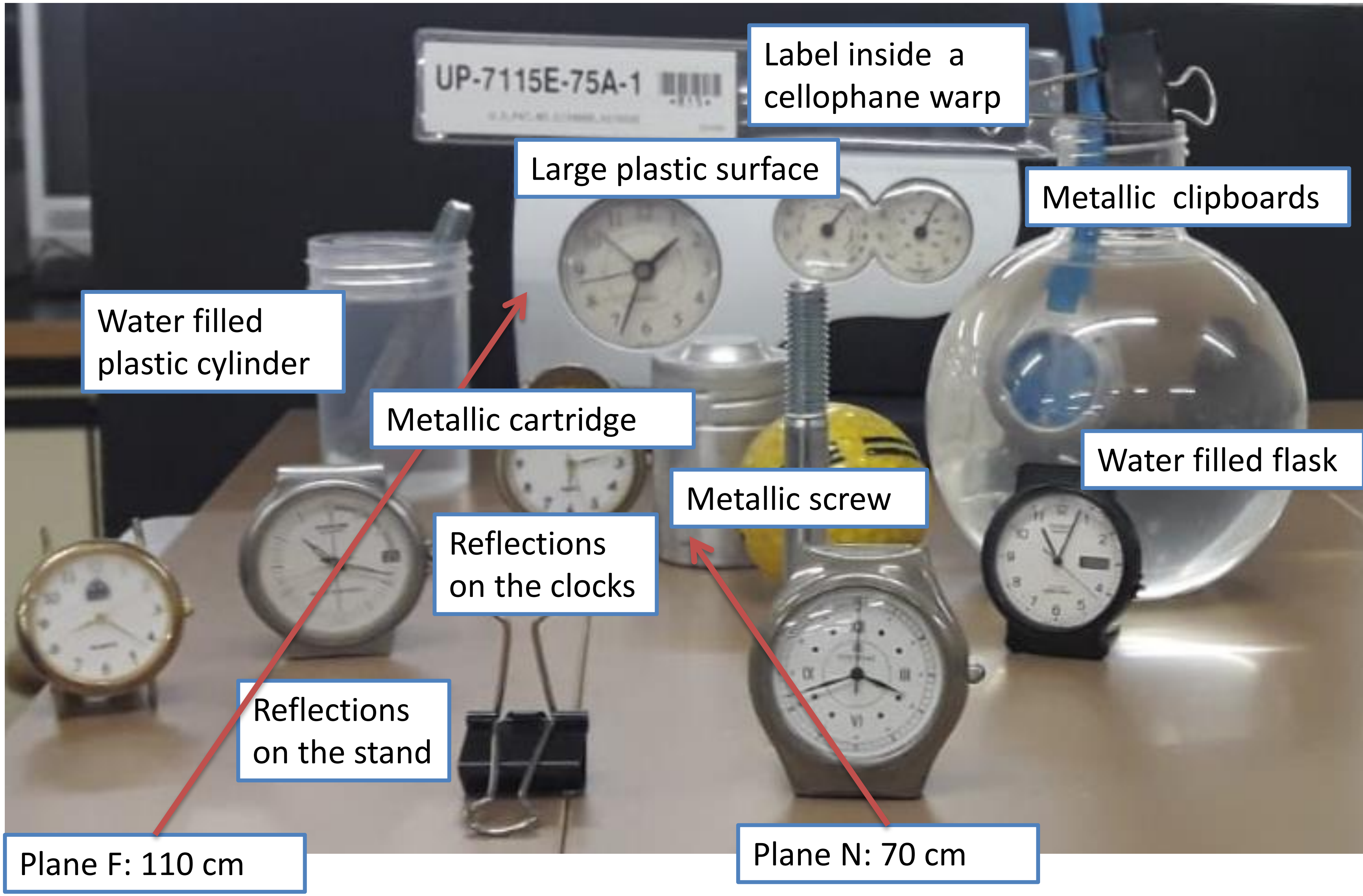


Xiao Xiao, Bahram Javidi, Genaro Saavedra, Michael Eismann, and Manuel Martinez-Corral, "Three-dimensional polarimetric computational integral imaging," Opt. Express **20**, 15481-15488 (2012)

