Depolarization and enpolarization DOP histograms measured for surface and bulk speckle patterns

Ayman Ghabbach, Myriam Zerrad,* Gabriel Soriano, Simona Liukaityte, and Claude Amra

Institut Fresnel, UMR7249, Aix-Marseille-Université, CNRS, Ecole Centrale Marseille Faculté des Sciences et Techniques de St Jérôme, 13397 Marseille Cedex 20, France

**myriam.zerrad@fresnel.fr*

Abstract: dop histograms are measured in the off-specular far field speckle of disordered media under polarized and unpolarized illumination. Three surface samples with increasing roughnesses, and three bulk samples with different absorption levels, are investigated. Results show that both rough surfaces and absorbing bulks hold the incident polarization, while transparent bulks allow to depolarize or to enpolarize the incident light. Hence we provide a first experimental evidence of such effects.

©2014 Optical Society of America

OCIS codes: (030.6140) Speckle; (260.2130) Ellipsometry and polarimetry; (260.5430) Polarization; (290.5855) Scattering, polarization; (120.2130) Ellipsometry and polarimetry; (120.3930) Metrological instrumentation; (120.3940) Metrology.

References and links

1. E. Wolf and L. Mandel, *Optical Coherence and Quantum Optics* (Cambridge University Press, ed. 1995)
2. C. Brosseau, *Fundamentals of Polarized Light - A Statistical Approach* (Wiley, New York, 1998)
3. J. W. Goodman, *Statistical Optics* (Wiley- Interscience, 2000).
4. E. Jakeman and K. D. Ridley, *Modeling Fluctuations in Scattered Waves* (Taylor and Francis Group, ed. 2006)
5. E. Wolf, *Theory of Coherence and Polarization of Light* (Cambridge University Press, ed. 2007)
6. M. Zerrad, J. Sorrentini, G. Soriano, and C. Amra, "Gradual loss of polarization in light scattered from rough surfaces: electromagnetic prediction," Opt. Express **18**(15), 15832–15843 (2010).
7. G. Soriano, M. Zerrad, and C. Amra, "Enpolarization and depolarization of light scattered from chromatic complex media," Opt. Express **22**(10), 12603–12613 (2014).
8. J. Sorrentini, M. Zerrad, G. Soriano, and C. Amra, "Enpolarization of light by scattering media," Opt. Express **19**(22 Issue 22), 21313–21320 (2011).
9. M. Zerrad, G. Soriano, A. Ghabbach, and C. Amra, "Light enpolarization by disordered media under partial polarized illumination: The role of cross-scattering coefficients," Opt. Express **21**(3), 2787–2794 (2013).
10. A. Ghabbach, M. Zerrad, G. Soriano, and C. Amra, "Accurate metrology of polarization curves measured at the speckle size of visible light scattering," Opt. Express **22**(12), 14594–14609 (2014).
11. O. V. Angelsky, S. G. Hanson, C. Y. Zenkova, M. P. Gorsky, and N. V. Gorodyns'ka, "On polarization metrology (estimation) of the degree of coherence of optical waves," Opt. Express **17**(18), 15623–15634 (2009).
12. F. Goudail and A. Bénière, "Estimation precision of the degree of linear polarization and of the angle of polarization in the presence of different sources of noise," Appl. Opt. **49**(4), 683–693 (2010).
14. L. Pouget, J. Fade, C. Hamel, and M. Alouini, "Polarimetric imaging beyond the speckle grain scale," Appl. Opt. **51**(30), 7345–7356 (2012).
15. J. Ellis, A. Dogariu, S. Ponomarenko, and E. Wolf, "Correlation matrix of a completely polarized, statistically stationary electromagnetic field," Opt. Lett. **29**(13), 1536–1538 (2004).
16. J. Broky and A. Dogariu, "Complex degree of mutual polarization in randomly scattered fields," Opt. Express **18**(19 Issue 19), 20105–20113 (2010).
17. J. Broky and A. Dogariu, "Correlations of polarization in random electro-magnetic fields," Opt. Express **19**(17), 15711–15719 (2011).
18. O. V. Angelsky, I. I. Mokhun, A. I. Mokhun, and M. S. Soskin, "Interferometric methods in diagnostics of polarization singularities," Phys. Rev. E Stat. Nonlin. Soft Matter Phys. **65**(3 3 Pt 2B), 036602 (2002).
19. A. A. Chernyshov, Ch. V. Felde, H. V. Bogatyryova, P. V. Polyanskii, and M. S. Soskin, "Vector singularities of the combined beams assembled from mutually incoherent orthogonally polarized components," J. Opt. A, Pure Appl. Opt. **11**(9), 094010 (2009).

20. G. Zhang, L. Tsang, and K. Pak, "Angular correlation function and scattering coefficient of electromagnetic waves scattered by a buried object under a two-dimensional rough surface," J. Opt. Soc. Am. A **15**(12), 2995–3002 (1998).
21. F. C. MacKintosh, J. X. Zhu, D. J. Pine, and D. A. Weitz, "Polarization memory of multiply scattered light," Phys. Rev. B Condens. Matter **40**(13), 9342–9345 (1989).

1. Introduction

Recent and new efforts have been devoted to the study of light polarization [1–5] in the speckle of disordered media. In particular electromagnetic theories and phenomenological models have allowed to predict specific properties of complex media such as spatial depolarization [6], temporal depolarization [7] and enpolarization effects [7–9]. Such effects may occur or not depending on the scattering origins (surface or bulk), and they may dominate the polarization process, depending on their microstructure [6–9].

