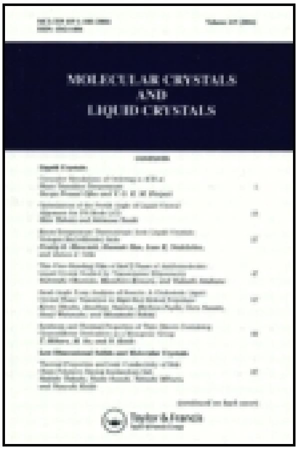

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

An Auto-Aligning Photopolarimeter

Giuseppe Lombardo [a], Christopher J. Newton [b] & John C. Rudin [b]

[a] INFM Research Unit, c/o Physics Dep, University of Calabria, Via P. Bucci, Rende, 87036, Italy

[b] Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol, BS34 8QZ, United Kingdom

Version of record first published: 18 Oct 2010

To cite this article: Giuseppe Lombardo, Christopher J. Newton & John C. Rudin (2003): An Auto-Aligning Photopolarimeter, Molecular Crystals and Liquid Crystals, 398:1, 117-126

To link to this article: http://dx.doi.org/10.1080/15421400390221493

Mol. Cryst. Liq. Cryst., Vol. 398, pp. 117–126, 2003

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400390221493

AN AUTO-ALIGNING PHOTOPOLARIMETER

Giuseppe Lombardo
INFM Research Unit, c/o Physics Dep, University of Calabria, Via P. Bucci 87036 Rende, Italy

Christopher J. Newton and John C. Rudin
Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol BS34 8QZ, United Kingdom

A new auto-aligning photopolarimeter, that will be used to probe a liquid crystal (LC) cell, is described. As the LC cell is rotated, it steers the probing laser beam and the photopolarimeter head must be re-aligned to allow for this. To efficiently collect data this re-alignment must be done automatically. We show that using a quadrant photodetector (QD) and a two dimensional duo-lateral position sensing detector (PSD) it is possible to dynamically re-align the head. Also we introduce a new method to calibrate this auto-aligning system. We can collect data from points distributed over the Poincairé sphere and then use all of these to find the instrument matrix $\mathbf{M}_c$ *that minimizes the error (in the least squares sense).*

Keywords: optics; polarimetry; stokes parameters; instrument matrix

INTRODUCTION

The state of polarization and intensity of a light beam, can be described by its four Stokes parameters [1]. Azzam has described a photopolarimeter for the simultaneous measurement of all four Stokes parameters of an incident light beam, that consists of only four photodetectors without any other optical elements [2]. Using this method the Stokes parameters of the light beam are given by

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \mathbf{M}_c(\theta, \phi) \begin{pmatrix} V_0 \\ V_1 \\ V_2 \\ V_3 \end{pmatrix} \tag{1}$$

The authors would like to thank Dr. Susanne Klein for her assistance with the initial optical set-up. One of us (G.L) would also like to thank the University of Reggio Calabria and European Scientific Network SILC-NET contract ERBFMRX-CT98–0209 for support.

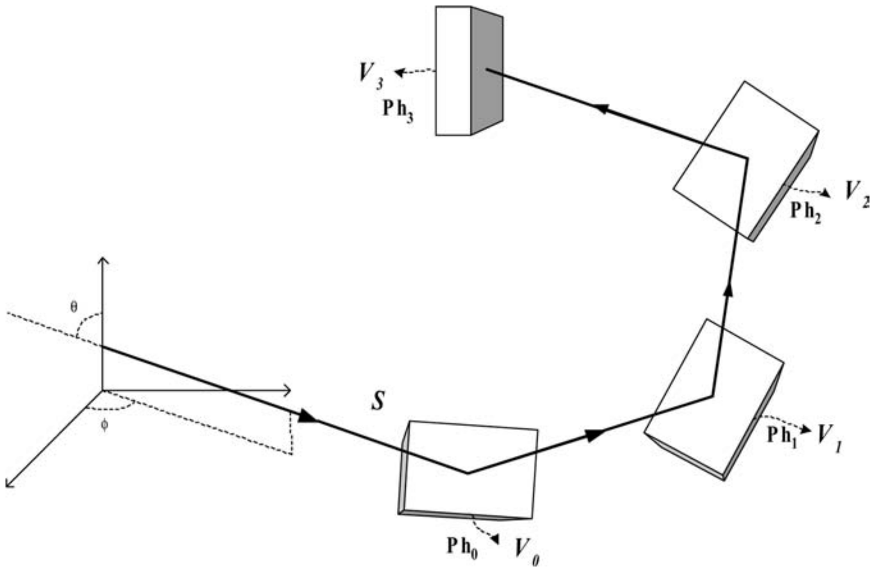

FIGURE 1 Calculation of the Stokes parameters of a light beam whose directions is determined by θ and ϕ: $\bar{S} = \mathbf{M}_c(\theta, \phi) \cdot \bar{V}$, where Ph_i $i = 0.3$ are photodetectors, V_i $i = 0.3$ are voltages.