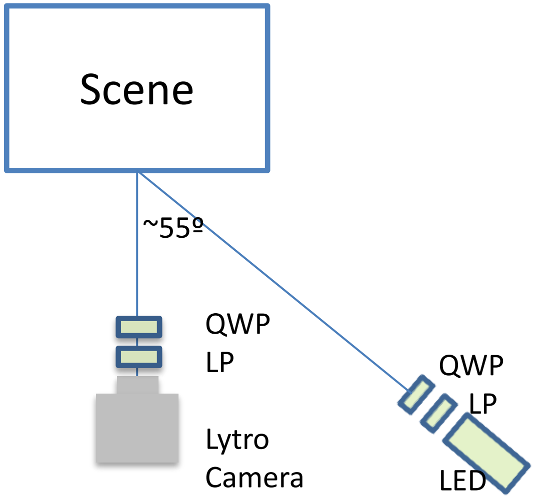


Xin Shen, Artur Carnicer, and Bahram Javidi, "Three-dimensional polarimetric integral imaging under low illumination conditions," Opt. Lett. **44**, 3230-3233 (2019)

Scene: areas of interest



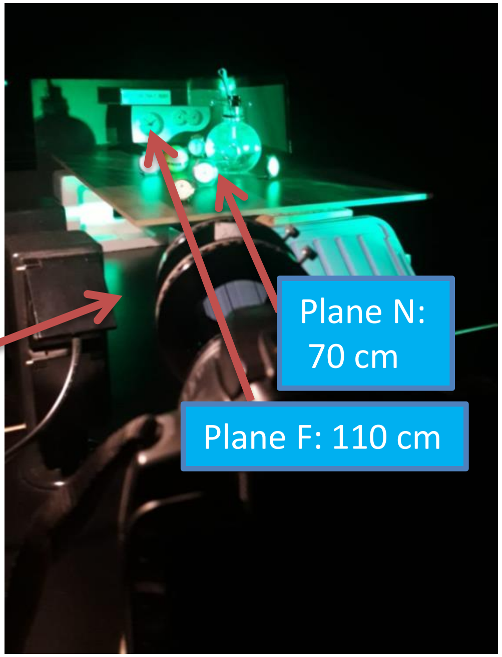
Optical setup & scene



Green LED + linear polarizer + quarter wave plate.

LYTRO ILLUM specs:
15x15 elementary views
434x 625 pixels
Color: 24 bit.

Quarter wave plate + linear polarizer + camera.



3D Mueller Matrix Integral Imaging estimation

1. A green LED is used as light source. In combination with a quarter wave plate and a linear polarizer, the following six input states of polarization are produced:

	L_1	L_2	L_3	L_4	L_5	L_6
S_0	1	1	1	1	1	1
S_1	1	0	0	-1	0	0
S_2	0	1	0	0	-1	0
S_3	0	0	1	0	0	-1

$$\mathbf{V}^{inp} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{pmatrix}$$

2. A quarter wave plate and a polarizer are placed in front of the camera. Six polarimetric images should be recorded for calculating the output Stokes parameters.

$$\mathbf{V}^{out}(i,j) = \begin{pmatrix} S_0(\mathrm{L}_1;i,j) & S_0(\mathrm{L}_2;i,j) & S_0(\mathrm{L}_3;i,j) & S_0(\mathrm{L}_4;i,j) & S_0(\mathrm{L}_5;i,j) & S_0(\mathrm{L}_6;i,j) \\ S_1(\mathrm{L}_1;i,j) & S_1(\mathrm{L}_2;i,j) & S_1(\mathrm{L}_3;i,j) & S_1(\mathrm{L}_4;i,j) & S_1(\mathrm{L}_5;i,j) & S_1(\mathrm{L}_6;i,j) \\ S_2(\mathrm{L}_1;i,j) & S_2(\mathrm{L}_2;i,j) & S_2(\mathrm{L}_3;i,j) & S_2(\mathrm{L}_4;i,j) & S_2(\mathrm{L}_5;i,j) & S_2(\mathrm{L}_6;i,j) \\ S_3(\mathrm{L}_1;i,j) & S_3(\mathrm{L}_2;i,j) & S_3(\mathrm{L}_3;i,j) & S_3(\mathrm{L}_4;i,j) & S_3(\mathrm{L}_5;i,j) & S_3(\mathrm{L}_6;i,j) \end{pmatrix}$$