However whereas most papers address theoretical analysis on these topics, few are concerned with polarization measurements at the speckle size [10–14]. Filling this gap was the main motivation of this work since a number of phenomena have not yet been confirmed by experiment. This work is devoted to the analysis of polarization degree histograms measured for different kinds of surfaces and bulks. It is shown how these dop histograms:

- ✓ confirm most theoretical predictions in connection with the microstructure of the scattering samples
- ✓ provide additional signatures to identify the origins of scattering within a series of surface or bulk samples

The experimental set-up is not presented since it has been the focus of a recent paper [10] with a first validation step. To summarize, the set-up allows to measure the polarization state and polarization degree [15–17] at the speckle size within a far field speckle pattern at visible wavelengths. Here we use this set-up to investigate a series of samples (surfaces and bulks) under polarized and unpolarized illumination.

2. Surface scattering

We use a series of 3 surface samples shown in Fig. 1 and 2. Their scattering patterns decrease from the first to the third (Fig. 2). Sample S_1 is a metallic (Au) surface which delivers a lambertian pattern, which means that the whole incident light is scattered by reflection with a cosine law. Samples S_2 and S_3 are opaque (black) glasses respectively grounded and moderately polished; the incident light is mainly absorbed (around 96%) in the visible while the amount of scattering approaches some % (grounded sample) or much less (polished sample).

Fig. 1. Photographs of the 3 surface samples: lambertian (left), grounded (middle) and polished (right).

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

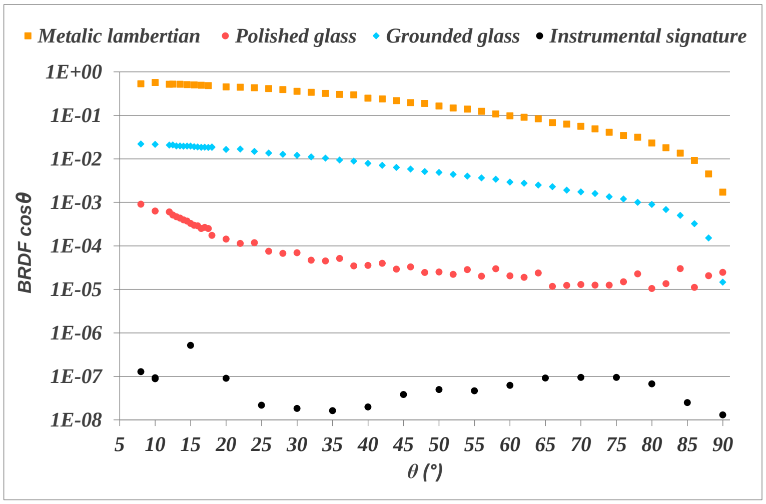

Fig. 2. Angle-resolved scattering curves (ARS) of the surface samples in Fig. 1.

2.1 Incident polarized illumination

The samples were first illuminated with a fully polarized (45° linear) and coherent quasi-monochromatic laser beam (He-Ne, 633nm, 2 mm spot size) at normal incidence, and the scattering data were recorded around 15° in the far field (80cm) on a CCD camera (10^6 pixels with 13µm size). Each speckle grain is resolved with 256 pixels. A least mean square (LMS) procedure [10] was used to extract both polarization degree and polarization states within all speckle patterns.

The resulting 3 sample histograms are given in Fig. 3. A 4th histogram is given as a reference, which was measured for the direct (specular) beam [10]. Strictly speaking the reference histogram would be a Dirac curve so that its width characterizes all uncertainties in the measurement process (bias, noise, LMS procedure…).

Concerning the scattering samples now, their histograms in Fig. 3 are wider than that of the reference. The largest root-mean-square is observed for the rougher (lambertian) sample (S_1). The average dop is 0.94 and the mean deviation is 0.08 for this sample S_1. Then for lower roughnesses (samples S_2 and S_3), the dop curves are very similar.

To be complete, the polarization states are also plotted in Fig. 4 and 5 (Poincaré spheres) for the 3 surface samples. In Fig. 4 we considered 3 speckle grains to check that polarization is quasi-constant within one grain, and also from one grain to another. Notice on the spheres that the color indicates the maximum grey level on the pixel where the dop is measured [10].

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA 8 September 2014 | Vol. 22, No. 18 | DOI:10.1364/OE.22.021427 | OPTICS EXPRESS 21429

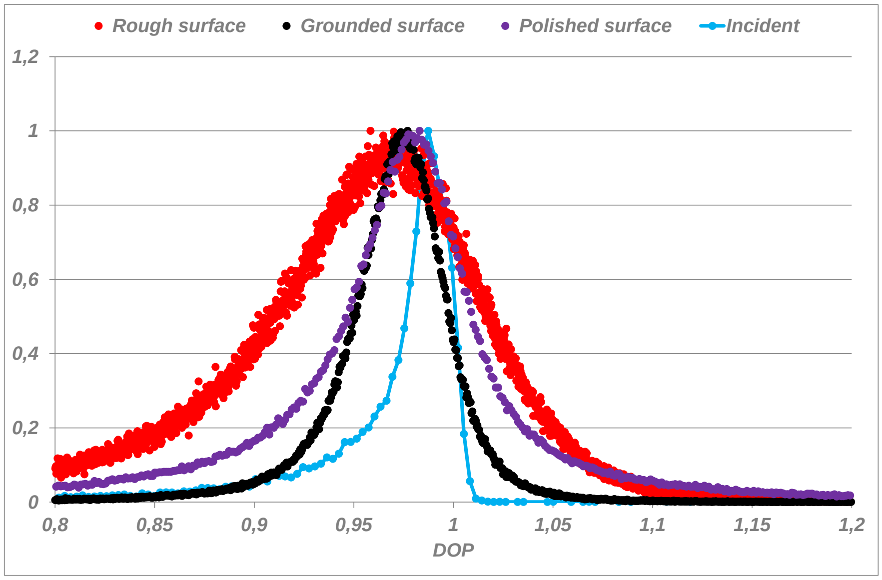

Fig. 3. Normalized dop histograms measured for the lambertian (in red), grounded (black) and polished (in purple) surfaces- Case of polarized illumination.

