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► To cite this version:

Jonathan Staes, Julien Fade. Optimized Stokes imaging for highly resolved optical speckle fields, Part I: optimized experimental setup. *Journal of the Optical Society of America. A Optics, Image Science, and Vision*, 2024, 41 (5), pp.789. 10.1364/josaa.516693 . hal-04596342

HAL Id: hal-04596342

<https://hal.science/hal-04596342v1>

Submitted on 14 Nov 2024

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Optimized Stokes imaging for highly resolved optical speckle fields, part I: Optimized experimental setup

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Abstract: In this first article of a three-paper series focusing on Stokes polarimetry of optical speckle fields resolved at the individual speckle grain scale, a review of the state of the art techniques for such experimental investigations is first provided. An optimized experimental setup is then extensively described which allows polarimetric Stokes measurements on such complex interference patterns to be carried out at each location of the speckle field without disturbing the wavefront. Specific calibration procedures are also described in order to provide the estimation of trustful polarimetric properties of light across a resolved speckle field.

1. Introduction

The phenomenon of speckle, very well-known in coherent optics, can be observed at the surface of a material when a coherent light source, such as laser light, illuminates a rough surface or propagates through a complex and/or random medium. The speckle pattern, an example of which is shown in Fig. 1, is made of more or less bright zones, termed speckle *grains*, which result from the constructive and destructive interferences of light components being scattered by the random medium. More precisely, a “grain” corresponds to an area of spatial coherence across the optical light field observed. Such phenomenon attracted an intense research in statistical optics to model and predict the characteristics of such complex interference patterns (size, shape, dynamic, polarization/coherence properties,...), resorting to stochastic (random) modeling of the light-matter interaction. Although commonly seen as a source of noise limiting the image quality [1–4] in the context of coherent imaging, the sensitivity of the speckle pattern, as an interferometric phenomenon, has enabled uncountable applications of speckle-based metrology or imaging modalities, especially in the biomedical domain with laser speckle contrast imaging for instance [5, 6].

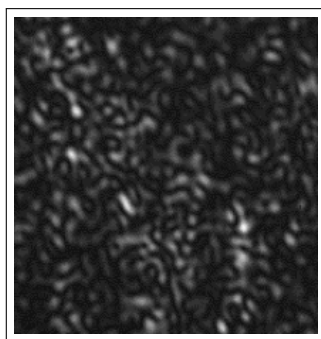


Fig. 1. Example of speckle pattern obtained by illuminating a scattering material (Spectralon) with a laser and imaging the backscattered field on a camera.

Besides theoretical characterization and practical applications of the speckle phenomenon, the polarization properties of speckle patterns has also been a domain of interest for research,

32 either theoretically [7–9], or for more applied purposes [10–12]. In particular, in the context of
33 active coherent polarimetric imaging, the phenomenon of depolarization of a polarized light field
34 by a rough surface has led to a fertile scientific literature [13–15]. Indeed, the depolarization
35 process not only depends on the optical and structural properties of the imaged object, but also
36 depends on the experimental conditions (illumination, detection...) in which it is observed. If the
37 depolarization properties were well known and understood at a macroscopic scale, i.e., when the
38 speckle grains are properly “averaged” over the surface of the detector or the pixel, the situation
39 was observed to be different when the size of the speckle grains become equal or greater than
40 a pixel of the detector, i.e., when the speckle pattern is “resolved” by the camera. Due to the
41 high sensitivity to all experimental conditions of speckle interference patterns, such observations
42 were issued from statistical analyses of experimental data, without a clear understanding of
43 the deterministic spatial distribution of the polarization state across the speckle field. This
44 motivated the development of specific imaging setups and measurement protocols able to perform
45 full-Stokes imaging analysis of the polarization properties of a highly resolved speckle pattern,
46 at a highly “sub-speckle grain” scale, i.e., with speckle grains covering hundreds or thousands
47 of pixels [16–18]. This article series focuses on this specific domain, and provides an optimal
48 instrumental and processing design to perform such measurements with best accuracy, precision
49 and robustness.

50
51 This paper is the first of a series of three joint articles, describing an optimized experimental
52 study of the polarimetric properties of highly resolved multiscale speckle patterns, including the
53 description of the optimized experimental setup used, a theoretical/simulation study to devise
54 optimized sensing/data processing in this particular context, and lastly, original results including
55 the proposal of new visualisation modalities to represent polarimetric information (and especially
56 polarimetric information in the vicinity of field polarization singularities). More precisely, this
57 series of articles can be decomposed as follows:

58 **Part 1: Experimental setup:** In the present article, we first provide in Section 2 a short
59 review of the previous works in polarization metrology of highly resolved speckle fields
60 in the optical domain. We then technically detail in Section 3 the experimental setup
61 used to perform the full-Stokes polarimetric analysis of the speckle pattern in a highly
62 resolved manner. We then detail the automated acquisition procedure involving the
63 so-called “SOPAFP” approach that will be detailed below, along with the processing
64 strategy for the generation of a so-called photometric image. Such processing includes a
65 dedicated calibration protocol used to correct the defects of the camera, while enabling
66 high-dynamic range imaging on the intensity images acquired experimentally. Finally, we
67 present in Section 6 preliminary results confirming the validity of the setup and of the
68 calibration/processing/measurement approach used.

69 **Part 2: Optimal acquisition & estimation strategies:** The second paper of this series [19]
70 presents a theoretical and numerical simulation study of the optimal sensing and processing
71 strategies for highly resolved polarimetric analysis of a speckle pattern in the optical
72 domain. These results allow us to clearly justify, for the first time to our best knowledge, the
73 clear interest of the SOPAFP approach with respect to more classical sensing modalities,
74 in particular to ensure best robustness of the estimated polarimetric states with respect to
75 experimental imperfections (alignment, calibration defect, temperature drift...). This second
76 paper provides a clear justification of the technical choices involved in the experimental
77 setup that are to be described below in the first article of this series.

78 **Part 3: Topological analysis of polarimetric states distribution with optimized data**
79 **representations:** In the last article of the series [20], original experimental results
80 issued from the optimized experimental bench developed are presented, allowing us to

81 confirm previous conclusions from anterior works, and to exhibit interesting structures
82 of polarization state distributions in the vicinity of field polarization singularities in the
83 speckle pattern. This third article also provides a discussion about the different available
84 choices for multi-scale graphical representations of the polarimetric information, and a
85 preferred original representation based on a specific planispheric projection is proposed and
86 used.

87 **2. State of the art of highly resolved Stokes imaging at the speckle grain scale**

88 As stated above, questioning the depolarization phenomenon in the context of coherent light
89 and speckled images justified the development of specific imaging instruments to measure the
90 distribution of polarization states across a highly resolved speckle pattern. To our best knowledge,
91 the first highly resolved Stokes imaging system at the speckle grain scale in the optics domain
92 was developed in 2011 and reported by Pouget *et al.* [16]. This first contribution made it
93 possible to highlight the many experimental difficulties of studying such a the speckle pattern
94 locally because of its utmost sensitivity to all experimental conditions (air flow, temperature
95 drift, vibration, laser stability, movement of optical components...), and proposed original ways
96 to circumvent these difficulties. Highly resolved speckle patterns ($\sim 10^3$ pixels per grain)
97 were obtained by imaging the sample under study through a $200\ \mu\text{m}$ pinhole. To estimate the
98 complete polarimetric state at each location of the speckle pattern, Stokes imaging was performed,
99 which consists in measuring the 4-component Stokes vector (which completely describes the
100 polarization state [21]) through various intensity image acquisitions performed with different
101 configuration of a polarization-analyzing component. In this work, a polarization state analyzer
102 (PSA) consisting of a retarding (quarter-wave) plate and a linear polarizer were placed in front
103 of the detector. To probe several polarimetric states, mechanically rotation of the PSA was
104 necessary, which implied tiny modifications of the optical path, which showed sufficient to
105 modify the wavefront at the surface of the detector, and hence modify the speckle pattern that
106 was under study. Despite the experimental difficulties and using a specific wavefront "recovery"
107 protocol [16], this first dedicated experimental setup made it possible to experimentally compare
108 the degree of polarization (DOP) at multiple scales and thus experimentally analyze the evolution
109 of the DOP from an unresolved speckle pattern to a resolved one [16]. More importantly, this
110 work established the first experimental confirmation (to our knowledge in the optics domain) of
111 the fact that, for a perfectly static sample under continuous single-mode laser illumination, the
112 polarization state at the grain scale is perfectly deterministic, i.e., with a degree of polarization
113 (DOP) equal to 1. It also confirmed the previous statistical studies which stated that depolarization
114 in this context of coherent imaging resulted from a spatial averaging (*spatial depolarization*)
115 at the surface of the detector (pixel) of speckle grains having each a specific and deterministic
116 polarization state. This work also allowed to study experimentally for the first time polarimetric
117 states "trajectories" at the transition between two contiguous grains.