The instrument matrix, $\mathbf{M}_c(\theta, \phi)$, must first be obtained by calibrating the system using a number of known polarization states (at least four independent states are needed). The instrument matrix depends upon the angles θ and ϕ shown in Figure 1. When the LC cell is rotated the angles θ and ϕ can change and the photopolarimeter head must be re-aligned to keep θ and ϕ constant if accurate results are to be obtained. While this can be done manually for each data point an automatic system allows the data to be collected much more quickly and efficiently.

We briefly describe the calibration method that we use, then we show how changing the angles θ and ϕ (effectively steering the beam) introduces errors. Finally we describe how we automatically align the photopolarimeter head and present results obtained using the system.

CALIBRATION

Practically, $\mathbf{M}_c$ is measured by recording the output signal vector $\bar{V}$ for a number ($\geq$4) of known input polarization states. When only four known polarization states are used, the optimum choice of these states corresponds to the vertices of a tetrahedron (maximum-volume pyramid) inscribed inside a Poincairé sphere [3,4]. To improve the calibration accuracy a number of different methods have been introduced [5,6], but these involve using a Fourier transform or a complicated locus of points on the Poincairé sphere. We have used a different approach to determine $\mathbf{M}_c$ more accurately. As we can easily collect data for points spread over the Poincairé sphere, we can calibrate the instrument using a large number of known polarization states ($\gg$4) and the matrix $\mathbf{M}_c$ is then obtained using a least squares fitting procedure [7].

The method will be described in more detail and further results given in another article.

ERRORS INTRODUCED BY STEERING THE BEAM LIGHT

We have measured how much the steering of the light beam influences the measurement of the Stokes parameters. In Figure 2 we show the percentage error that we obtain when the light beam hits the 4-photodetectors in directions $\theta = \theta_0 + \Delta\theta$ and $\phi = \phi_0 + \Delta\phi$ different from that used to calibrate the Stokes head. The axes $\Delta\theta$ and $\Delta\phi$ (in degrees) shows the shifts of the laser beam relative to centre the position, and θ_0 and ϕ_0. The error surface

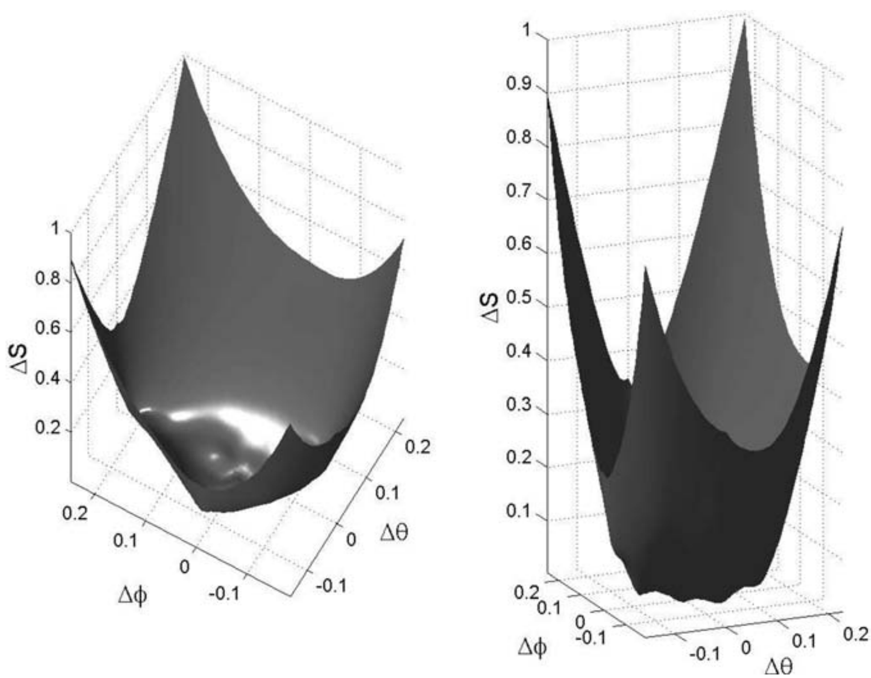

FIGURE 2 Percent error of the Stokes parameters due to the steering of the light beam away from θ_0 and ϕ_0.

consists of a smooth "valley" that surrounds the 0,0 position, but as $\Delta\theta$ and $\Delta\phi$ increase, there is a rapid increase in the error. The sensitivity with respect to θ and ϕ is the same.

