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Complex degree of mutual polarization in randomly scattered fields

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Abstract: Random electromagnetic fields resulting from light-matter interaction have strong intensity fluctuations and are characterized by various statistical parameters. The local polarization of these fields can also vary randomly leading to different degrees of global depolarization. Here we demonstrate that the spatial variability of the vectorial properties contains information about the origins of randomly scattered fields. In particular, we show that the complex degree of mutual polarization provides the high-order polarization correlations necessary to identify the sources of different random fields. Scattered fields with similar global properties but different origins can be efficiently discriminated from one single realization of the light-matter interaction.

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1. Introduction

Random electromagnetic fields (REFs) exist in all forms and commonly result from the interaction of coherent fields with randomly inhomogeneous media. This coherent light-matter interaction is a complex interference process leading to fields with strong fluctuations in intensity, commonly called speckles [1]. Besides their intensity fluctuations, REFs are characterized by specific coherence and polarization properties [2]. Even though, in general, the distributions of REFs are three-dimensional [3], in the following we will only be concerned with two-dimensional fields characteristic to paraxial imaging situations.

A simple way to describe the intensity speckles is to consider the superposition of waves originating from discrete scattering centers. Different scattering regimes may vary from "single scattering" specific to mostly surface scattering to different degrees of multiple scattering characteristic to the interaction with three-dimensionally disordered media. When one single polarization component is analyzed, i.e. when the speckle field is measured through a polarizer, the intensity contrast often reaches unity. This is the case of the so-called fully developed speckle pattern, a manifestation of interference between a large number of wavelets with uniformly distributed random phases. This is a rather universal behavior present in scattering from a variety of media ranging from metallic rough surfaces to diffusive materials.

However, the distribution of polarization states in REFs is much richer and non-universal properties are to be expected. Most importantly, it is anticipated that the polarization properties of REFs corresponding to different scattering regimes will depend greatly on the strength of the scattering process. For instance, it is likely that when the wave interaction is dominated by single scattering processes, a fully developed speckle pattern will occur but the REF polarization will strongly resemble the incident state of polarization. On the other hand, when the interaction is subject to strong multiple scattering, the scattered field remains locally fully polarized but its state of polarization will vary spatially. When the scattering process is completely diffusive, universal distributions emerge for the polarization parameters [4, 5]. It is therefore of interest to examine in detail the relation between the degree (order) of scattering and the polarization properties of the resulting REF.

A number of studies and experiments have been aimed at characterizing scattered fields [5–12]. The fluctuations of one-dimensional speckles (1-D) and the global non-stationarities of two-dimensional fields have been used to characterize specific properties of REFs [13, 14]. In this paper we will examine different means to discriminate between REFs originating from different scattering regimes. We will specifically focus on fields having similar global properties and discuss a number of high-order polarization correlators as means to assess the strength of different types of scattering.

2. Different scattered fields and their characteristics

Usually, the formation of speckle is described as a scalar process in terms of a random walk of complex phasors [1]. The addition of a large number of random phasors with different lengths and directions leads to a scattered intensity pattern which has a negative exponential probability distribution. If the initial source of radiation is fully polarized and coherent, the wave interacting