118 In 2013, a similar experimental bench was developed by Ghabbach *et al.*, but this setup
119 included a voltage-controlled liquid crystal cell, which behaved as a polarimetric rotator [17].
120 Such configuration eliminates the need for any moving parts in the PSA, thereby ensuring the
121 best preservation of the optical path during polarimetric analysis. This setup, with a resolution of
122 the order of a few hundreds pixels per grain, demonstrated the interest of using liquid crystal
123 variable retarders (LCVR) to optimize the preservation of the wavefront, and confirmed the
124 abovementioned experimental observations. With this setup, a study of the polarization properties
125 of a speckle pattern using an unpolarized coherent illumination made it possible to experimentally
126 observe the so-called "repolarization" phenomenon obtained when a diffusing sample (assumed
127 to be totally depolarizing) is illuminated by a totally unpolarized coherent source [22, 23]. In this
128 situation, the expected and measured value of the spatial average of the DOP is $3/4$. Although this
129 phenomenon may be surprising given the depolarizing nature of the sample, it can be explained

130 theoretically by modelling the depolarized beam as the sum of two linearly polarized waves,
131 orthogonal to each other, and incoherent with each other.

132 Another setup was developed in 2014 by Dupont *et al.* [18,24] relying also on voltage controlled
133 LCVRs to avoid any moving part. In this work, an original sensing approach was used to estimate
134 the Stokes vector at each pixel by probing numerous polarimetric states distributed over the
135 surface of the Poincaré's sphere that maps all possible perfectly polarized states of light across
136 a unit sphere. This method was termed SOPAFP (for State Of Polarization Analysis by Full
137 Projection), and will be described in detail below in this paper and in the second article of this
138 series [19], as we shall use this approach for Stokes imaging. According to the first experimental
139 results, this approach makes it possible to carry out a more accurate polarimetric analysis of the
140 speckle pattern experimentally [18]. This work has also enabled polarimetric singularities to be
141 studied experimentally [24].

142 In this article series, we present an updated version of the seminal setup developed at University
143 of Rennes [16], including the advances proposed by the abovementioned contributors to this
144 field. We also establish through numerical simulations how the SOPAFP can be optimized in its
145 implementation in order to guarantee best estimation precision, accuracy and robustness [19].
146 We also present new experimental results and new representation modalities of the polarimetric
147 information that are best adapted to this particular domain of investigation [20].

148 3. Optimized experimental setup

149 3.1. General overview of the experimental setup

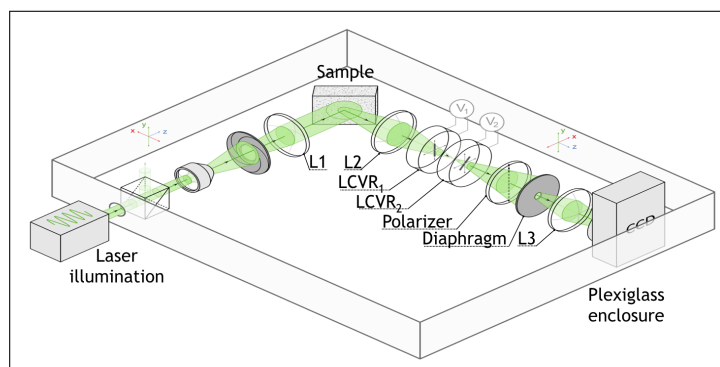


Fig. 2. Representation of the polarimetric imaging bench resolved at the speckle grain scale. For the sake of readability, the alignment mirrors between the laser source and the thermalization enclosure are not shown. In addition, the angle between the beam incident on the sample and the polarimetric analyzer is exaggerated here (90° in the figure, whereas 15° was implemented in the actual experiment to remain in a quasi monostatic configuration).

150 In order to gain better understanding of the depolarization/repolarization processes within the
151 grains of a speckle pattern or to study polarization state distributions/transitions between grains
152 or at the vicinity of field singularities, some hardware improvements to the initial polarimetric
153 imaging bench described in [16] have been made and are detailed in this section. The existing
154 setup has been installed in a plexiglass enclosure, itself placed on an air-cushioned optical
155 table to minimize, respectively, the variations of the airflow in the optical path, and mechanical
156 vibrations that can modify the interference pattern, as shown in [16]. In addition, this makes
157 it possible to temperature-stabilize the whole experiment, thereby ensuring further long-term
158 mechanical stability, but also stability of the optical response of the LCVR which is significantly

159 temperature-dependent. The temperature of the enclosure was regulated at 26°C, a few degrees
160 above the ambient temperature, using an on/off control and a heating cord, providing a $\pm 1^\circ$
161 stability over long periods of time. Yet, before each experimental acquisition, a thermalization
162 step lasting around twenty minutes was carried out, in order to compensate for the additional
163 heating of the setup by the laser illumination on the sample.

164 The various elements and characteristics of the imaging setup are now detailed in the following
165 subsections.

166 3.2. Laser illumination and samples

167 The illumination source is a highly coherent frequency-doubled optically pumped Nd:YVO₄
168 laser (COHERENT Verdi V12) with a coherence length of ~ 100 m and a wavelength of 532
169 nm. A calcite Glan polarizer is placed at the entrance of the setup to ensure perfect vertical
170 linear polarization of the beam (typical extinction ration 1:100,000), which undergoes several
171 mirror reflections to convey the beam from the laser to the setup entrance (these mirrors are
172 not shown in Fig.2). A telescopic arrangement of a microscope objective ($\times 10$, 0.25 NA,
173 OLYMPUS), a diaphragm and a convex lens L1 ($f=200$ mm) makes it possible to control the
174 width of the homogeneous collimated beam used to shine the sample, and to eliminate unwanted
175 reflections/diffraction artifacts. The aperture of the diaphragm is adjusted so as to obtain a
176 uniform spot of light on the sample of 2.5 cm in diameter.

177 The samples that have been studied consist of thick metallic plates, marble blocks of different
178 colours obtained with an homogenous layer of spray paint and a Spectralon reflectance standard.
179 These samples allowed us to perform experiments on opaque reflective/scattering materials with
180 various depolarization properties ranging from non depolarizing to totally depolarizing samples.
181 For each sample, preliminary thermalization was carried out as mentioned above.

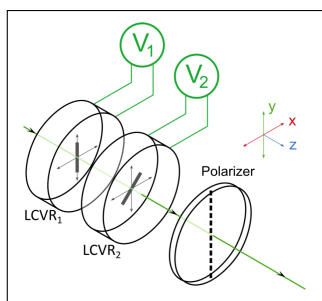


Fig. 3. Representation of the polarimetric analyzer based on voltage-controlled liquid crystal variable retarder (LCVR) plates.

182 3.3. Polarization analysis and imaging devices

183 On the light analysis/detection side, the imager consists of a polarimetric state analyser (PSA)
184 placed between two converging lenses (L2 ($f=80$ mm) and L3 ($f=40$ mm)), the whole PSA being
185 located upstream of the image sensor. In order to ensure similar conditions as coherent imaging
186 applications, the sample plane is conjugated with an intermediate image plane located at the
187 center of the PSA using the first converging lens L2. This intermediate image plane is finally
188 itself conjugated with the sensor plane with lens L3. As a result, the sample and the sensor
189 are located in conjugate planes, ensuring an imaging configuration of speckle observation, also
190 termed *subjective speckle* [25].