So correct alignment of the laser beam with respect to the Stokes head is most important if accurate results are to be obtained.

AUTO ALIGNED SYSTEM STOKES HEAD

We have designed and built an electronic system that auto-aligns the Stokes head* (Fig. 3).

We have mounted the Stokes head on two stages, the x-z and the pan-tilt stage, such that the centre of rotation for pan-tilt is about the entrance aperture. The input beam is centred in this aperture by the x-z state using a quadrant photodetector (QD) with a small aperture in the centre (Fig. 4).

The pan-tilt is used to centre the final beam on the second detector, a two dimensional duo-lateral position sensing detector (PSD), placed after the four angled detectors (P_{hi}).

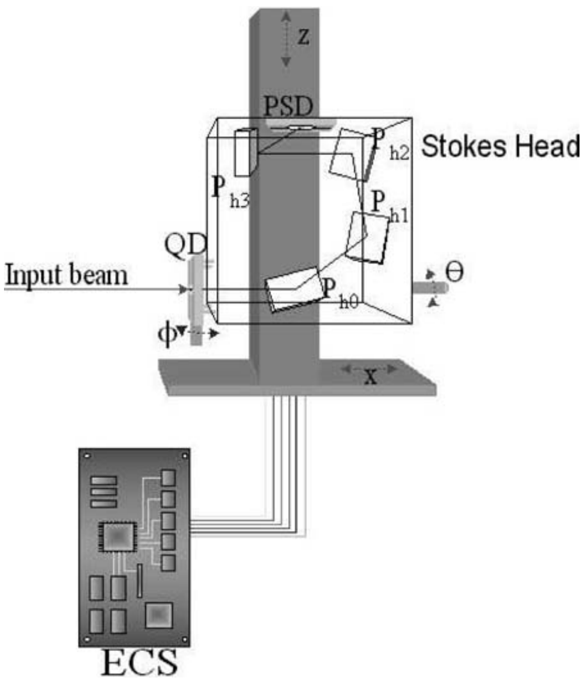

FIGURE 3 Electronic system used to auto-aligned the Stokes Head.

*We are using a commercial Stokes Head produced by Gaertner Scientific Corporation

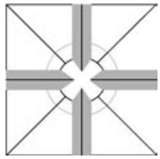

FIGURE 4 Quadrant photodetector (QD) with a small aperture so that the light beam can pass through it.

When the direction of the laser beam changes, the Electronic Control System (ECS) moves, at the same time and independently, the x-z and the pan-tilt stages following a Proportional Integral Derivative (PID) algorithm as response to the signals coming from the QD and the PSD detectors. This ensures that the angles θ and ϕ are always kept the same. The experimental set-up used to calibrate the system is shown in Figure 5. F is a gray filter, it serves to reduce the beam's intensity so that the photodiodes work in their linear region. P_1 and P_2 are linear polarizers, L and C are $\lambda/4$ retarders. The laser beam goes through the retarder, L, which has its axis is fixed at 45 degree relative to the polarizer P_1. In this way the light that comes out from the retarder L, is circularly polarized, this means that the intensity of the beam exiting the second polarizer P_2 is constant. Varying the direction of P_2 and C we can map all the points of the Poincaré sphere to obtain the instrument matrix. The data are collected by a DAQ Card that is able to acquire data up to 200 ks/sec.