3. This set is used to determine the Mueller matrix $\mathbf{M}(i,j)$ for each pixel of the scene.

$$\mathbf{V}^{out}(i,j) = \mathbf{M}(i,j)\mathbf{V}^{inp}$$

3. Since the number of unknowns (16) is smaller that the number of equations (24), **M**(i,j) is determined using the least squares approximation with the orthogonal-triangular decomposition method.

$$\mathbf{M}^{est}(i,\, j) = \mathbf{V}^{out}(i,\, j) \,/\, \mathbf{V}^{inp}$$

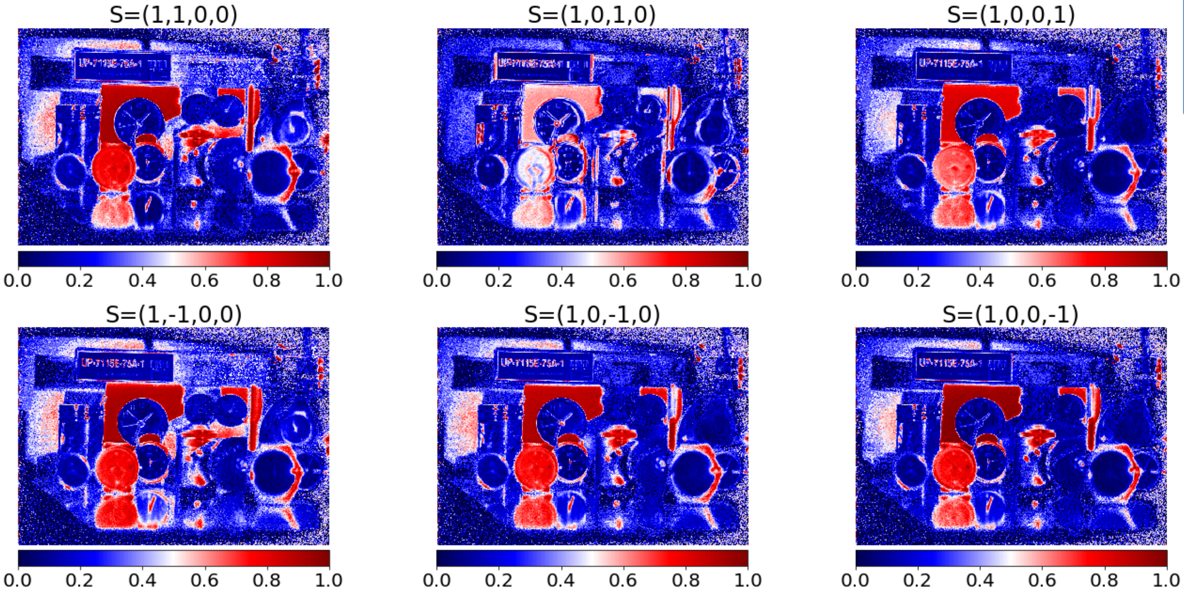
4. The procedure is extended to 3D imaging. NxM elementary images have to be recorded. In partiular, the Lytro Illum camera produces 15x15 EI, 434x625 24-bit color pixels each.