191 3.3.1. Polarization State Analyzer (PSA)

192 The PSA consists of two voltage-controlled, temperature-stabilized LCVR (MAEDOWLARK),
 193 named $LCVR_1$ and $LCVR_2$, and of a linear polarizer (Thorlabs). These two LCVRs have been
 194 adjusted so that their fast axes are aligned respectively along the vertical axis (parallel to the
 195 illumination polarization direction) and at -45° from the horizontal axis in a clockwise direction,
 196 as shown in Fig. 3. As for the polarizer, its axis is aligned vertically. Thus the Mueller matrix of
 197 such PSA is theoretically given by:

$$M_{PSA} = \frac{1}{2} \begin{pmatrix} 1 & -\cos(\phi_2) & \sin(\phi_1)\sin(\phi_2) & -\cos(\phi_1)\sin(\phi_2) \\ -1 & \cos(\phi_2) & -\sin(\phi_1)\sin(\phi_2) & \cos(\phi_1)\sin(\phi_2) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

198 where ϕ_1 and ϕ_2 represent the phase shifts introduced respectively on $LCVR_1$ and $LCVR_2$
 199 when a voltage pair V_{LCVR1} and V_{LCVR2} is applied. After a meticulous alignment step, the
 200 LCVRs require a conventional calibration stage (which will not be detailed here) in order to
 201 estimate the bijective polynomial functions f_i that map ϕ_i and V_{LCVRi} , i.e., $\phi_i = f_i(V_{LCVRi})$,
 202 with $i = 1, 2$ (An example of such calibration curves is reported in Fig. 10 of the second article
 203 of this series [19]). This PSA is positioned in the intermediate image plane between L2 and
 204 L3, to minimize the surface of interaction between the light beam and the PSA elements. As
 205 described below and in [19], the estimation of the incident Stokes vector $\mathbf{S}^n = [S_0, S_1, S_2, S_3]^T$
 206 is performed from the set of intensity images recorded, each image resulting from the projection
 207 of the incident state onto a given analysis polarization state defined by the PSA.

208 3.3.2. Diaphragm & image sensor

209 To obtain highly resolved speckle patterns on the camera, a tiny aperture diaphragm (pinhole) of
 210 diameter d is placed in front of the detector, on the converging lens nearest to the camera (L3).
 211 The average size of a speckle grain is indeed given, in an imaging configuration, as [25]:

$$\delta = 1.22\lambda \frac{2D}{d} \quad (2)$$

212 where D represents the distance between the detector surface and the upstream lens, which is
 213 equal to 6 cm in our configuration. Four sizes of pinholes ranging from 200 to 500 μm in steps
 214 of 100 μm were available and were tested in this study.

215 The detector is a visible silicon graylevel CMOS camera (PHOTONFOCUS A1312) with a
 216 full well capacity of 9×10^4 electrons (e^-), 4×10^3 e^-/s dark current, a readout noise of 110 e^-
 217 and a conversion dynamic range of 12 bits, i.e., 4096 grey levels. The sensor has a resolution of
 218 1312 x 1082 pixels, with square pixel size of 8×8 μm . As a result, the typical size of a grain
 219 ranges from 0.16 to 0.39 mm on the detector, giving a respective resolution (assuming circular
 220 speckle grains) of around 300 pixels per grain to 1900 pixels per grain. Such resolutions ensure
 221 in all cases that the speckle pattern is clearly resolved at the speckle grain scale by the sensor, as
 222 shown in Fig.1. The choice of the most appropriate diameter $d = 300$ μm and binning factor of
 223 4×4 pixels on the camera are justified below in the next subsection.

224 3.3.3. Characterization of the speckle grain size

225 In the experimental context addressed, the choice of the pinhole and speckle size is of utmost
 226 importance. There is indeed a compromise between using a small pinhole diameter and ensuring
 227 highly resolved speckle fields, but at the expense of a huge limitation of the quantity of light

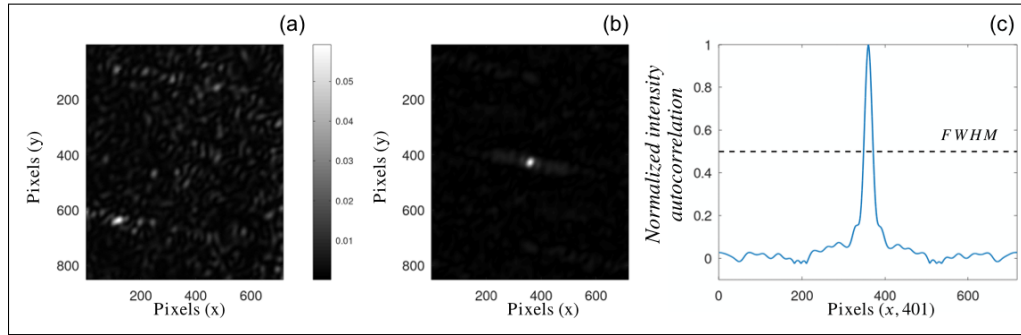


Fig. 4. Experimental estimation of the speckle grain size in pixels at the detector surface with a $300\ \mu\text{m}$ aperture. (a) The intensity image of the speckle pattern averaged over 20 images. (b) Autocorrelation of the speckle pattern. (c) Normalized autocorrelation profile at $y=401$. The size of the speckle grain is determined by the width at half-height of the autocorrelation peak normalized at $y=401$.

228 reaching each pixel, and hence of an increase of exposure time on the camera. We thus
 229 experimentally characterized the average speckle grain size without PSA, on a metallic plate,
 230 for the 4 different pinholes available. The intensity image of the interference pattern studied,
 231 shown in Fig. 4.a for the $300\ \mu\text{m}$ pinhole, results from the averaging of 20 intensity images.
 232 The power spectral density (as a function of spatial frequencies ν_x, ν_y) was classically obtained
 233 by computing $PSD_I(\nu_x, \nu_y) = |TF[I(x, y)]|^2$, with TF denoting 2-D Fourier transform, and
 234 $I(x, y)$ denoting the measured intensity at location (x, y) on the camera. Then, the autocorrelation
 235 function $R(x, y)$ was finally obtained by inverse Fourier transform of $PSD_I(\nu_x, \nu_y)$ after filtering
 236 out the intense zero frequency component (DC). The autocorrelation map obtained is displayed
 237 in Fig. 4.b, and the normalized autocorrelation horizontal profile at the center of the image is
 238 plotted in Fig. 4.c. The average speckle grain size is then determined by measuring the width at
 239 half-height maximum of the normalized autocorrelation function. The average width of a speckle
 240 grain is determined for different diaphragm diameters placed successively upstream of the image
 241 sensor. These values are shown in Table 1, as well as the corresponding number of pixels per
 242 speckle grain (without binning on the camera). All configurations clearly lead to very highly
 243 resolved speckle patterns.

244 However, another experimental parameter that can be adjusted on the camera is the binning
 245 factor, which is commonly used to smooth out measurement noise on the detector, but at the
 246 expense of a loss in resolution. A thorough study of the influence of the binning factor on the
 247 quality of estimation of Stokes vectors has been conducted, but which will not be detailed here
 248 for the sake of brevity (see [26] for more details). Such study allowed us to conclude that a 4×4
 249 binning factor on the detector was an interesting compromise to diminish estimation variance.
 250 As a result, the final choice of parameters that was retained and which will be used throughout
 251 this article series correspond to the association of a 4×4 binning factor, and a $300\ \mu\text{m}$ pinhole,
 252 which leads to approximately 25 binned pixels (also termed *superpixels* below) per speckle grain,
 253 thereby ensuring at the same time well resolved speckle patterns, satisfactory noise reduction,
 254 and sufficient intensity reaching the detector.

255 The plot of Fig. 5 allows us to check that this compromise is optimal: on the one hand, above
 256 ~ 10 binned pixels (or *superpixels*) per speckle grain, the standard deviation of the Stokes
 257 parameters (here S_0) is approximately constant and depends only on the noise characteristics of
 258 the camera. On the other hand, for non resolved speckle pattern, the standard deviation does not
 259 depend anymore on the number of averaged speckle grains per pixel. In between, the crossover
 260 region corresponds to the transition between non resolved speckle patterns and fully resolved

261 ones. As can be seen in Fig. 5, the proposed compromise to use 25 *superpixels* per speckle grain
 262 corresponds well to the situation of a resolved speckle field without any influence on estimation
 263 precision of the spatial sampling by the camera.

Table 1. Average speckle grain diameter (in pixels) and average number of pixels per speckle grain as a function of diaphragm diameter.

