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# A comprehensive model of depth-resolved polarization gating imaging

Julien Fade,<sup>1,2,\*</sup> Valentin Espinas,<sup>1,2</sup> Julien Wojak,<sup>1,2</sup> Jana Zaher,<sup>1,2</sup> Laure Siozade,<sup>1,2</sup> Carole Deumié,<sup>1,2</sup> and Anabela Da Silva<sup>1,2,\*</sup>

<sup>1</sup> Aix Marseille Univ, CNRS, Centrale Méditerranée, Institut Fresnel, Marseille, France

<sup>2</sup> Aix-Marseille Univ, Centre Européen de Recherche en Imagerie Médicale (CERIMED), Marseille, France

\* julien.fade@fresnel.fr; anabela.dasilva@fresnel.fr

**Abstract:** A simplified Mueller Matrix decomposition model is proposed to describe depth probing of biological tissues using wide-field polarization gating. The model, with elliptically polarized light, facilitates quantitative retrieval of polarization-maintained contributions in gated image measurements amid multiple scattering. © 2023 The Author(s)

## 1. INTRODUCTION

Imaging techniques using polarization filters are now popular and non invasive techniques used to examine biological tissues in backscattering geometry. Commercial systems exist for dermatology (e.g. DE350 Wireless Polarizing Dermatoscope/Dermascope, Firefly, USA), subsuperficial vascular imaging, phlebology (e.g. v900L, Syris scientific, USA). Most of the time, these techniques use linear polarization to enhance contrasts at the surface of a tissue by performing measurements under colinear illumination/detection configuration, or, on the contrary, under cross-linear configuration, to filter out high intensity mirror reflections at the surface, for deeper subsurface screening [1]. Several groups have proposed to exploit the "polarization memory effect" and extend this property of filtration to the use of circularly [2,3] and, more generally, elliptically polarized light [4–7] to probe the tissues at different depths.

Here we propose to analyze this phenomenon through a simple decomposition model, where the Mueller Matrix (MM) of a biological sample is split into a specular/mirror reflection and a pure depolarizing contributions. Although simple, this model allows to highlight how an elliptical polarization gating technique can be used to selectively probe the tissue in depth by filtering linear, elliptical and circular polarization-maintained light out of multiply-scattered light. The model of the biological sample is first described which allows to understand how a standard polarization-gating technique can be enhanced by considering combinations of images acquired under different elliptical polarization filters, and how this protocol allows the linear, elliptical and circular polarization-maintained contributions to be quantified and isolated from the (potentially dominant) specular contribution.

## 2. Description of the model of Polarization gating with elliptically polarized light

The principle of the technique relies on acquiring images with varying the polarization ellipticity of the illumination beam, while analyzing the light along the same polarization direction (co-polarized), and the orthogonal polarization direction (cross/counter-polarized). Such measurements are performed by means of a combination of a linear polarizer (LP) and a quarter-wave plate (QWP) at the illumination, and of a QWP and a linear polarizer at the detection. In order to ensure a modification of the beam ellipticity without changing the principal axis of the ellipse, the setup is as follows: (i) The illumination and detection QWP's have a fixed position (eigenaxes along 0, vertical, and  $\pi/2$ , horizontal directions); (ii) The polarizers are rotated by an angle  $\varphi$  varying between 0 to a  $\pi/4$  with respect to the eigenaxis of the QWP, allowing to continuously modify the state of polarization between linear to circular polarization, without modifying the azimuth of the generated/analyzed elliptical state whose ellipticity is  $\varphi$ . We assume that, at each pixel of an image, the Mueller matrix  $M$  of the sample can be modeled as a sum of a specular contribution, of amount  $\tau_s$  and with a MM of a specular reflection  $M_s$ , and of a pure depolarization contribution from the diffuse light, of amount  $\tau_d$  and with a Mueller matrix  $M_d$  of a pure depolarizer:

$$M = \tau_s M_s + \tau_d M_d. \quad (1)$$

with classical models of MM of pure depolarization  $M_d$  and mirror/specular reflection  $M_s$ :