5. The Degree of polarization for each illumination L_k, at each pixel $(i$,j) is :

$$\mathrm{DoP}\left(\mathrm{L}_k;i,\, j\right) = \frac{\sqrt{S_1\left(\mathrm{L}_k;i,\, j\right)^2 + S_2\left(\mathrm{L}_k;i,\, j\right)^2 + S_3\left(\mathrm{L}_k;i,\, j\right)^2}}{S_0\left(\mathrm{L}_k;i,\, j\right)}$$

$$k = 1,\ldots,6$$

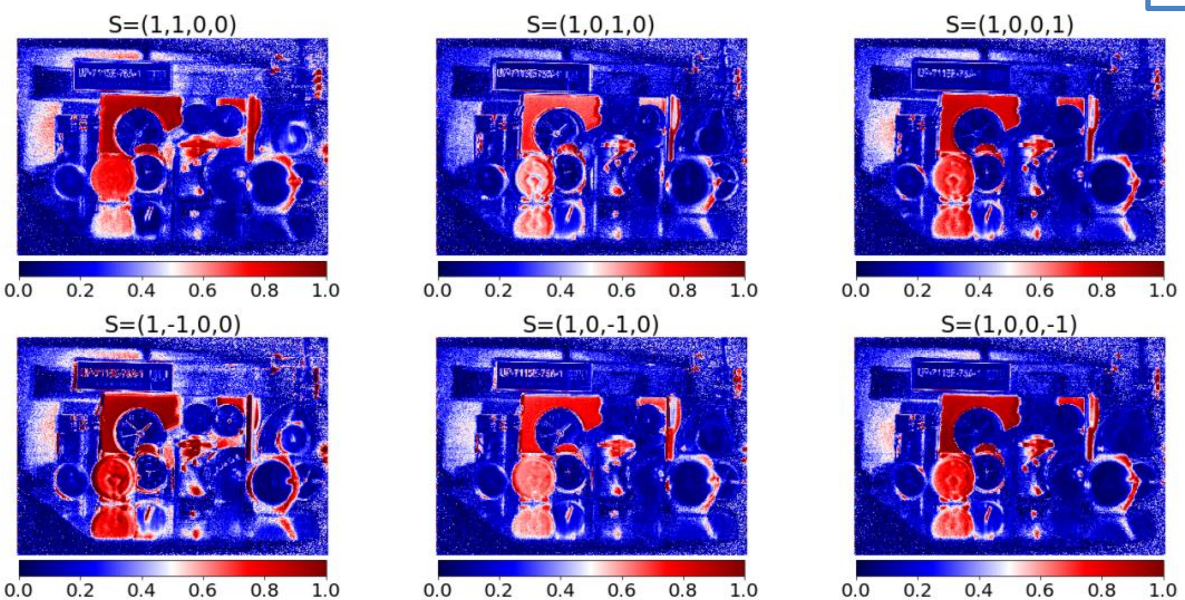
Experimental measurement of the 3D DOP at plane F



Initial checking:

Comparison between estimated and experimental DOP

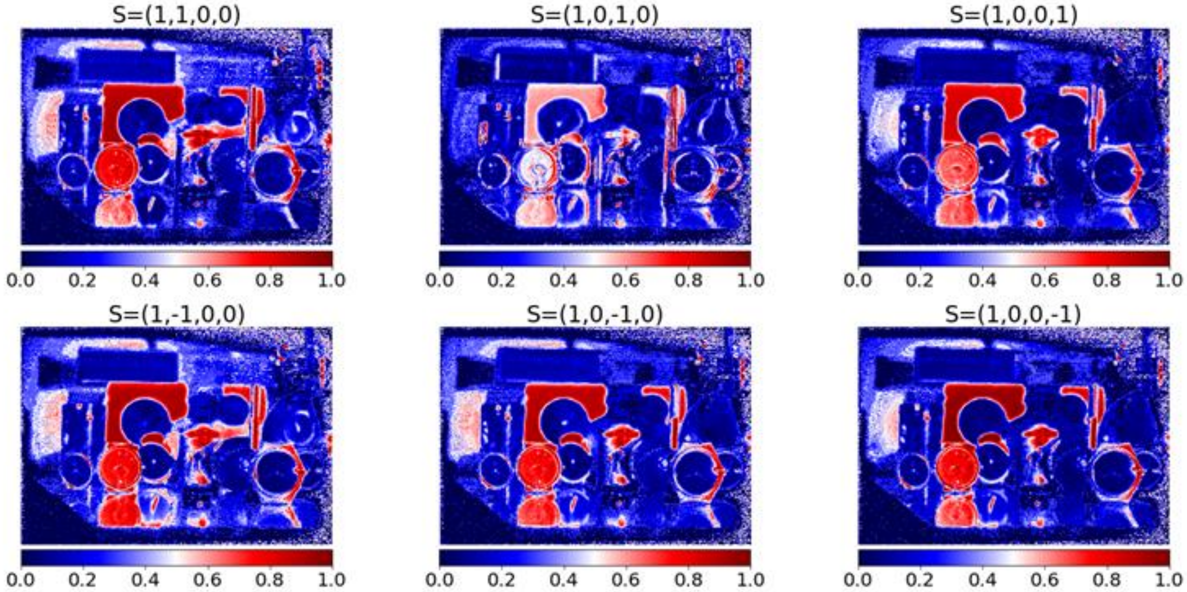
Numerical evaluation of the 3D DOP at plane F