Diaphragm diameter (μm)	200	300	400	500
Experimental grain size (pixels)	26	20	18	11
Average number of pixels per grain (no binning)	676	400	324	121

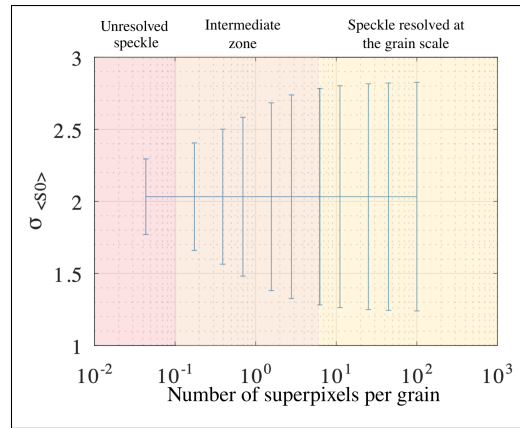


Fig. 5. Representation of the standard deviation of the S_0 parameter as a function of the number of "super" pixels per grain.

264 3.4. SOPAFP approach and polarization analysis states

265 In polarimetric imaging, one aims at measuring, at each pixel (i, j) of the image, the Stokes
 266 vector $(\mathbf{S}^{in})_{ij}$ (\mathbf{S}^{in} denoting the distribution of the Stokes vector across the whole image). For
 267 that purpose, several intensity image measurements are performed on the image sensor, through
 268 various configurations of the PSA. At each pixel location (i, j) , this process amounts to record
 269 a vector of measured intensities $(I_k)_{ij} = \mathbf{S}_{PSA,k}^T \cdot (\mathbf{S}^{in})_{ij}$ which results from the projection of
 270 the incident state $(\mathbf{S}^{in})_{ij}$ onto the k^{th} analysis state encoded on the PSA, denoted $\mathbf{S}_{PSA,k}$,
 271 where the index k represents the index of the analysis state. Since the process is similar
 272 at each pixel location, we will drop out the dependency in (i, j) in the following for clarity
 273 reasons. The set of measured intensities can be thus written as a N -dimensional column vector:
 274 $\mathbf{I} = [I_1, \dots, I_k, \dots, I_N]^T = \mathbf{W} \mathbf{S}^{in}$ where \mathbf{W} represents the *analysis* matrix, composed of N
 275 vectors of the analysis states $\mathbf{S}_{PSA,k}$ ($k \in [1, N]$). Classically, Stokes imaging requires 4
 276 to 6 intensity image measurements and optimal sensing strategies are well-known in these
 277 cases [27, 28]. Further considerations about Stokes imaging principles, polarization estimation

278 strategies and optimal configurations will be given in Part 2 of this article series [19], and are not
279 presented here for the sake of conciseness.

280 However, as stated in Section 2, in the context of polarimetric analysis of a highly resolved
281 speckle pattern, the SOPAFP approach was proposed as an alternative sensing method which
282 proved particularly well-suited in this context [18, 24]. Indeed, this technique enables the
283 polarimetric state to be estimated with greater precision while reducing sensitivity to experimental
284 biases. This will be shown in the second paper of this articles series [19], along with a more
285 extensive description of the SOPAFP technique, which basically consists in using numerous
286 (several tens to several hundreds) probe states $\mathbf{S}_{PSA,k}$ distributed over the surface of the Poincaré's
287 sphere. In that case, the set of measures $\{I_1, \dots, I_k, \dots, I_N\}$ at a given pixel location can be
288 represented as a particular waveform, which is characteristic of the input Stokes vector \mathbf{S}^{in}
289 to estimate. An example of such waveform is shown in Fig. 6 and consists of the concatenation of
290 150 intensity measurements obtained on a given set of 150 polarization analysis states generated
291 on the PSA, for a left-handed circular polarization input state.

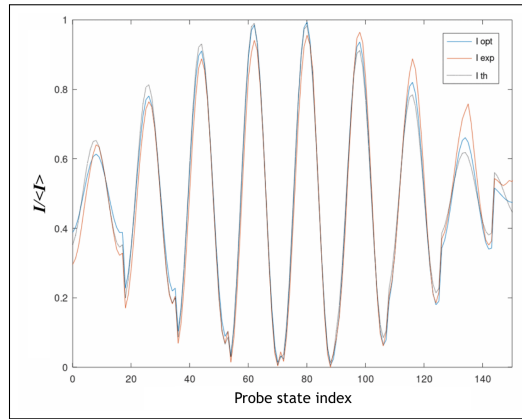


Fig. 6. Averaged intensity curve, normalized by the mean value, over the entire image
obtained with a left-hand circularly polarized illumination source and for a given set of
150 projection states. In black: simulated intensity curve theoretically detected by the
camera. In red: experimentally measured intensity curve. Blue: optimized intensity
curve obtained by non-linear regression.

292 In [24], it was proposed to estimate the Stokes vector from this characteristic waveform
293 by carrying out a non linear regression of the curve, which can be theoretically expressed as
294 a function of the Stokes vector's parameters (4 parameters) and of the PSA configuration (2
295 parameters). As detailed in the second article of this series, such non-linear regression is efficient,
296 but very long in terms of computation time, due to the number of pixels in the image sensor
297 (several hundred thousands) and the number of acquisitions (several hundreds). For instance,
298 about 42 minutes were required to process acquisitions of 700×700 pixels undergoing 4×4
299 binning, for 150 probe states such as the ones implemented in the above example of Fig. 6. As
300 will be shown in the next paper of this series, we have proposed to implement a direct matrix
301 inversion that was shown to have the same estimation performances as the non linear regression,
302 but with a gain in processing time of a factor of 1.5×10^3 .

303 It is well-known in the field of Stokes imaging that estimation errors occurring during inversion
304 of such linear system can be minimized through an appropriate choice of analyzing states which
305 ensure best conditioning of the sensing linear operator (matrix). For instance, in classical Stokes
306 imaging with 4 intensity acquisitions, the optimal states should lie at the vertices of a regular
307 tetrahedron within the Poincaré's sphere. This discussion about the optimal choice of probing

308 states is also reported in the second article of this series, where we demonstrate that even in the
 309 context of the SOPAFP approach (i.e., with $N \gg 4$), one can design an optimal set of sensing
 310 states to ensure best conditioning of the sensing operator. We will also establish that a set of $N=96$
 311 measures appears to be a good tradeoff between estimation quality and acquisition/processing
 312 delays [19].

313 4. Automated acquisition protocol

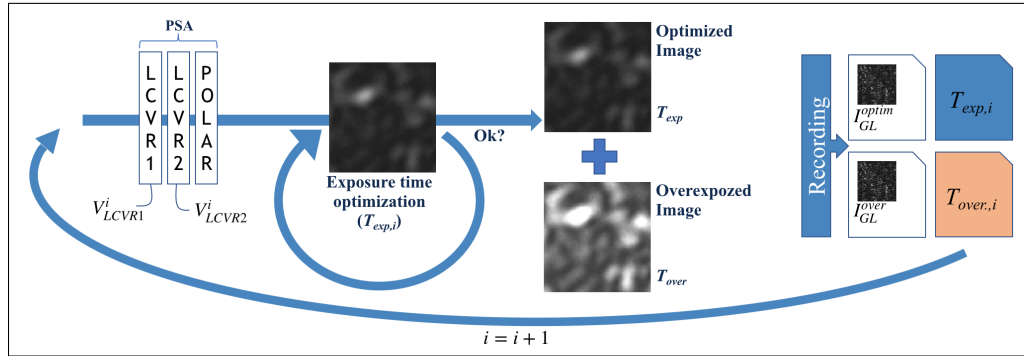


Fig. 7. Schematic diagram of the automated acquisition protocol.