$$M_d = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - P_L & 0 & 0 \\ 0 & 0 & 1 - P_L & 0 \\ 0 & 0 & 0 & 1 - P_C \end{pmatrix}, \quad M_s = \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & -1 + \varepsilon & -v \\ 0 & 0 & v & -1 + \varepsilon \end{pmatrix}, \quad (2)$$

where  $P_L$  and  $P_C$  respectively correspond to the depolarization factor along a linear or circular polarization direction. This model splits the contribution of specular/mirror reflection at the sample's surface, and partial pure depolarization in the bulk volume of the sample, due to multiple scattering. For the sake of simplicity, it is therefore assumed that no anisotropic polarization effect (such as diattenuation or birefringence) occurs in the back-scattered light detected from the bulk sample. The mirror reflection MM is modelled resorting to the  $S$  and  $P$  Fresnel coefficients of the reflection at the air-tissue interface along polarization directions  $S$  and  $P$ , which depend on the incidence angle  $\theta_i$ , and a refraction index mismatch  $n$ , with  $N = -\cos(2\Psi)$ ,  $v = \sin(2\Psi)\sin(\delta)$ ,  $\varepsilon = 1 + \sin(2\Psi)\cos(\delta)$ , verifying  $N^2 + (\varepsilon - 1)^2 + v^2 = 1$ , and with  $\Psi$  and  $\delta$  the classical ellipsometric quantities defined such that  $\tan\Psi = |\rho| = |r_s/r_p|$ ,  $\delta = \text{Arg}(\rho) = \text{Arg}(r_s/r_p)$ ,  $r_s$  and  $r_p$  being the Fresnel coefficients.

Two series of measurements are acquired by varying the same rotation angle  $\varphi$  to both linear polarizers placed under *co-* (denoted  $I(\varphi)$ ) or *cross/counter-* (denoted  $J(\varphi)$ ) configurations. These measurements correspond to polarization states of same ellipticity  $\varphi$  at the illumination and the detection, with same (measurements  $I(\varphi)$ ) or counter (measurements  $J(\varphi)$ ) helicity. As a result, the two sets of images acquired  $I(\varphi)$  (respectively  $J(\varphi)$ ) correspond to a gradual transition from linear co-polarized to circular cross-polarized image (respectively from linear cross-polarized to circular co-polarized image). The illumination is assumed to be of total intensity  $I_0$  and fully depolarized, *i.e.* with input Stokes vector  $S_{in} = I_0[1\ 0\ 0\ 0]^T$ . These experimental measurements/images are combined to define Elliptical polarization-difference (EPD) measurements/images as follows  $EPD(\varphi) = I(\varphi) - J(\varphi)$ . Taking into account the MMs expressions introduced above, these images/measurements channels can be shown to take the following analytical expressions:

$$EPD(\varphi) = f^-(\varphi)PM_L - f^+(\varphi)PM_C + S_p[1 - N\cos(2\varphi) - \varepsilon f^+(\varphi)] \quad (3)$$

where  $f^+(\varphi) = \sin(2\varphi)^2 = \frac{1-\cos(4\varphi)}{2}$ , and,  $f^-(\varphi) = \cos(2\varphi)^2 = \frac{1+\cos(4\varphi)}{2}$ . Such a compact expression clearly highlights the *multiply-scattered polarization-maintained* linear ( $PM_L$ ) and circular ( $PM_C$ ) contributions, as well as the specular contributions ( $S_p$ ).

### 3. Optimizing elliptical polarization filtering and data processing in backscattering configuration

This work proposes a generic signal processing workflow that could be applied to any location in the image, whether affected by specular reflection or not, in order to sort out the polarization-maintaining contributions of the linear and circular light respectively, and henceby recover some depth filtering capability. The study of these analytical expressions leads to clear identifications of more or less perfect filtering, under various situations, in specular and specular-free regions of the gated images. A calibration protocol has been established to achieve a real in-depth examination of the tissue sample by polarization gating with elliptically polarized light. The study will be illustrated on numerical simulations and with demonstrative experiments on actual data acquired on tissue phantoms and on test biological samples.

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