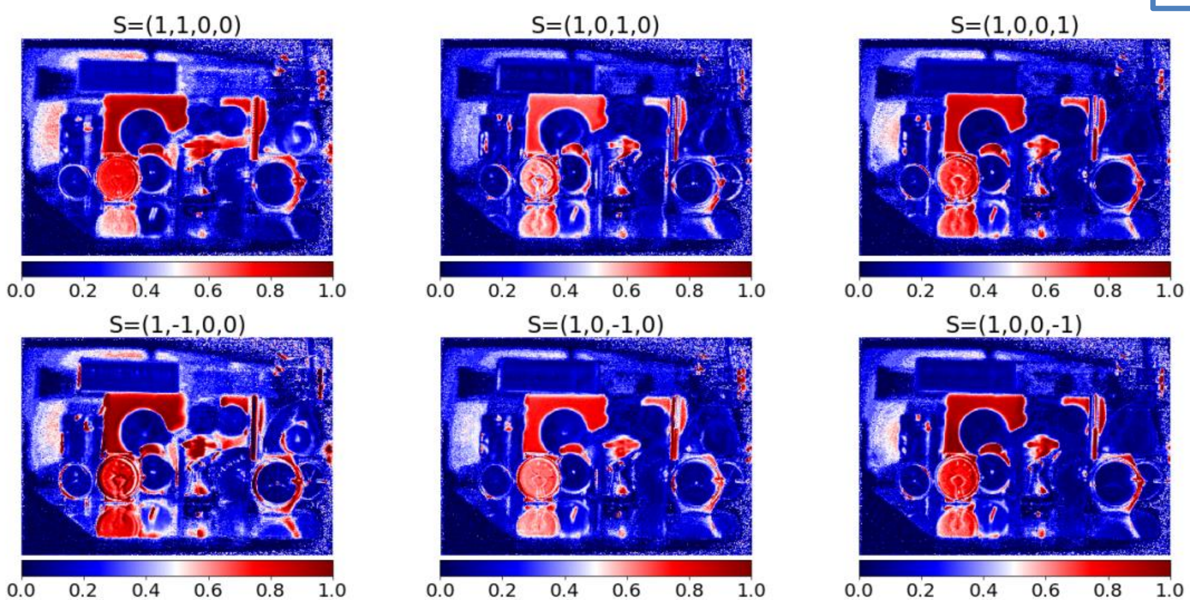
Comparison between numerical and experimental results

Plane F		
	SSIM	Norm. Corr.
(1,1,0,0)	0.83	0.94
(1,0,1,0)	0.83	0.91
(1,0,0,1)	0.86	0.96
(1,1,-0,0)	0.77	0.86
(1,0,-1,0)	0.82	0.92
(1,0,0,-1)	0.86	0.97