314 As mentioned above, the acquisition protocol is fully automated and implements a high dynamic
 315 range (HDR) imaging approach, in order to increase the dynamic range of the measurement (and
 316 thus extend the native 12 bits dynamics of the camera) which is necessary in such a context
 317 of imaging an interference pattern composed of very bright and dark spots. This consists in
 318 acquiring and appropriately recombining two images, one with optimized exposure time to avoid
 319 saturation of the sensor (referred to as optimized image, I_{GL}^{optim}) and a second image which is
 320 overexposed in order to increase the measurement dynamics in the dark regions of the scene
 321 (referred to as overexposed image, I_{GL}^{over}). Control of probe states, HDR acquisition and images
 322 recording has been fully automated by computer using the LabVIEW software. The acquisition
 323 protocol can be decomposed as follows:

- 324 • **Thermalization** : As mentioned previously, before each acquisition, the whole imaging
 325 bench is thermalized at 26 °C with laser illumination turned on for about 30 min.
- 326 • **Probe states selection**: A voltage pair (V_{LCVR1}^k, V_{LCVR2}^k), corresponding to the k^{th} probe
 327 state, with $k \in [1, N]$ is applied to the PSA LCVRs plates.
- 328 • **Exposure time optimization**: the exposure time is optimized for each image acquisition,
 329 through an automated numerical control loop that ensures the following criterion:

$$90\% \text{ max. sensor dynamics} \leq \max\{I_{GL}\} < 100\% \text{ max. sensor dynamics}, \quad (3)$$

330 with I_{GL} denoting the acquired image in graylevel values. This criterion requires that the
 331 maximum value of the image (in graylevels) must be less than 100% of the camera dynamic
 332 range (in graylevels) to avoid any saturation. In addition, this maximum value must reach
 333 at least 90% of the dynamic range, thus guaranteeing the use of a large part of the camera's
 334 native dynamic range. The control loop corresponds to a numerical implementation of a
 335 PID regulator. The optimized image is then acquired once the exposure time T_{exp} is set.

- 336 • **Overexposed image**: A second image is then recorded with a longer exposure time T_{over} ,
 337 corresponding to the multiplication of the optimized exposure time by an overexposure

338 coefficient of 4. For these optimization conditions to be fulfilled, it is necessary to ensure
 339 the absence of hot pixels on the sensor. These pixels have abnormally high distorted values,
 340 generally due to a local defect in the pixel. The camera used in this work has on-board
 341 correction processing to overcome these biases by applying a correction based on linear
 342 interpolation of the surrounding pixels.

343 • **HDR recombination:** After acquiring the "optimized" and "overexposed" images and
 344 normalizing them by their respective exposure times, they can be recombined, for each
 345 pixel of discrete integer coordinates (p, q) as:

$$I^{\text{recomb}}(p, q) = \begin{cases} I^{\text{over}}(p, q) = \frac{I^{\text{over}}(p, q)}{T_{\text{over}}} & \text{if } I_{\text{GL}}^{\text{over}}(p, q) < 4095 \\ I^{\text{optim}}(p, q) = \frac{I^{\text{optim}}(p, q)}{T_{\text{exp}}} & \text{otherwise.} \end{cases} \quad (4)$$

346 In this way, the pixel value of the recombined image is equal to that of the normalized
 347 overexposed image unless this pixel is saturated, in which latter case the pixel value of the
 348 normalized optimized image is selected.

349 However, this simple recombination procedure was shown to be unsuccessful to provide
 350 satisfactory recombined HDR images, which allowed us to identify significant non-linearities
 351 in the response of the sensor as a function of illumination and of exposure time. Owing to this
 352 imperfection of the sensor, the above HDR recombination was inoperative. Such defects showed
 353 that it was necessary to be able to relate the measured graylevels on the camera to calibrated
 354 photometric quantities, in order to provide rigorous experimental results and trustful polarimetric
 355 state estimations. To overcome this problem, we propose in the next section a camera calibration
 356 procedure and intensity image correction protocol that can be applied to any non-linear imaging
 357 sensor in order to provide satisfactory photometric measurements.

358 5. Non-linear sensor calibration/correction procedure

359 We first detail the calibration protocol that allowed us to estimate the non-linear response of the
 360 sensor, and we then report the original image correction technique that was proposed, making it
 361 possible to provide reliable photometric measurements from the graylevel pixel data acquired,
 362 and to implement a HDR recombination technique.

363 5.1. Camera calibration

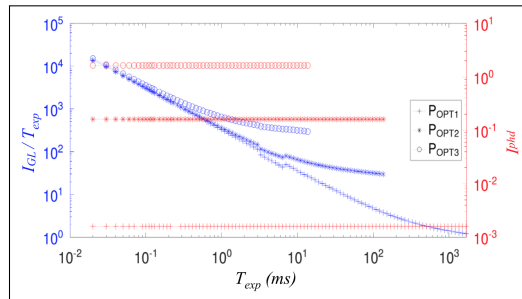


Fig. 8. Measurement of the non-linear intensity response of the camera (average graylevel value normalized by the exposure time, in blue symbols) as a function of the exposure time, for three distinct values of the optical power injected in an integrating sphere. The red symbols correspond to the reference photometric measurement of the light intensity I^{phd} obtained with a calibrated photodiode.

364 The characterization of the non-linear response of the camera was carried out using the
 365 illumination laser which was injected in one port of a 40 cm diameter integrating sphere
 366 (LABSPHERE). The CMOS focal plane was placed in front of the main port (5 cm diameter) of
 367 the integrating sphere, thereby enabling perfectly homogeneous and isotropic illumination of the
 368 sensor due to strong scattering of the incident beam by the integrating sphere coated with highly
 369 scattering Spectralon. The sphere was equipped with a reference photodiode located inside
 370 the sphere, and coupled to a pico-amperemeter (KEITHLEY) providing us with a trustful and
 371 calibrated (albeit relative) measurement of the photometric intensity on the sensor. In Fig. 8, one
 372 can observe the strong non-linearity of the sensor since, at a given power, the ratio of intensity
 373 normalized by the exposure time T_{exp} is not constant. For a camera with a linear response, the
 374 normalized graylevel intensity should be constant at a constant power, which is not the case for our
 375 sensor, hence highlighting the non-linear nature of the intensity (greyscale) response as a function
 376 of exposure time of our camera. To fully characterize the camera non-linearities, an automated
 377 protocol was implemented to simultaneously measure the camera intensity in graylevels I_{GL}
 378 (average over the whole sensor) and the photometric intensity I_{phd} measured with the photodiode,
 379 while performing a slow sweep of the laser power P_{opt} coupled with a fast sweep of the camera
 380 exposure time T_{exp} (ranging from durations of 0.01 to 1667 ms). In this way, 8×10^3 calibration
 381 points were measured and recorded. The 12-bit graylevel values measured on the camera are
 382 displayed in Fig. 9 for these 8×10^3 calibration points, as a function of the exposure time, and for
 383 various illumination powers. A corresponding 2-D map was obtained for the 8×10^3 calibration
 384 points, providing the photometric intensity value measured on the reference photodiode as a
 385 function of illumination power. These two mappings allow us to design an automated and fast
 386 correction protocol for all the image acquisitions performed after this calibration step.

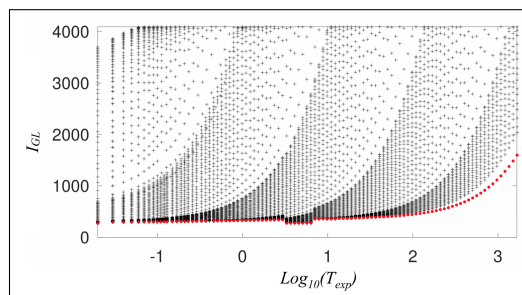


Fig. 9. Plot of the graylevel values (12 bits) measured by the camera as a function of exposure time for various illumination powers.

387 5.2. Correction protocol

388 The above calibration experiment provided us with two mappings of the camera intensity in
 389 graylevel and of the photometric intensity measured by calibration. The 8×10^3 calibration
 390 points are located in a non-regular grid mapping the experimental parameters: exposure time and
 391 optical power. In order to be able to correct acquired data at each pixel for any situation, it is
 392 necessary to interpolate such calibration set. This was operated by first computing a Delaunay
 393 tessellation mesh on this calibration data, followed by a linear data interpolation step. The whole
 394 calibration/correction processing comprises four main steps:

- 395 • **Computation of the Delaunay's triangulation mesh:** The calibration procedure proposed
 396 relies on the computation of a Delaunay triangulation mesh between calibration datapoints
 397 in the $(\log(T_{\text{exp}}), I_{\text{GL}})$ plane (see Fig. 9). Such operation is also referred to as Delaunay

398 tessellation, which consists of connecting all the data points with a triangular mesh that is
 399 optimized so to as to avoid sliver triangles [29].