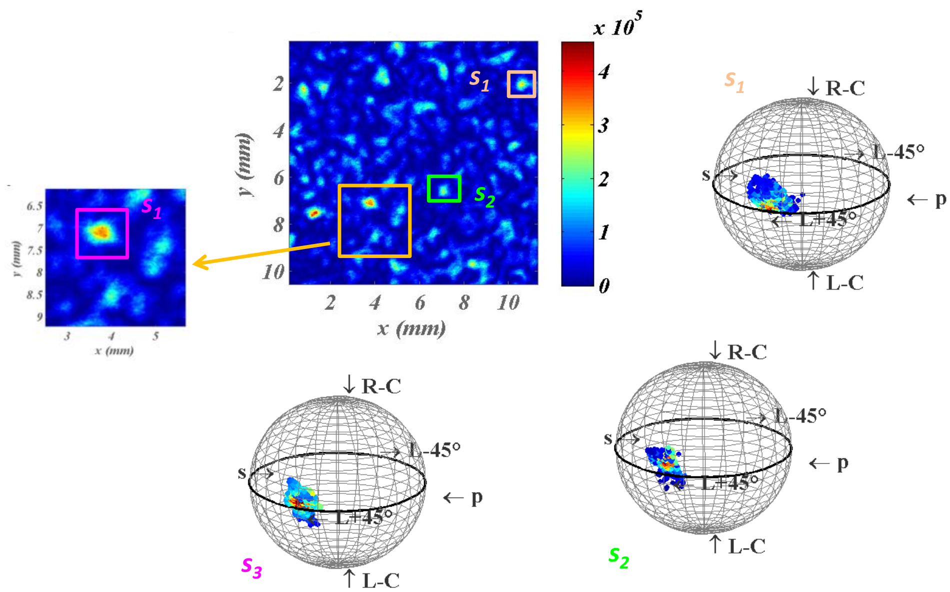

Fig. 4. Polarization states on the Poincaré sphere for the Au lambertian sample (S_1)- Polarized illumination.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

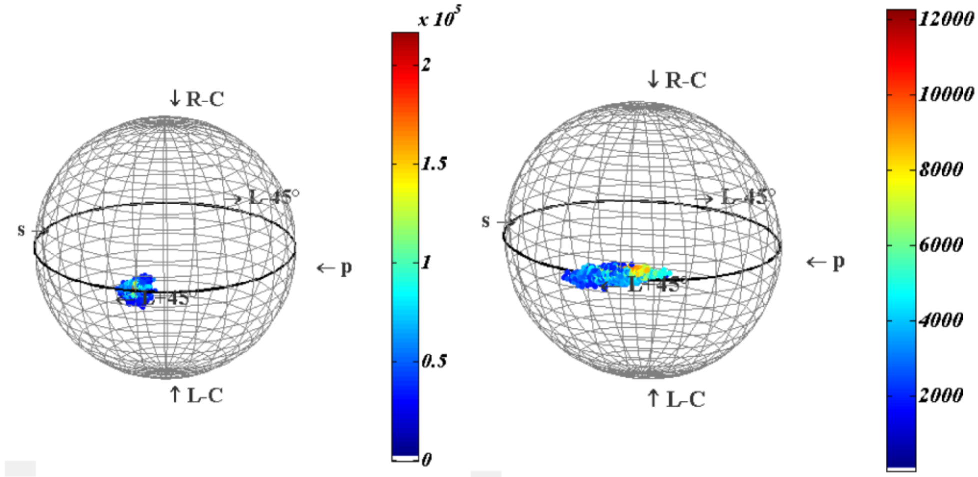

Fig. 5. Polarization states on the Poincaré sphere for the grounded (left, S_2) and the polished (right, S_3) black surfaces - Polarized illumination.

2.2 Incident un-polarized illumination

The same procedure was used with the samples illuminated with an un-polarized He-Ne laser beam. Results are plotted in Fig. 6, with all the histograms around the origins (dop ≈0). Again we observe that all root-mean-squares are larger than that of the reference, and the largest one is again for the rougher sample S_1. The polarization states are plotted in Figs. 7, 8, and 9 where a sphere section is introduced to emphasize the non-unity dop.

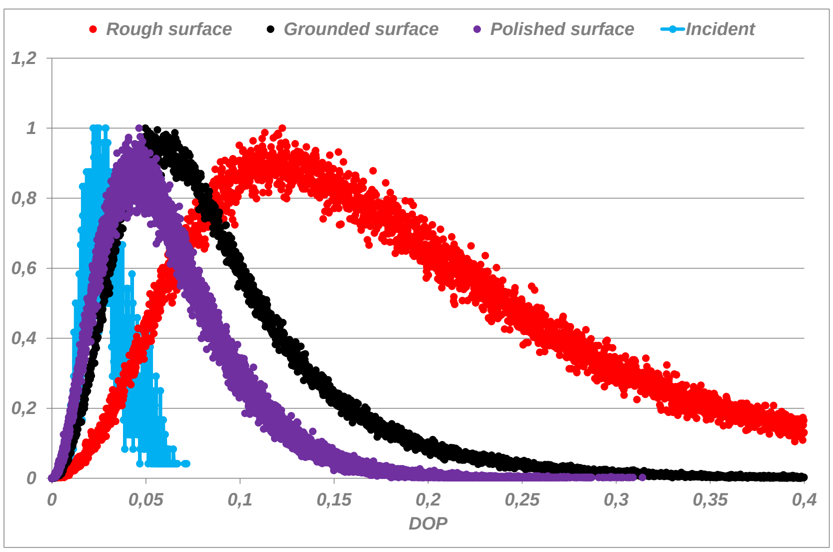

Fig. 6. Normalized dop histograms measured for the lambertian, grounded and polished surfaces- Unpolarized illumination.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