Experimental measurement of the 3D DOP at plane N



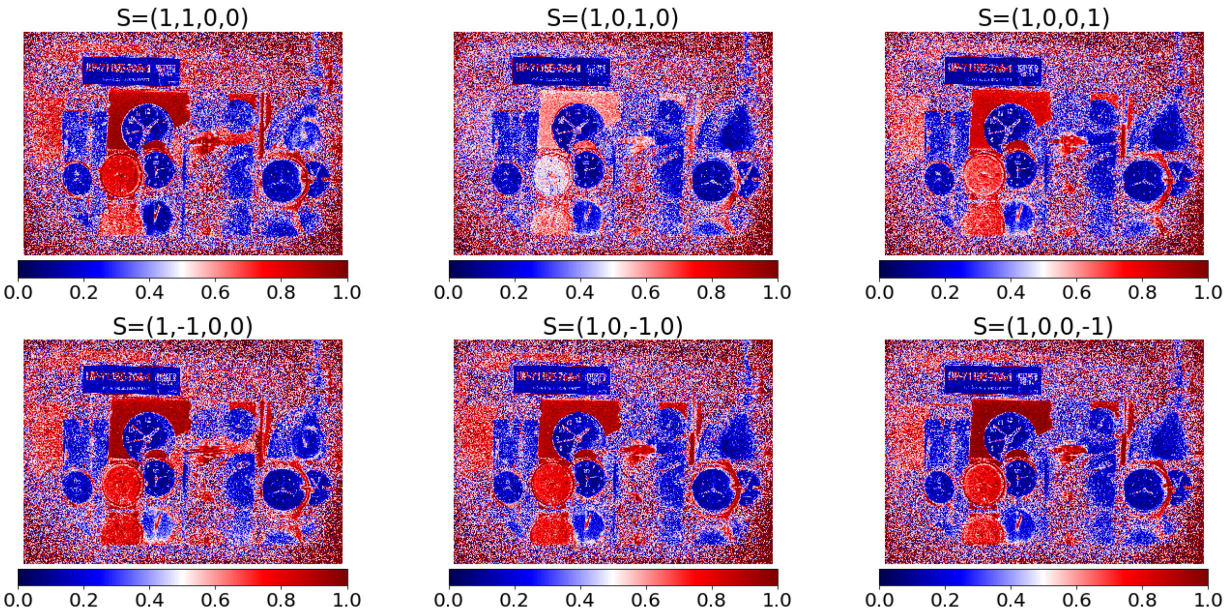
Numerical evaluation of the 3D DOP at plane N



Comparison between numerical and experimental results

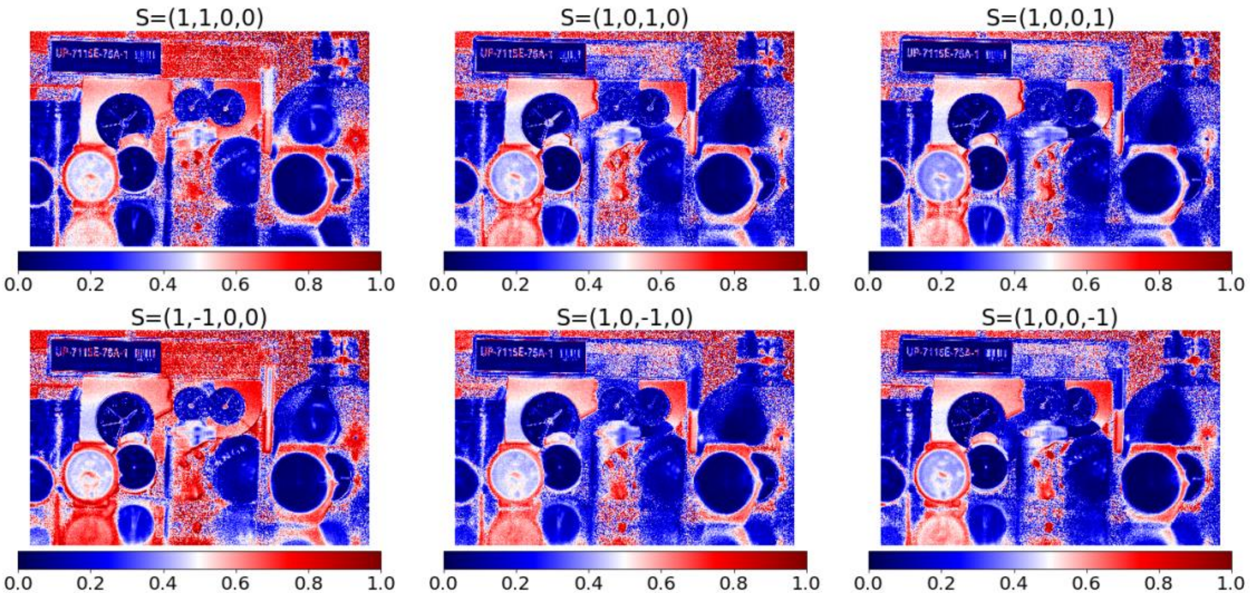
Plane N		
	SSIM	Norm. Corr.
(1,1,0,0)	0.80	0.92
(1,0,1,0)	0.82	0.89
(1,0,0,1)	0.83	0.94
(1,1,-0,0)	0.75	0.85
(1,0,-1,0)	0.80	0.90
(1,0,0,-1)	0.83	0.95