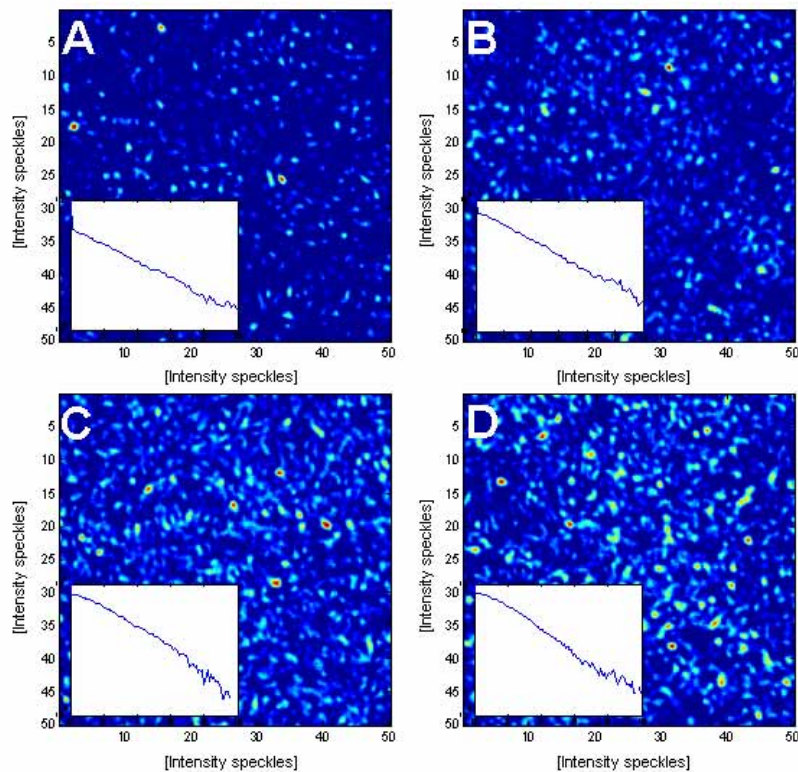


Fig. 1. Intensity patterns scattered from four different media: a rough metallic surface (A), a thin kaolin based diffuse coating (B), a cellulose membrane (C), and a polyvinylidene fluoride membrane (D). The insets show the corresponding $\log(p(I/\langle I \rangle))$ vs. $I/\langle I \rangle$ distributions.

with a non-absorbing medium remains coherent and fully polarized at each point in space. As mentioned in the introduction, in a fully developed speckle, the global field is fully polarized, often arising from a strong single scattering process such as the interaction with a rough metallic surface. In cases in which the interaction with the medium is a multiple scattering process, the individual speckles remain locally fully polarized although globally the field becomes partially polarized. Even a completely globally “unpolarized” speckle pattern is locally fully polarized.

A simple experiment was designed to image the REF at the surface of scattering media in a backscattering geometry. The samples were illuminated with a large, linearly polarized beam from a laser with a wavelength of 488 nm and the surface was imaged onto a CCD. At the surface of the medium, the size of the speckles is of the order of the wavelength and, in order to fully resolve them, they were magnified about one hundred times to about $80 \mu\text{m}$ in size. We used a number of sample media with varying degrees of surface roughness and volume scattering. Figure 1 illustrates several experimentally obtained REFs corresponding to a rough metallic surface (A) and three diffuse volume scattering media characterized by different transport mean free paths: a thin kaolin based diffuse coating (B), a cellulose membrane (C), and a polyvinylidene fluoride membrane (D).

As can be seen, in spite of their different origins, the random fields illustrated in Fig. 1 are all developed speckle patterns as demonstrated by the probability density functions of normalized intensities shown in the corresponding insets; the $p(I/\langle I \rangle)$ distributions all manifest negative

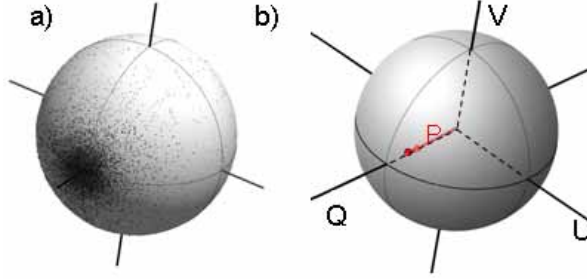


Fig. 2. (a) Distribution of polarization states on the Poincaré sphere. (b) Both the average state of polarization and the degree of polarization are ensemble properties of the distribution of polarization states.

exponential decays. In addition, from the intensity distributions one can evaluate the second order intensity correlations $\langle I(r)I(r+\rho) \rangle$, i.e. the average speckle size. In all cases shown in Fig. 1, the average speckle size is approximately the wavelength of light. As such, one can conclude that both 1st and 2nd order intensity correlations are quite similar in spite of the fact that the REFs are generated by scattering on quite different random media. This means that the intensity statistics are insufficient to discriminate between REFs that are generated via different regimes of scattering.

In contrast, it is known that the polarization is more robust and resistant to random fluctuations. For instance, in single scattering from rough surfaces, the state of polarization is maintained [15]. As the contribution from multiple scattering increases, the wave depolarizes, usually over length scales greater than the transport mean free path [16]. Therefore, it is expected that the correlation between polarization states at the surface should be indicative of the scattering level within the random medium.