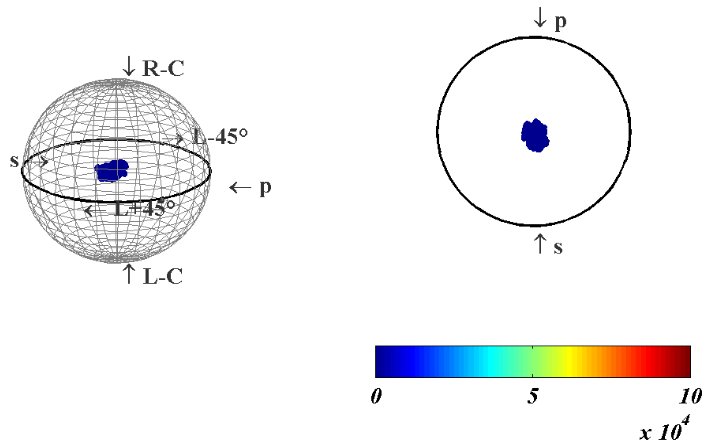

Fig. 7. Polarization states on the Poincaré sphere for the Au lambertian surface sample (S_1). Unpolarized illumination.

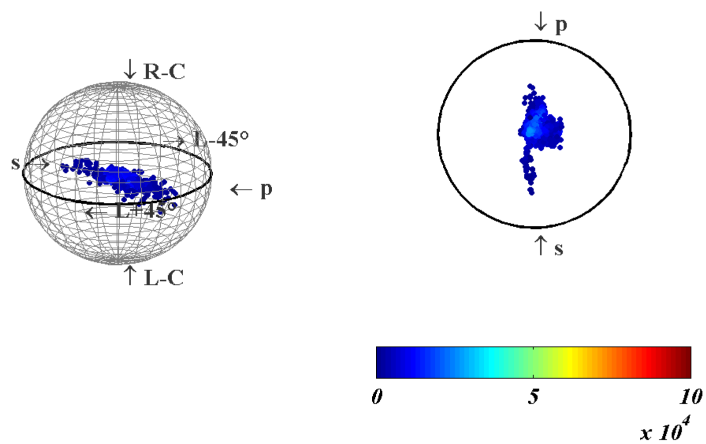

Fig. 8. Polarization states on the Poincaré sphere for the grounded surface sample (S_2). Unpolarized illumination.

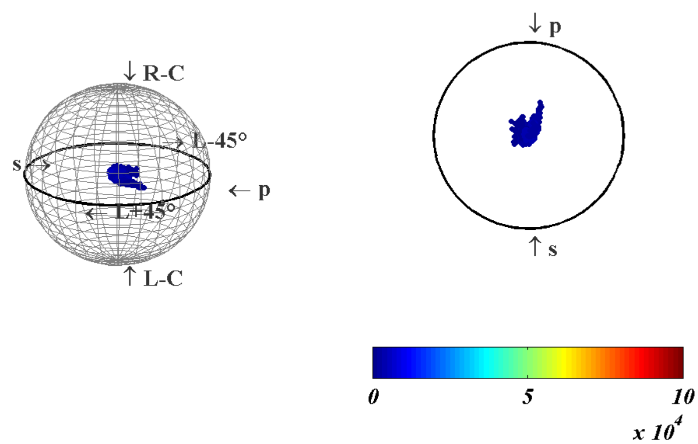

Fig. 9. Polarization states on the Poincaré sphere for the polished surface sample (S_3). Unpolarized illumination.

2.3 Conclusion for the surface samples

These results show that whatever the surface roughness, the polarization degree of the speckle pattern remains close to that of the incident light. Furthermore, the polarization states rely in the vicinity of the incident state. Notice however that we could observe at high roughness (Au sample) a slight departure from the incident polarization. To conclude, surfaces approximately hold the polarization state of the incident light.

3. Bulk scattering

The second investigation concerned 3 bulk samples (B_i). Bulk samples are usually known not to hold the polarization, and vector singular optics have shown that even within a speckle area the polarization state could move throughout the whole Poincaré sphere [18,19].

The bulk photographs are given in Fig. 10. For each sample, the whole incident light is scattered or absorbed. From B_1 to B_3, and due to absorption properties, the scattering level decreases from 1 (white sample) to 10% (grey sample) and less (10^{-3} black sample). The ARS curves are given in Fig. 11.

Fig. 10. Pictures of the 3 bulk (B_i) samples. From left to right: white (B_1), grey (B_2) and black (B_3).