400 As the 8×10^3 calibration points are spread over 5 decades of T_{exp} , and in order to minimize
 401 the processing time, it appeared irrelevant to use the whole calibration data set (which
 402 would hav implied computing and handling a huge amount of data in the recorded mesh) to
 403 process each pixel value of each acquired image. We thus rather computed “local” meshes
 404 from subsets of the calibration data in the vicinity of the actual frame exposure time T_{exp}
 405 as shown in Fig. 10 b. This subset is defined as follows:

$$\left\{ i \in [1; 8 \times 10^3] \quad / \quad \log(T_{\text{exp}}) - 0.1 \leq \log(T_{\text{exp},i}^{\text{cal}}) \leq \log(T_{\text{exp}}) + 0.1 \right\} \quad (5)$$

406 with log denoting decimal logarithm, and where T_{exp} is the exposure time of the image/pixel
 407 to be processed, and $T_{\text{exp},i}^{\text{cal}}$ is the exposure time of the i^{th} calibration point. A Delaunay
 408 tessellation mesh is then calculated on the selected calibration points (Fig. 10.b), and
 409 stored in the computer for further image correction. It can be noted that this calibration
 410 step has to be performed only once, since the recorded meshes can be then used later on for
 411 images correction steps detailed below.

- 412 • **Positioning pixel value in the calibration mesh:** For the pixel with coordinates (p,q)
 413 in the sensor, the greyscale intensity value to be corrected $I_{\text{GL}}(p, q)$ is positioned in the
 414 $(\log(T_{\text{exp}}), I_{\text{GL}})$ plane (see Fig. 10.a).
- 415 • **Mesh cell identification :** The coordinates of the three vertices of the mesh surrounding
 416 $I_{\text{GL}}(p, q)$ in the $(\log(T_{\text{exp}}), I_{\text{GL}})$ plane are determined (see Fig. 10.b).
- 417 • **Data interpolation and photometric correction:** Finally, the corrected photometric
 418 intensity value $I_{\text{corr}}(p, q)$ is obtained using a linear interpolation in triangular coordinates
 419 of the calibration data available at the three vertices (see Fig. 10.c).

420 To perform HDR imaging, this correction protocol has to be applied a second time for the
 421 pixels corresponding to the overexposed image, hence requiring the use of a second "local"
 422 Delaunay mesh stored from calibration. HDR recombination must now be carried out on the
 423 corrected images, using the same criterion as in Eq. (6):

$$I_{\text{corr}}^{\text{recomb}}(p, q) = \begin{cases} I_{\text{corr}}^{\text{over}}(p, q) & \text{if } I_{\text{GL}}^{\text{over}}(p, q) < 4095 \\ I_{\text{corr}}^{\text{optim}}(p, q) & \text{otherwise.} \end{cases} \quad (6)$$

424 The advantage of this calibration/correction method is that it makes it possible to convert
 425 (non-linear) camera greyscale data into a photometric quantity (relative, but guaranteeing good
 426 linearity), while preserving the advantages of the HDR approach. This generic approach could
 427 be applied to any type of camera, to the expense of a meticulous and time-consuming calibration
 428 stage, but with calibration datapoints that are not necessarily on a regular grid. The proposed
 429 correction procedure sufficiently fast in the context of this study where real-time imaging and
 430 processing is not required (typically 1.3 seconds required for correcting a 700×700 pixel image).

431 5.3. Validation of the calibration/correction protocol

432 In order to assess the effectiveness of the calibration/correction protocol proposed above for
 433 correcting the non-linearity of the sensor, a first validation was carried out on a subset of
 434 calibration data points. First, we removed from the calibration dataset (Fig. 9) all calibration
 435 points corresponding to a constant relative photometric intensity of $I_{phd} = 1.633$. The selected
 436 points were considered as a test dataset, while the remainder of the calibration points were used as

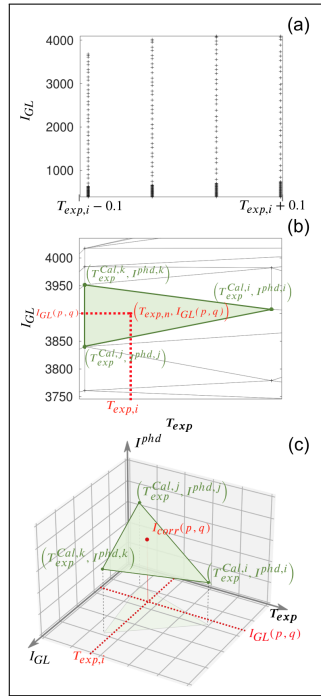


Fig. 10. Illustration of the correction protocol proposed to convert the grayscale value $I_{GL}(p, q)$, detected at pixel (p, q) for an exposure time T_{exp} , into a calibrated photometric intensity value $I_{corr}(p, q)$. For the sake of readability, a logarithmic scale is used for the exposure times

437 the calibration dataset for this validation step. Secondly, the entire correction protocol (Delaunay
 438 tessellation and linear interpolation in triangular coordinates) was applied to correct the test
 439 dataset from the calibration dataset, and to compute photometric corrected intensity values I_{corr} .
 440 This allowed us to compare these corrected intensity values to the ground-truth photometric
 441 intensity measurements available in the original calibration dataset. Such comparison is shown
 442 in Fig. 11, where it can be seen that, for a constant photometric intensity value of $I_{phd} = 1.633$
 443 (black diamonds and dotted line), the range of corrected intensity values lies within a 5.4% margin
 444 from the calibrated photometric value (black triangles). This plot demonstrates the efficiency
 445 of the calibration/correction protocol proposed to ensure reliable photometric quantities in the
 446 measured images, while simple normalization of the greylevel values by the exposure time is
 447 very inoperative with such a non-linear sensor (red circles).

448 A further validation step on experimental data was conducted to prove the relevance of this
 449 protocol, as well as the efficiency of the HDR recombination. The calibration/correction protocol
 450 was applied to Stokes imaging data, obtained experimentally on a metallic plate probed by 80
 451 polarimetric states distributed uniformly over the Poincaré's sphere, with a binning factor of 4×4
 452 pixels, and with the dual exposure time HDR approach detailed above. From this polarimetric data,
 453 we computed the S_0 image (total intensity) plotted in Fig. 12 ((a) and (e)), the map of the DOP
 454 ((b) and (f)), and its corresponding histogram ((c) and (g)). The first row of Fig. 12 corresponds
 455 to the results obtained when the acquired images are simply normalized by their respective
 456 exposure time and with HDR recombination using Eq. (4), whereas the second row corresponds
 457 to data after correction of the sensor's non-linearities and HDR recombination through Eq. (6).
 458 Although no clear difference can be observed between the intensity images ((a) and (e)), the

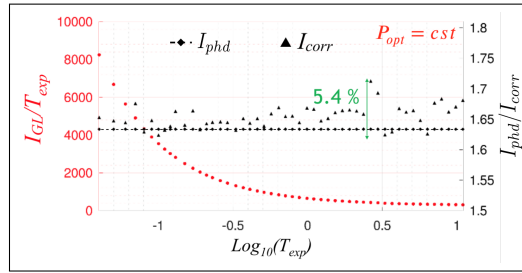


Fig. 11. Graphical comparison between the greyscale intensity values of the selected points normalized by the respective exposure time I_{GL}/T_{exp} (red circles), the intensity value after correction I_{corr} (black triangles) and the relative photometric intensity I_{phd} (black diamonds and dotted horizontal line).