DOP experimental measurements using a single elementary image



The estimation of the DOP provides very noisy results.

DOP experimental measurements using a conventional 2D camera

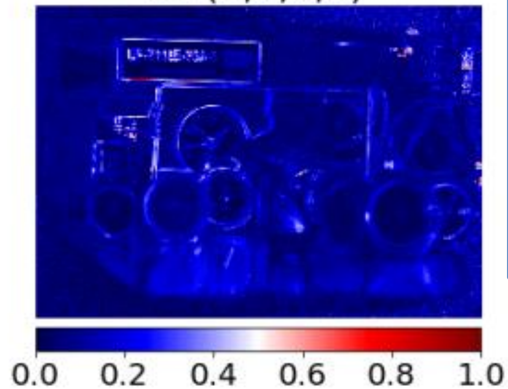


The DOP seems to be overestimated Again the result is noisy.

Natural (synthetic) light

Using natural light it might be difficult to analyze the parts of the scene that display polarimetric behavior.

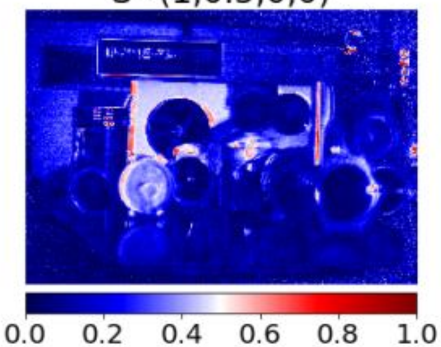
S=(1,0,0,0)



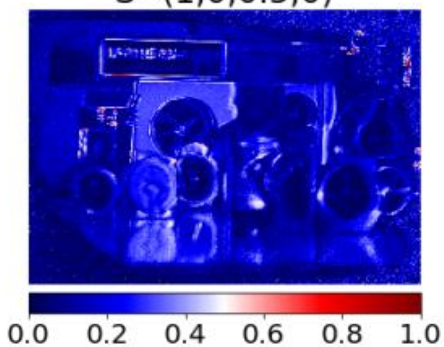
The method enables to produce results with illuminations that are more difficult to produce or not considered.