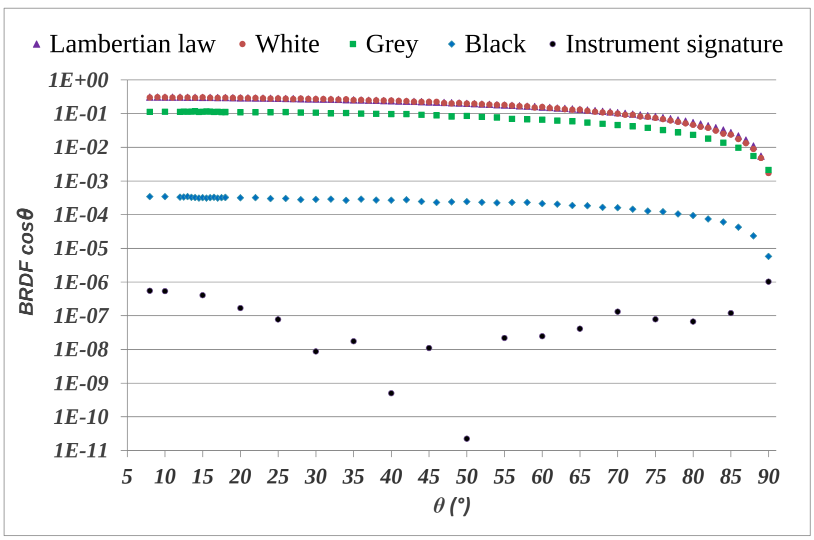

Fig. 11. ARS curves of the 3 bulk samples.

3.1 Incident polarized illumination

Figure 12 gives the histograms of the 3 bulk samples under full polarized illumination. The largest departure from the reference, and the largest root-mean-square, is obtained with the white sample (highest scattering level). Otherwise we observe that the histogram root-mean-square decreases when absorption increases (from B_1 to B_3). Such effect can be explained by the weight of multiple reflections which is absorption dependent. In case of high-absorption level (sample B_3), the bulk behavior is similar to the surface one. On the other hand, in case of low-absorption (samples B_1 and B_2), and in regard to the surface histograms of Fig. 3, the bulk histograms are clearly wider. These higher bulk root-mean-squares of the dop can be seen as the result of depolarization effects [7].

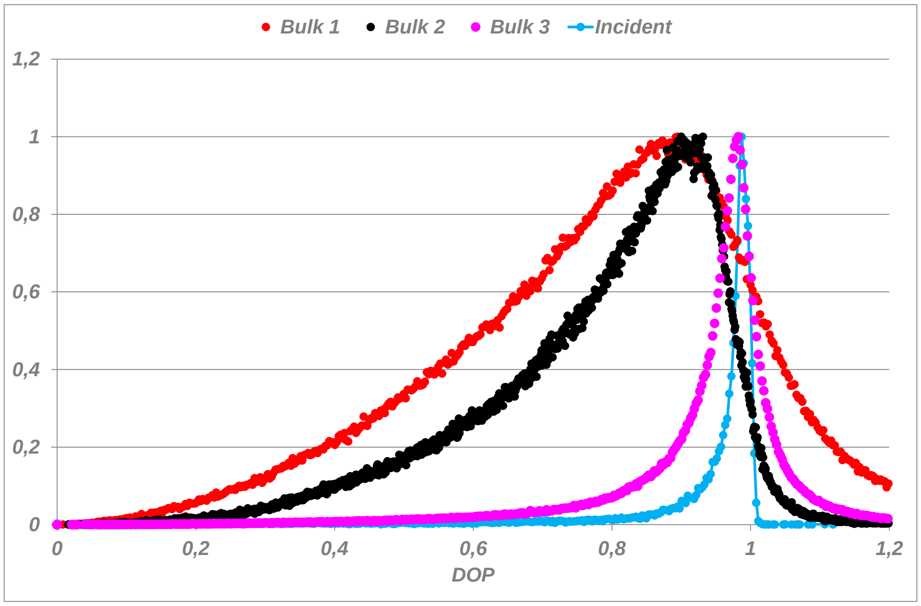

Fig. 12. Normalized dop histograms of the 3 bulk samples -Polarized illumination. B_1: white bulk, B_2: grey bulk, B_3: black bulk.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

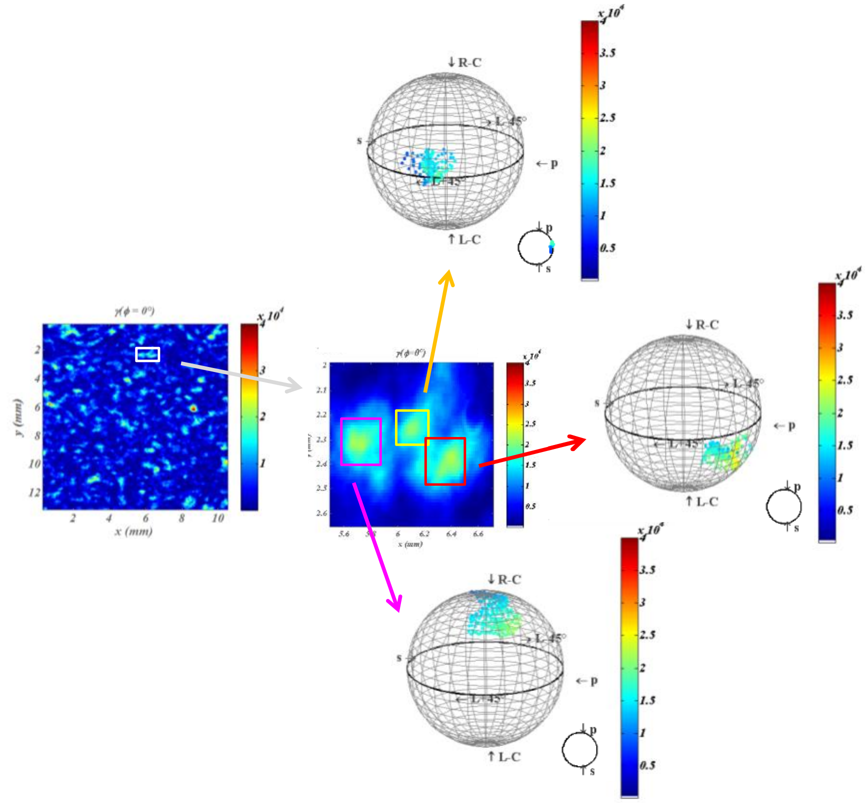

Fig. 13. Polarization states of the white bulk sample. Polarized illumination.