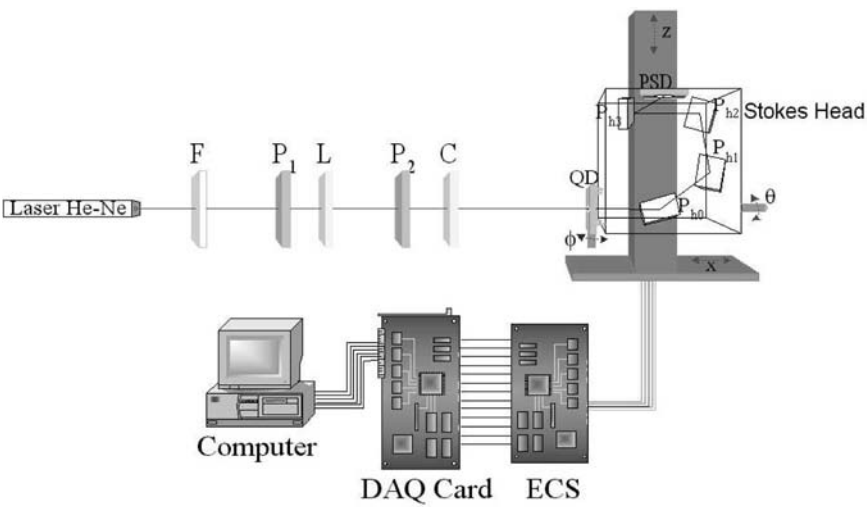

FIGURE 5 Experimental set-up used to collect data for calibration.

RESULTS AND CONCLUSIONS

We show the main results that we have obtained from the auto-aligning photopolarimeter. The points on the Poincairé sphere that we used to calculate the instrument matrix are shown in Figure 6. The matrix $\mathbf{M}_c$ that minimizes the error was:

$$\mathbf{M}_c = \begin{bmatrix} 16.80 & 7.45 & 1.69 & -0.214 \\ 17.39 & -31.12 & -26.67 & 39.33 \\ 35.21 & -20.68 & -4.16 & -2.57 \\ -15.22 & -20.43 & 29.23 & -2.86 \end{bmatrix} \quad (2)$$

with a condition number $\mu(M_c) = 6.88$.

To test this procedure we input a set of test points with known Stokes parameters and with unit intensity ($S_0^2 = 1.0$). The Stokes parameters calculated from the measured data do not in general have $S_1^2 + S_2^2 + S_3^2 = 1.0$ because the instrument matrix, has been obtained by

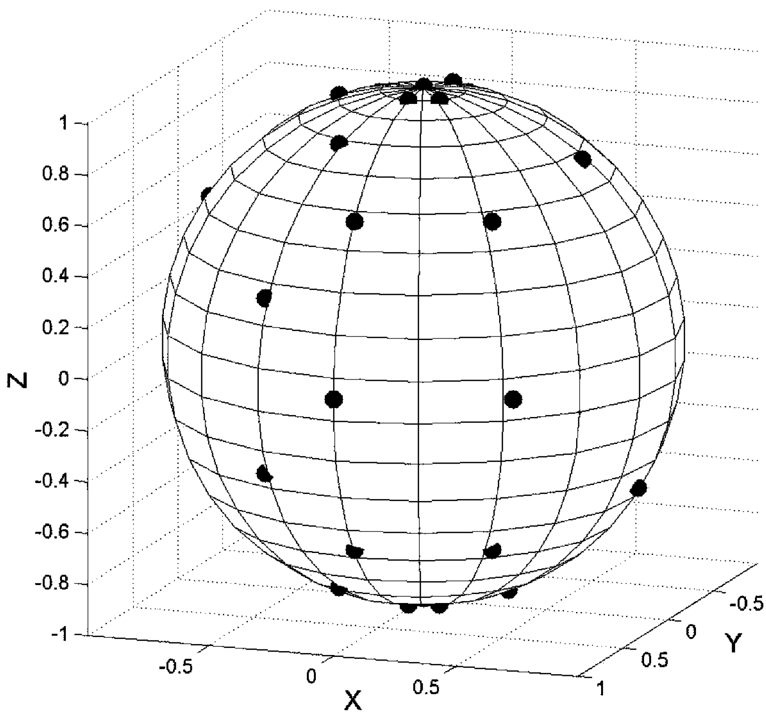

FIGURE 6 Points, in the Poincairé sphere, used to calibrate the instrument matrix of the auto-aligning photopolarimeter.

averaging, in least squares sense, over calibration points covering the whole Poincairé sphere. Normalizing the points shows that the direction is accurately obtained, most of the error is in the intensity value. To normalize we use the following procedure. Calling 2ω and 2λ the latitude and longitude of a point $\boldsymbol{P}$ on the surface of (unit-radius) Poincairé we will have:

$$2\omega = \arcsin\left(\frac{S_{3\mathrm{raw}}}{\sqrt{S_{1\mathrm{raw}}^2 + S_{2\mathrm{raw}}^2 + S_{3\mathrm{raw}}^2}}\right)$$

$$2\lambda = \arctan\left(\frac{S_{2\mathrm{raw}}}{S_{1\mathrm{raw}}}\right)$$

Then with this normalization we obtain our new Stokes value:

$$S_{1n} = \cos(2\omega)\cos(2\lambda)$$
$$S_{2n} = \cos(2\omega)\sin(2\lambda)$$
$$S_{3n} = \sin(2\omega)$$