Partially polarized synthetic light

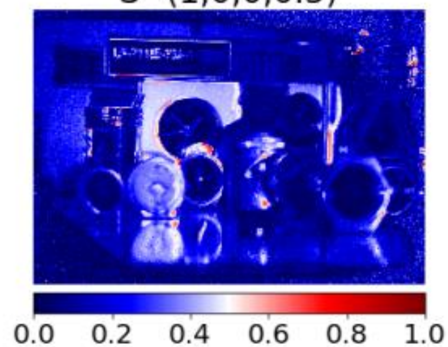
S=(1,0.5,0,0)



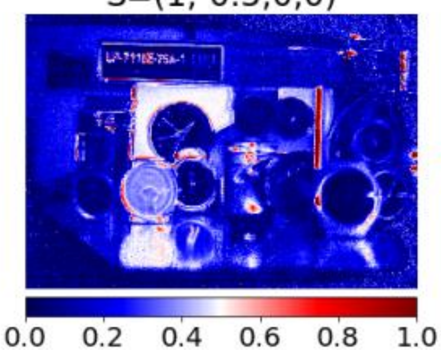
S=(1,0,0.5,0)



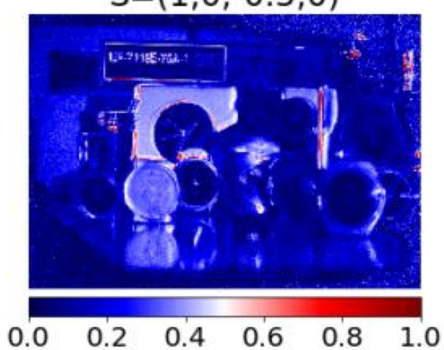
S=(1,0,0,0.5)



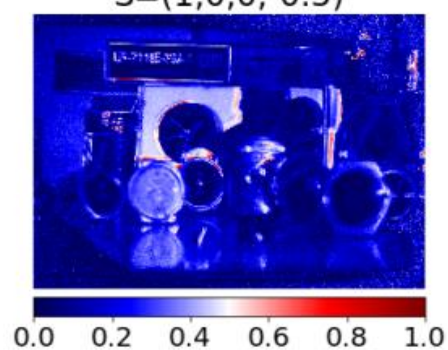
S=(1,-0.5,0,0)



S=(1,0,-0.5,0)



S=(1,0,0,-0.5)

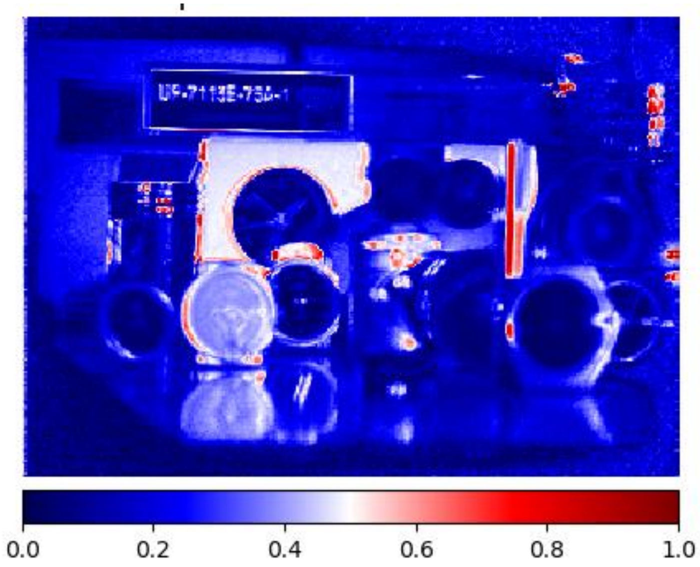


When the system is illuminated with fully polarized light some parts of the scene display DOP close 1.

Using partially polarized light results are more discriminant.

Conclusions

1. We introduced the Mueller matrix imaging concepts for 3D Integral Imaging Polarimetry
2. The DOP can be estimated at any selected plane for any arbitrary synthetic illumination source
3. Image fusion is used to produce synthetic polarimetric maps.



More Info:

A. Carnicer, S. Bosch, and B. Javidi, "Mueller matrix polarimetry with 3D integral imaging," Opt. Express **27**, 11525-11536 (2019)
https://www.osapublishing.org/oe/abstract.cfm?uri=oe-27-8-11525

Funding

This work was partially supported by MINECO project # FIS2016-75147-C3-1-P.