459 maps of the DOP clearly demonstrates the necessity of the non-linear calibration/correction
 460 stage. Indeed, as expected on a non-depolarizing sample (such as a metallic blade) illuminated
 461 with linearly polarized light, the DOP value should be equal to one over the whole field of
 462 view (at least in significantly bright regions where the estimation of the state of polarization
 463 can be trusted). This is clearly not the case when the data is not preliminary corrected before
 464 HDR recombination, the histogram of the DOP showing a clearly unexpected bimodal behaviour
 465 with an average value of 0.27. Much more satisfactory are the map and histogram of the DOP
 466 obtained (on the same experimental data acquisition) after photometric correction: a majority of
 467 pixels show high value of the DOP, as expected, with an average value of 0.74 and with very few
 468 abnormal data (only about 1.2% of the pixels having an unphysical estimated DOP value above
 469 1). In order to confirm the efficiency of the correction approach implemented, and to demonstrate
 470 the fact that low values of DOP are obtained in low intensity regions where the estimation of
 471 the Stokes parameters is less reliable, scatter plots displaying the estimated value of the DOP
 472 at each location of the image as a function of the S_0 value are provided in Fig. 12 (d) and (h).
 473 First, the analysis of the plot of Fig. 12 (d) confirms the inability of the simple normalization by
 474 exposure time to provide satisfactory maps of the DOP. Then, it can be seen in Fig. 12 (h) that
 475 the correction approach leads to a much more trustworthy distribution of the DOP (expected to
 476 be unitary across the image for a metallic non depolarizing plate under polarized illumination),
 477 where low values of the DOP are clearly obtained for low values of the S_0 intensity across the
 478 speckle pattern. Finally, as these results are in agreement with anterior studies [16], we consider
 479 that these results validate the efficiency of the proposed calibration/correction protocol.

480 In the next section, and in all the remainder of this article series, this calibration/correction
 481 processing scheme will be applied to all experimental data reported. Of course, the calibration/
 482 correction protocol described above would be unnecessary when using a camera with a
 483 satisfactory linear response of its graylevels with illumination power and exposure time, thereby
 484 saving some post-processing time. However, such a calibration/correction technique can prove
 485 interesting in any imaging context where relevant relative photometric measures are required,
 486 and in particular in spectral domains where the sensors technology is less mature than in the
 487 visible range.

488 6. Preliminary results and validation of the experimental setup

489 In the last section of this paper, we briefly illustrate the relevance of the choices discussed above
 490 for the various experimental parameters at stakes for Stokes polarimetric analysis resolved at the
 491 speckle grain scale. Stokes imaging results obtained on two samples are presented below: on a
 492 metallic plate (non-depolarizing sample) and on a sample of Spectralon (totally depolarizing

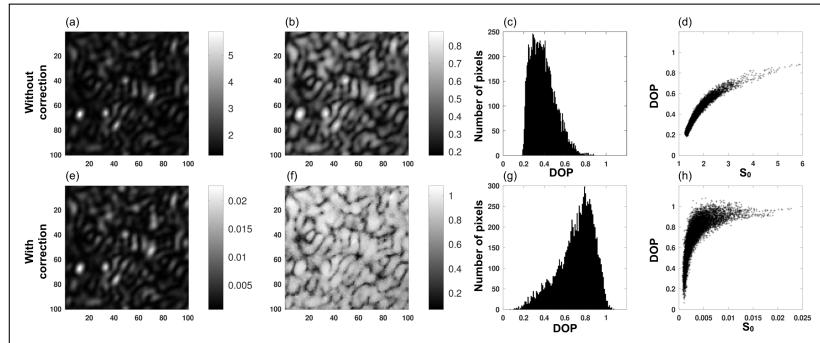


Fig. 12. Experimental images of S_0 (first column), DOP (second column) and histogram of the DOP (third column) without correction (respectively (a), (b), (c)), and after application of the correction protocol (respectively (e), (f), (g)). The scatter plots displayed in (d) and (h) show the correlation of the measured DOP values with the speckle field intensity S_0 respectively before and after correction.

493 scattering sample). These acquisitions were made with a vertically polarized input light beam
 494 and a diaphragm diameter of $300 \mu\text{m}$. For Stokes measurements, $N = 80$ polarimetric states
 495 uniformly distributed over the surface of the Poincaré's sphere, according to the above mentioned
 496 SOPAFP approach, are probed using the liquid crystal variable delay plate PSA. In addition, the
 497 two-image HDR approach described in Section 4 is used during acquisition, and the grey-scale
 498 intensity images are recombined and corrected to obtain photometric intensity images, as stated
 499 above in the description of the calibration process. A 4×4 pixel binning factor is used before
 500 estimation of the various Stokes parameters and of the DOP, which are deduced from these
 501 intensity images.

502 These first validation results are presented in Fig. 13 for both samples (metallic plate on the
 503 left-hand side, spectralon on the right-hand side). Plots of Fig. 13 display examples of intensity
 504 acquisitions (S_0) in graylevels in the first row. Then, the two next components s_1 and s_2 of the
 505 reduced Stokes vector (i.e., Stokes vector normalized by the value of S_0) are mapped in the
 506 second and third rows, with values between -1 and 1 represented with a green/pink colormap.
 507 The last component s_3 of the reduced Stokes vector, corresponding to the circular polarization
 508 contribution, is mapped in the fourth row, with values between -1 and 1 represented with a
 509 specific blue/red colormap, red color (respectively blue) denoting right (respectively left) circular
 510 polarization, i.e. negative (respectively positive) ellipticity. Finally, the DOP is computed and
 511 plotted in the last row in graylevels. These plots are analyzed below:

512 6.1. Metal plate

513 The first sample considered is a flat, metallic plate roughly polished so that it can scatter light at
 514 its surface, even at a non-specular angle, thereby producing a speckle field that can be imaged
 515 in the setup. Although such metallic rough surface can locally introduce retardance due to its
 516 complex refractive index at oblique incidences, we will consider in first approximation that
 517 this sample almost does not alter the polarization state of the incident light, which is linearly
 518 vertically polarized. As a result, only the s_1 component should differ from zero, with unit
 519 value. This is what is observed in the left column of Fig. 13, with very small values of s_2 and
 520 s_3 , while s_1 is almost uniformly very close to 1, at least in significantly bright regions of the
 521 speckle pattern. In very dark regions indeed, despite the HDR approach implemented, the level
 522 of confidence in the estimated values of the Stokes components is lower. Another interesting
 523 feature of non-depolarizing samples is that the speckle pattern spatial distribution should be

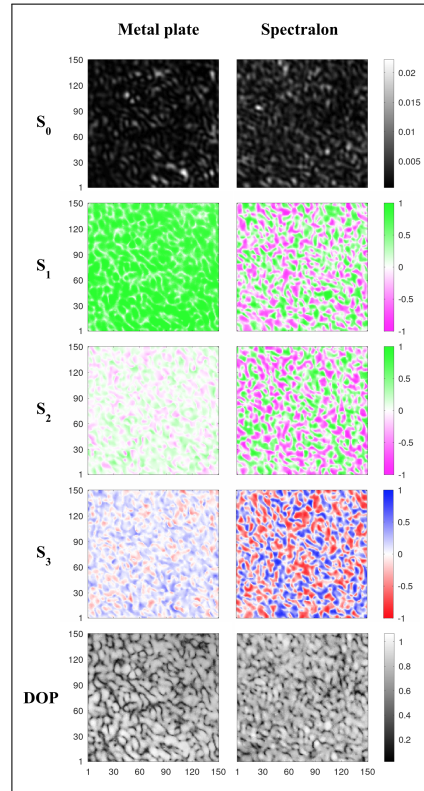


Fig. 13. Images of the various Stokes parameters and DOP determined for a sample corresponding to a metal plate in the left column and Spectralon in the right.

524 independent of the probe states, and hence should be the same in the various maps of the Stokes
 525 parameters [16, 30]. Although this is rather difficult to observe in the plots of Fig. 13, we have
 526 analyzed the comparative spatial distribution of the speckle pattern intensity for various analyzing
 527 states, and of the Stokes parameters maps, and we have experimentally checked that the speckle
 528 spatial distribution was not significantly modified during the whole set of acquisitions, thereby
 529 demonstrating the validity of our setup to preserve the analyzed complex wavefront throughout
 530 the measurement.

531 Lastly, it can also be checked that the local DOP in the last row shows values very close to 1
 532 in the constructive interference zones (sufficiently bright regions), which is in agreement with
 533 initial observations in [16].

534 6.2. Spectralon

535 The depolarizing nature of the Spectralon sample is due to its high reflectivity (reflectance of
 536 99%) and its complex microstructure which allows multiple bulk scattering of light within a thin
 537 layer of the material. Such multiple scattering events induce a local modification of the incident
 538 polarization state uniformly across the Poincaré's sphere, leading to a strong and total spatial
 539 depolarization when the local polarization states are coherently averaged over the surface of a
 540 single detector for instance. This is clearly observed in the maps of the s_1 , s_2 and s_3 parameters
 541 provided in Fig. 13, confirming the depolarizing nature of this sample. As before, the DOP image
 542 shows values close to 1 in the constructive interference zones, corresponding to the fact that the
 543 polarization state within a grain is deterministic, in agreement with anterior observations [16, 23].