3. Scale dependent degree of polarization

Let us now examine the vectorial nature of the scattered fields and inspect their polarization properties. A rotating quarter-wave plate was inserted in the imaging path of the experimental setup and a subsequent Fourier analysis provided the full Stokes vector in each pixel [17]. The spatially resolved polarimetric description of the REF can subsequently be analyzed in different ways. A common measure of polarization is the degree of polarization (DoP)

$$P(\bar{r}_i) = \sqrt{S_1^2(\bar{r}_i) + S_2^2(\bar{r}_i) + S_3^2(\bar{r}_i)} / S_0(\bar{r}_i), \quad (1)$$

where

$$\begin{aligned} S_1(r) &= E_x^*(r)E_x(r) - E_y^*(r)E_y(r) \\ S_2(r) &= E_x^*(r)E_y(r) - E_y^*(r)E_x(r) \\ S_3(r) &= i(E_x^*(r)E_y(r) - E_y^*(r)E_x(r)). \end{aligned} \quad (2)$$

As can be seen, the DoP is actually a 4th-order field correlator describing the properties of the electric field at point r [18]. Practically, one has access to an ensemble of different polarization states collected over a certain area and a scale dependent effective DoP can be estimated as

$$\bar{P}_A(r) = \sqrt{\int_A S_1^2 dr + \int_A S_2^2 dr + \int_A S_3^2 dr} / \int_A I dr. \quad (3)$$

The scale dependent DoP in Eq. (3) approaches zero when the ensemble of polarization states are randomly distributed over the Poincaré sphere as illustrated in Fig. 2. Of course a

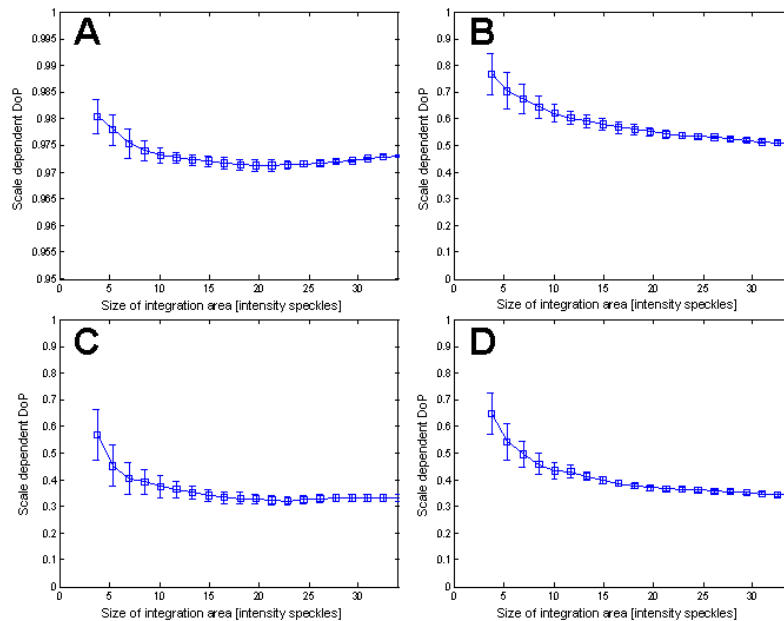


Fig. 3. The DoP calculated over an increasing integration area averaged over 100 integration centers. The error bars indicate the DoP standard deviation calculated for each integration area. Note that the y-scale in A is 0.95-1.0 while it is 0-1.0 for panels B, C, and D.

strong multiple scattering interaction leads to an overall depolarized scattered field when the DoP is evaluated over a large scale [15]. We emphasize that this depolarization only occurs in the global sense, as the resulting scattered light forms individually fully polarized speckles. The depolarization measurement can be viewed as a “center of mass” estimation, where the polarization of the average state lies within the sphere as seen in Fig. 2(b).

Results of calculations of scale-dependent DoP are presented in Fig. 3. As we increase the size of the area over which the estimation is performed, the DoP value eventually reaches saturation. The error bars in Fig. 3 were calculated using one hundred starting points for each size of analysis area. Their values reflect the fact that even if each speckle is fully polarized, $\bar{P}_A(r)$ varies significantly when only examining a small number of speckles.