The Poincaré spheres are also given in Figs. 13, 14, and 15 for the samples. We considered 3 speckle grains in Fig. 13 (lambertian sample B_1) to show that polarization strongly varies from one grain to another, which is a key difference with the surfaces. For this sample B_1, the sphere would be completely covered if we considered all the speckle grains on the CCD area. On the other hand, when absorption increases (samples B_3), the bulk behaviour again mimics the surface one.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014

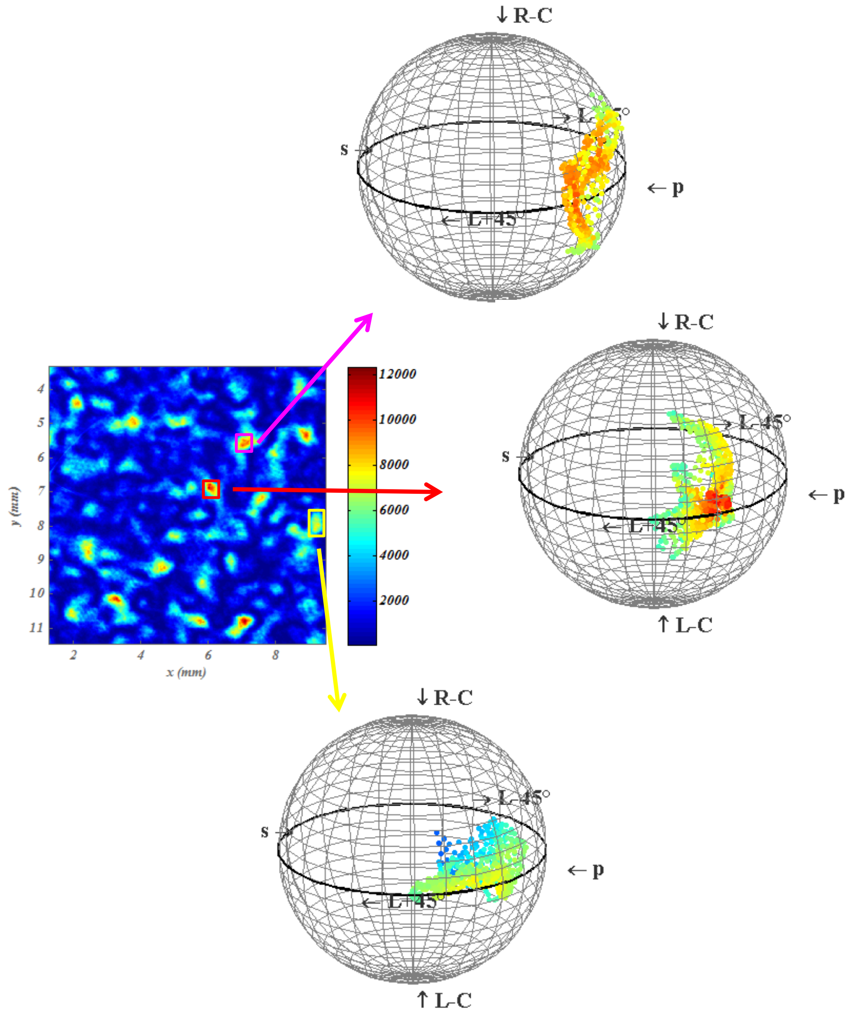

Fig. 14. Polarization states of the bulk grey sample. Polarized illumination.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA 8 September 2014 | Vol. 22, No. 18 | DOI:10.1364/OE.22.021427 | OPTICS EXPRESS 21436

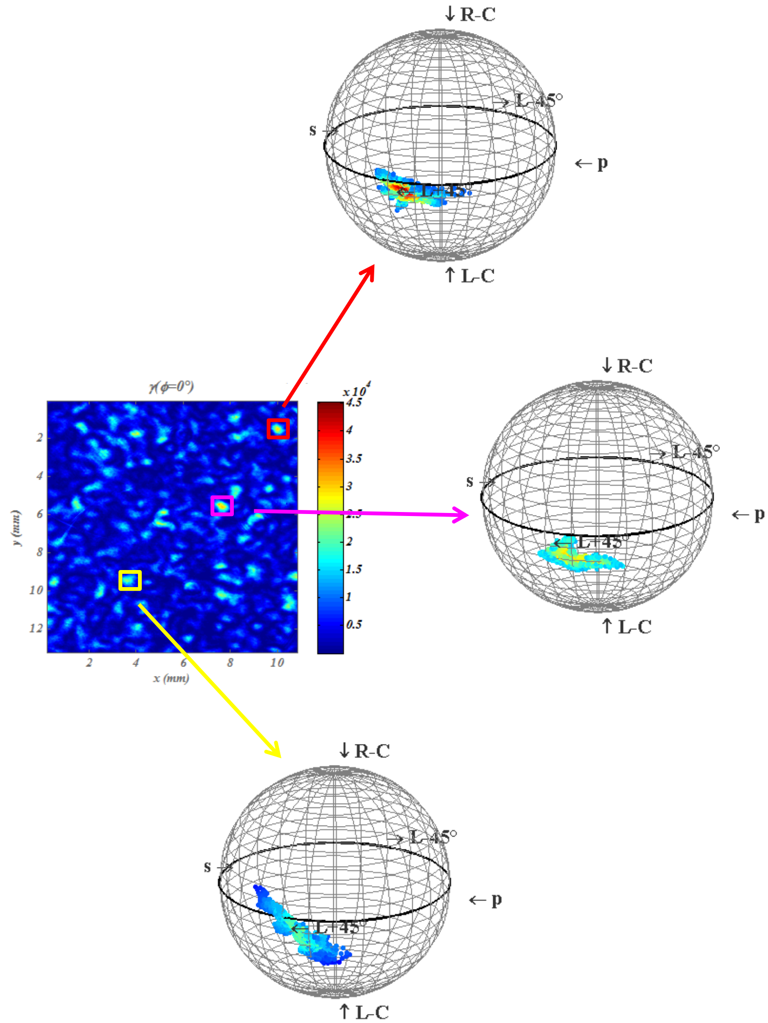

Fig. 15. Polarization states of the bulk black sample- Polarized illumination.