544 In view of the displayed patterns of the different Stokes parameters, we observe a rapid spatial
545 variation of the polarization state across the speckle pattern. This will be of particular interest in
546 the last paper of this article series for the study of the polarization behaviour across a speckle
547 field and in the vicinity of polarimetric singularities.

548 7. Conclusion

549 In this article, the implementation of an optimized polarimetric Stokes imaging bench resolved at
550 the speckle grain scale was described, along with a justification of all the choices of experimental
551 parameters used. The set of parameters described above will be considered in the remainder
552 of this article series, either for the theoretical/numerical study of the second paper, or for the
553 experimental results and analyses presented in the third paper. In the next paper of this series, we
554 conduct a theoretical study and numerical simulation analysis in order to demonstrate the validity
555 of the SOPAFP approach to provide optimal precision and accuracy of Stokes measurements,
556 and its superiority with respect to standard approaches in terms of robustness of the estimation
557 results in the presence of experimental defects in the setup.

558 **Acknowledgments.** The authors would like to thank the DOP team and in particular Mehdi Alouini,
559 Goulc'hen Loas for fruitful discussions and Steve Bouhier for technical help.

560 **Disclosures.** The authors declare no conflicts of interest.

561 **Data availability.** Data underlying the results presented in this paper are not publicly available at this time
562 but may be obtained from the authors upon reasonable request.

563 References

- 564 1. J. S. Lim and H. Nawab, "Techniques for speckle noise removal," in *Applications of speckle phenomena*, vol. 243
565 (SPIE, 1980), pp. 35–45.
- 566 2. B. Daino, G. De Marchis, and S. Piazzolla, "Speckle and modal noise in optical fibres theory and experiment," *Opt.*
567 *Acta: Int. J. Opt.* **27**, 1151–1159 (1980).
- 568 3. J. M. Schmitt, S. Xiang, and K. M. Yung, "Speckle in optical coherence tomography," *J. biomedical optics* **4**, 95–105
569 (1999).
- 570 4. S. Xiang, L. Zhou, and J. M. Schmitt, "Speckle noise reduction for optical coherence tomography," in *Optical and*
571 *Imaging Techniques for Biomonitring III*, vol. 3196 (SPIE, 1998), pp. 79–88.
- 572 5. D. A. Boas and A. K. Dunn, "Laser speckle contrast imaging in biomedical optics," *J. biomedical optics* **15**,
573 011109–011109 (2010).
- 574 6. P. G. Vaz, A. Humeau-Heurtier, E. Figueiras, C. Correia, and J. Cardoso, "Laser speckle imaging to monitor
575 microvascular blood flow: a review," *IEEE reviews biomedical engineering* **9**, 106–120 (2016).
- 576 7. J. Shamir, "Speckle polarization investigated by novel ellipsometry," *Opt. Eng.* **25**, 618–622 (1986).
- 577 8. Í. Í. Tarhan and G. H. Watson, "Polarization microstatistics of laser speckle," *Phys. Rev. A* **45**, 6013 (1992).
- 578 9. P. Elies, B. Le Jeune, F. Le Roy-Brehonnet, J. Cariou, and J. Lotrian, "Experimental investigation of the speckle
579 polarization for a polished aluminium sample," *J. Phys. D: Appl. Phys.* **30**, 29 (1997).
- 580 10. D. Briers, D. D. Duncan, E. Hirst, S. J. Kirkpatrick, M. Larsson, W. Steenbergen, T. Stromberg, and O. B. Thompson,
581 "Laser speckle contrast imaging: theoretical and practical limitations," *J. biomedical optics* **18**, 066018–066018
582 (2013).
- 583 11. W. Heeman, W. Steenbergen, G. M. van Dam, and E. C. Boerma, "Clinical applications of laser speckle contrast
584 imaging: a review," *J. biomedical optics* **24**, 080901–080901 (2019).
- 585 12. L. Tehvialeva, G. Dhadwal, H. Lui, S. Kalia, H. Zeng, D. I. McLean, and T. K. Lee, "Polarization speckle imaging as
586 a potential technique for in vivo skin cancer detection," *J. biomedical optics* **18**, 061211–061211 (2013).
- 587 13. M. Zerrad, H. Tortel, G. Soriano, A. Ghabbach, and C. Amra, "Spatial depolarization of light from the bulks:
588 electromagnetic prediction," *Opt. Express* **23**, 8246–8260 (2015).
- 589 14. K. Hirsch, T. Fricke-Begemann, G. Gülker, and K. Wolff, "Speckle correlation for the analysis of random processes
590 at rough surfaces," *Opt. Lasers Eng.* **33**, 87–105 (2000).
- 591 15. P. Hariharan, "Statistics of speckle patterns produced by a rough metal surface," *Opt. Acta: Int. J. Opt.* **24**, 979–987
592 (1977).
- 593 16. L. Pouget, J. Fade, C. Hamel, and M. Alouini, "Polarimetric imaging beyond the speckle grain scale," *Appl. optics*
594 **51**, 7345–7356 (2012).

- 595 17. A. Ghabbach, M. Zerrad, G. Soriano, and C. Amra, "Accurate metrology of polarization curves measured at the
596 speckle size of visible light scattering," *Opt. Express* **22**, 14594–14609 (2014).
- 597 18. J. Dupont, X. Orlik, A. Ghabbach, M. Zerrad, G. Soriano, and C. Amra, "Polarization analysis of speckle field below
598 its transverse correlation width: application to surface and bulk scattering," *Opt. Express* **22**, 24133–24141 (2014).
- 599 19. J. Staes and J. Fade, "Optimized stokes imaging for highly resolved optical speckle fields, part II: Optimal acquisition
600 & estimation strategies," submitted to *J. Opt. Soc. Am. A* (2024).
- 601 20. J. Staes and J. Fade, "Optimized stokes imaging for highly resolved optical speckle fields, part III: Optimized
602 polarimetric data representation & topological polarimetric analysis," submitted to *J. Opt. Soc. Am. A* (2024).
- 603 21. D. H. Goldstein, *Polarized light* (CRC press, 2017).
- 604 22. J. Sorrentini, M. Zerrad, G. Soriano, and C. Amra, "Enpolarization of light by scattering media," *Opt. Express* **19**,
605 21313–21320 (2011).
- 606 23. A. Ghabbach, M. Zerrad, G. Soriano, S. Liukaityte, and C. Amra, "Depolarization and enpolarization dop histograms
607 measured for surface and bulk speckle patterns," *Opt. express* **22**, 21427–21440 (2014).
- 608 24. J. Dupont and X. Orlik, "Speckle fields polarimetry: statistical analysis and polarization singularities measurements,"
609 in *SPECKLE 2015: VI International Conference on Speckle Metrology*, vol. 9660 (SPIE, 2015), pp. 259–269.
- 610 25. J. W. Goodman and P. Sutton, "Introduction to fourier optics," *Quantum Semiclassical Opt. Eur. Opt. Soc. Part B* **8**,
611 1095 (1996).
- 612 26. J. Staes, "Imagerie polarimétrique et physique de dépolariation lumineuse: polarimétrie de champs de speckle
613 ultra-résolus et approches optique-hyperfréquences," Ph.D. thesis, Université Rennes 1 (2022).
- 614 27. J. S. Tyo, "Design of optimal polarimeters: maximization of signal-to-noise ratio and minimization of systematic
615 error," *Appl. optics* **41**, 619–630 (2002).
- 616 28. A. Peinado, A. Lizana, J. Vidal, C. Iemmi, and J. Campos, "Optimization and performance criteria of a stokes
617 polarimeter based on two variable retarders," *Opt. express* **18**, 9815–9830 (2010).
- 618 29. B. Delaunay *et al.*, "Sur la sphere vide," *Izv. Akad. Nauk SSSR, Otdelenie Matematicheskii i Estestvennyka Nauk* **7**,
619 1–2 (1934).
- 620 30. M. Roche, J. Fade, and P. Réfrégier, "Parametric estimation of the square degree of polarization from two intensity
621 images degraded by fully developed speckle noise," *J. Opt. Soc. Am. A* **24**, 2719–2727 (2007).