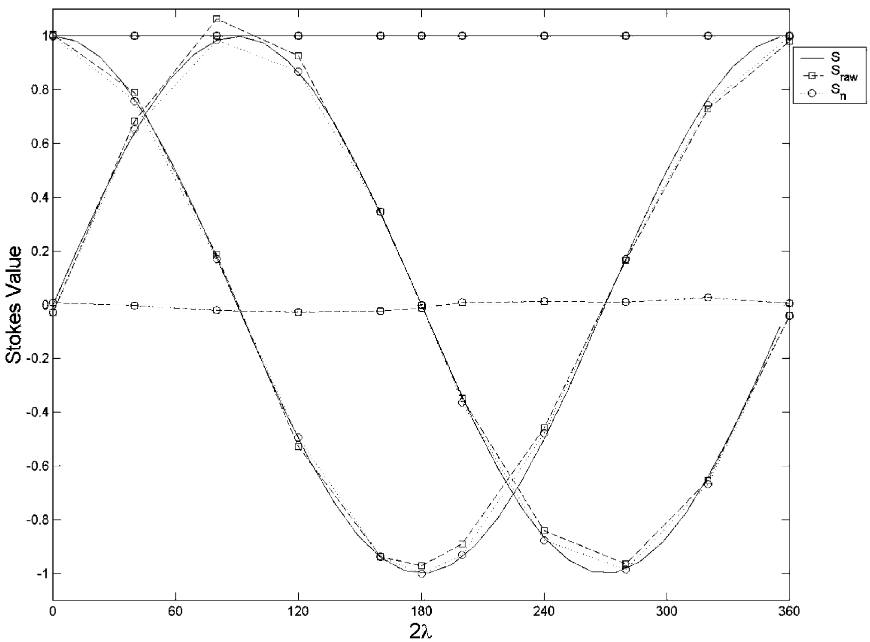

FIGURE 7 Stokes values of a linear polarized light: input S, raw S_{raw} and normalized S_n.

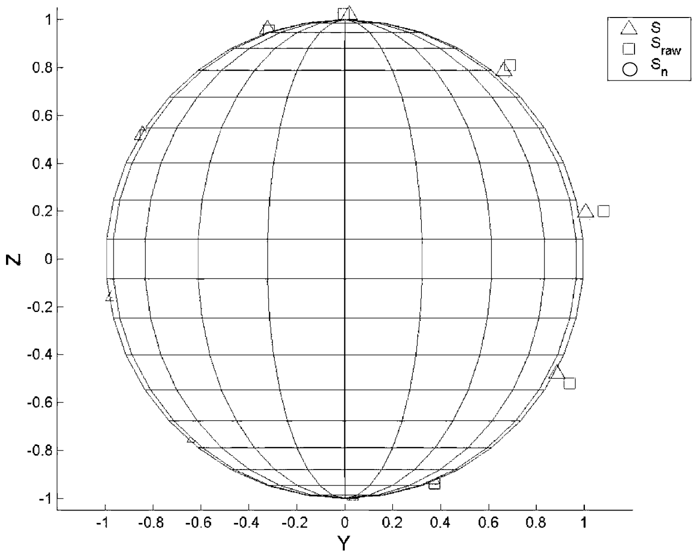

FIGURE 8 Poincairé sphere representation of a elliptical polarized light in the case that $2\lambda = 90$ and $-90 \leq 2\omega \leq 90$.