3.2 Incident un-polarized illumination

The 3 bulk samples now are under un-polarized illumination. The results are given in Fig. 16. As previously, higher absorption levels (sample B_3) make the bulk samples mimic the surface ones, that is, a narrow dop histogram around zero. On the other hand, the white and grey samples (B_1-B_2) emphasize a great root-mean square characteristic of an enpolarization effect [8,9]. To our knowledge it is the first experimental evidence of such polarization process. More information is plotted with the Poincaré spheres in Fig. 17, 18, and 19.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

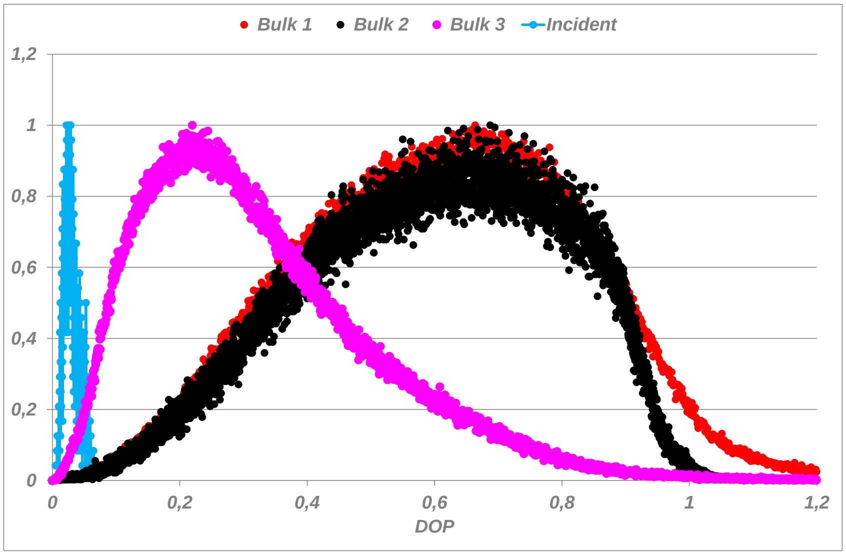

Fig. 16. Normalized dop histograms of the 3 bulk samples –Unpolarized illumination B_1: white bulk, B_2: grey bulk, B_3: black bulk.

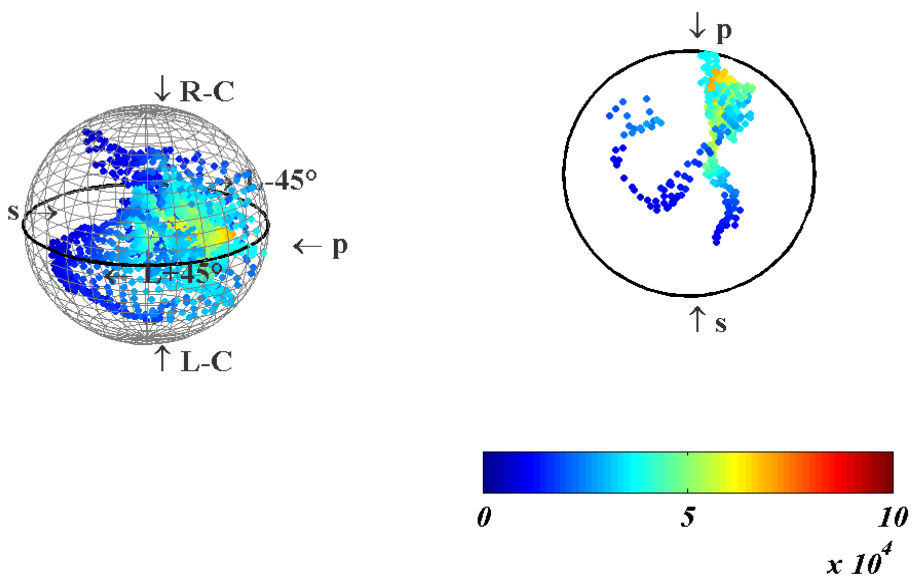

Fig. 17. Polarization states for the bulk white sample- unpolarized illumination.