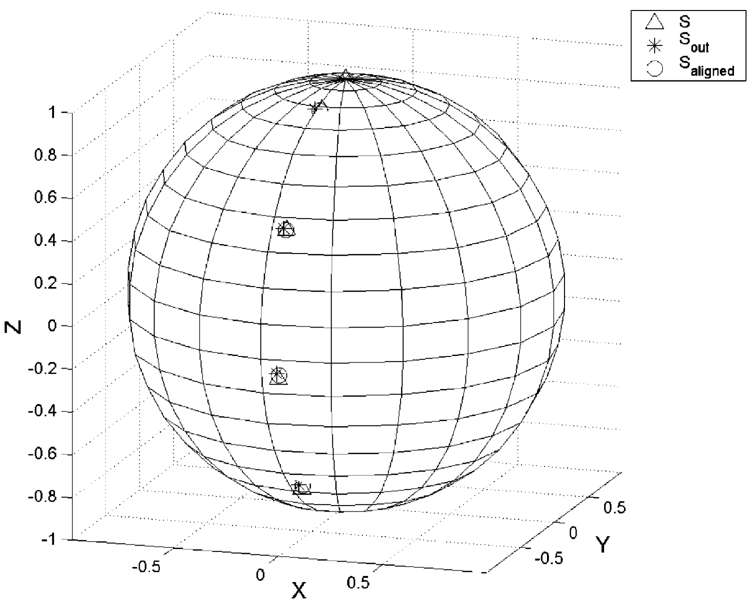

FIGURE 9 Comparison between the Stokes values S collected when the beam light is aligned S_{aligned} and when is steered S_{out} in.

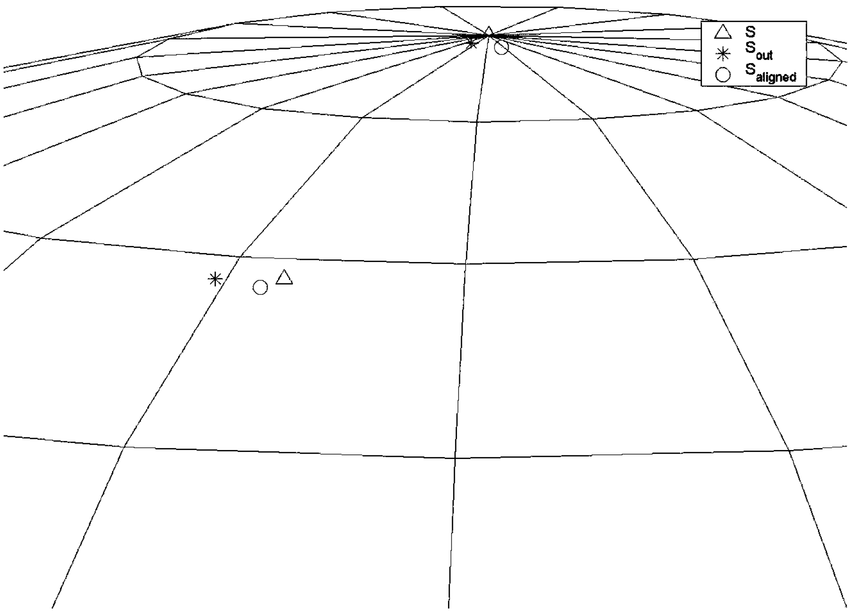

FIGURE 10 Enlargement of Figure 9.

In Figure 7 and in Figure 8 we show the raw (S_{raw}) and normalized (S_n) data relative to the input value of the Stokes parameters (S_i). We can see the direction of the points is the same, only the intensity changes.

To show how the auto-align system works in Figure 9 and in Figure 10 are showed the collected Stokes data for the case that the laser beam is aligned (S_{aligned}) and also when the light beam is steered (S_{out}) and we compared them to the real Stokes value (S).

In conclusions we have built an electronic system that is able to align the Stokes head if the light beam steers from the position used to calibrate the system. In this way we obtain an error less than 1 percent in the determination of the polarization of the light beam. Moreover, as we can easily collect data spread over the whole Poincairé sphere and use this to calibrate the system, we can obtain a better mapping for any input polarization (i.e. for any point on the Poincairé sphere).

REFERENCES

[1] Born, M. & Wolf, E. (1975). In: *Principles of Optics*, Pergamon: New York, 554.
[2] Azzam, R. M. A. (1985). *Optics Lett.*, *10*, 309–311.
[3] Azzam, R. M. A., Elminyawi, I. M., & El-Saba, A. M. (1988). *J. Opt. Soc. Am. A*, *5*, 681–689.

[4] Azzam, R. M. A., Masetti, E., Elminyawi, I. M., & Grosz, F. G. (1988). *Rev. Sci. Instrum.*, ***59***, 84–88.

[5] Azzam, R. M. A. & Lopez, A. G. (1989). ***J. Opt. Soc. Am. A***, ***6***, 1513–1521.

[6] Azzam, R. M. A. (1992). In: ***Direct and Inverse Methods in Radar Polarimetry, Part 1***, Kluwer Academic Publishers: Netherlands, 809–818.

[7] Press, W. H., Teukolsky, S. A., Vettering, W. T., & Flannery, B.P. In: ***Numerical Recipes in C, 2nd***, Cambridge University Press: Cambridge, 65–70.