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

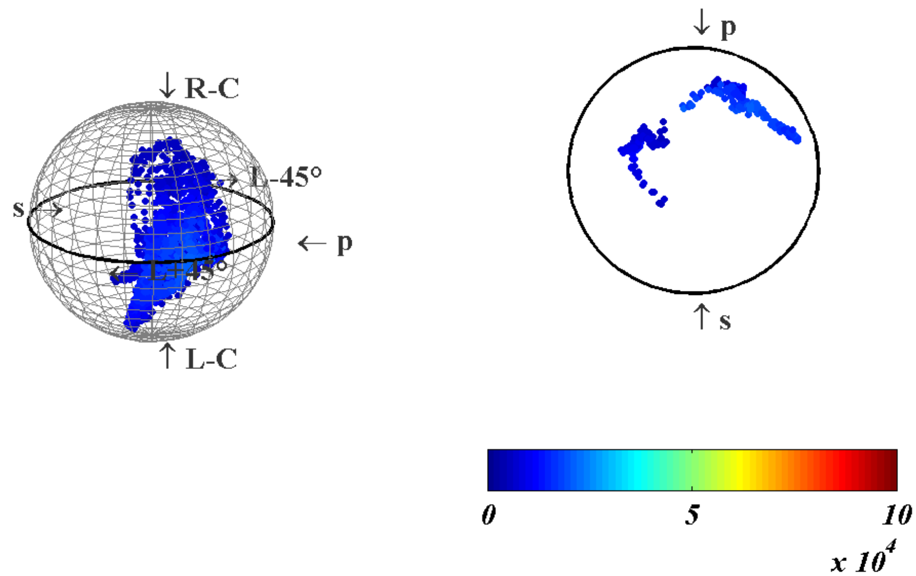

Fig. 18. Polarization states for the bulk grey sample- unpolarized illumination.

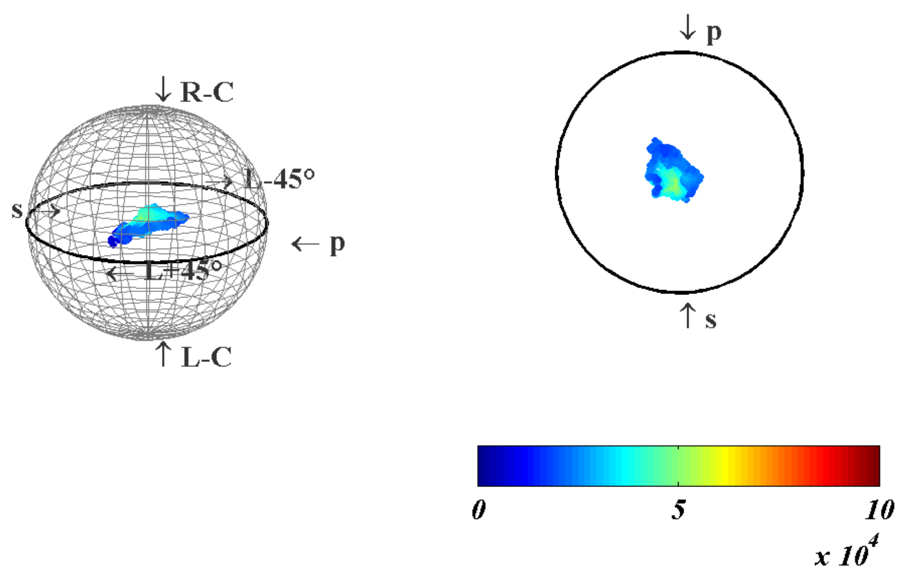

Fig. 19. Polarization states for the bulk black sample- unpolarized illumination.

3.3 Conclusion for the bulk samples

High absorption bulk samples reveal a polarization behavior similar to those of surfaces, what can be attributed to the weight of multiple reflections or mean-free path which is absorption dependent. On the other hand, transparent bulks clearly emphasize specific effects such as depolarization [7] and enpolarization [8,9].

Such effects (depolarization and enpolarization) were recently predicted [7–9] and are again emphasized in Fig. 20. To calculate these last data the spectral correlation length of the scattering coefficients and the laser band-pass were assumed to be of the same magnitude order. The green curve in Fig. 20 is calculated for a bulk sample under polarized illumination, and its dop histogram shows a depolarization effect similar to the grey bulk sample measured

#215089 - $15.00 USD Received 4 Jul 2014; revised 31 Jul 2014; accepted 19 Aug 2014; published 27 Aug 2014
(C) 2014 OSA

in Fig. 12. The blue curve of Fig. 20 is calculated for a bulk sample under un-polarized illumination, and its dop histogram emphasizes an en-polarization effect similar to the white and grey samples of Fig. 16. Notice that though en-polarization effects in bulks still occur for achromatic scattering coefficients [8,9], depolarization effects require a strong chromatic behavior [7] of the scattering coefficients within the source bandpass.

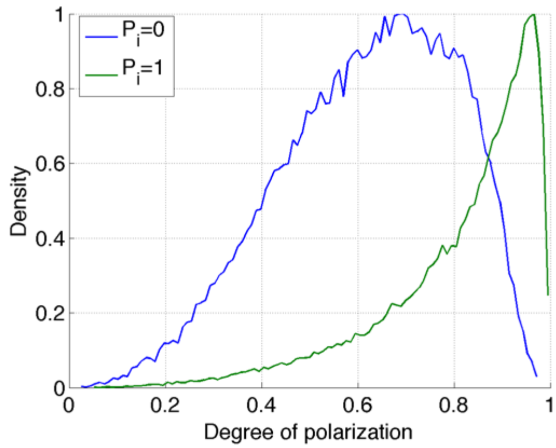

Fig. 20. pdf of the polarization degree calculated for a bulk sample under polarized (green curve) and un-polarized (blue curve) illumination.

4. Conclusion

To our knowledge these are the first dop histograms measured in the far-field speckle of surface and bulk media under polarized and un-polarized illumination. All results clearly show that surfaces approximately hold the polarization of the incident light, in the form of a memory effect [20, 21]. In the same way, absorbing bulk samples emphasize a behavior similar to those of surfaces. On the other hand, transparent bulk samples reveal a very specific signature in the sense that they can depolarize or enpolarize the incident light. This is again the first experimental evidence of such enpolarization effects predicted in [7–9].

Acknowledgments

This work was supported by the French National Research Agency (ANR) through the funding of TraMEL Project.