As evident from Fig. 3, there are two factors associated with the DoP scale dependence: the saturation level and the associated decay length. It is quite clear that the saturation levels can be quite different. For the samples illustrated here, the DoP saturation values are 0.97, 0.49, 0.32, and 0.32 \pm 0.02 for samples A, B, C, and D, respectively. Different saturation levels indicate different levels of global depolarization due to scattering: the higher the level of multiple scattering the lower the value of the corresponding degree of global polarization of the scattered field. However, the two membrane samples (C and D) show very similar DoP saturation values yet they have completely different material structures. In this case the DoP value is an insufficient to discriminate between different levels of multiple scattering.

The DoP decay length represents the spatial scale at which saturation is reached. Although the media examined here have different saturations, they all have similar decay lengths measuring about 15 intensity speckles. It appears that this decay length is an associated ensemble quantity that ignores any underlying material discrepancies.

To conclude, the DoP is a basic yet incomplete way to describe the polarization properties of REFs. As mentioned before, the DoP is evaluated based on 4th-order field correlations repre-

sentative for the properties of a field at one spatial location. $\bar{P}_A(r)$ is also an ensemble quantity, averaged over many spatial locations, and therefore it loses any information about spatial distribution of polarization states, i.e. the shape of the distribution of states on the Poincare sphere. For instance, there are many different REFs that can be characterized by the same value of the global DoP [18]. In the following we will examine a more refined, two-point descriptor of the polarization properties of a random field.

4. Two point polarization correlations

Another possibility to evaluate higher-order field correlations in REFs is to quantify the variability between the members of the ensemble of measurement points and a chosen reference. The measure for this is the complex degree of mutual polarization (CDMP) [19]. The magnitude of the CDMP measures the polarization similarity between two points, r_i and a reference r_0 , and under the assumption of a fully correlated and locally fully polarized field, it is defined as

$$V^2(r_i, r_0) = \frac{(E_x^*(r_i)E_x(r_0) + E_y^*(r_i)E_y(r_0))^2}{(|E_x(r_i)|^2 + |E_y(r_0)|^2)(|E_x(r_0)|^2 + |E_y(r_i)|^2)}. \quad (4)$$

As such, CDMP measures the distance between two points (states of polarization) on the Poincare sphere; orthogonal states, opposite to each other on the Poincare sphere, have an associated CDMP value of zero. The CDMP reflects the shape of the distribution of states on the Poincare sphere in contrast to the DoP, which is a measure of the location of the center of mass of the distribution. CDMP quantifies the spatial distribution of states by comparing the Stokes vectors in each point to a common reference. Recently, similar estimations of REF properties permitted to detect local non-stationarities such as the presence of a weak localization phenomenon [14].

It is important to note that CDMP is not an ensemble quantity and it can be calculated while maintaining spatial information. In Fig. 4 we show the spatial distribution of the REFs in Fig. 1, but this time encoded in the CDMP values calculated with respect to the constant state of polarization of the incident field.

As can be seen, the CDMP maps provide information about the similarity of polarization states in the REF. The rough metallic surface, sample (A) in Fig. 4, exhibits strong single scattering and as a result most of the scattered field is in the same state of polarization as the incident one; the CDMP is almost uniformly unity as a result of the strong spatial correlation of the polarization. As the level of multiple scattering increases, the spatial correlation of the CDMP maps reduces as seen for samples B, C, and D.

To assess quantitatively the differences between the CDMP maps, one can examine the probability density functions (PDFs) corresponding to the distributions of CDMP values across the image. As can be seen in Fig. 5, different distributions are found for the CDMP maps shown in Fig. 4. Clearly, the PDFs evolve from being peaked around unity in the case of single scattering (rough surface A) to a more uniform distribution corresponding to the higher order multiple scattering processes in volume scattering media. An interesting observation can be made in regard to samples C and D. Even though the REFs scattered by these media have almost the same global degree of polarization, the PDFs of their corresponding CDMP maps are noticeably different. This can be interpreted as different coverage on the Poincare sphere corresponding to similar centers of mass. Being a local 4th-order field correlation, CDMP preserves the spatial information and distinguishes between different underlying field distributions that have similar average properties.

We note that for a fully diffusive process of wave interaction all polarization states are equally probable and a uniform PDF is to be expected. The slight increase of the probability density

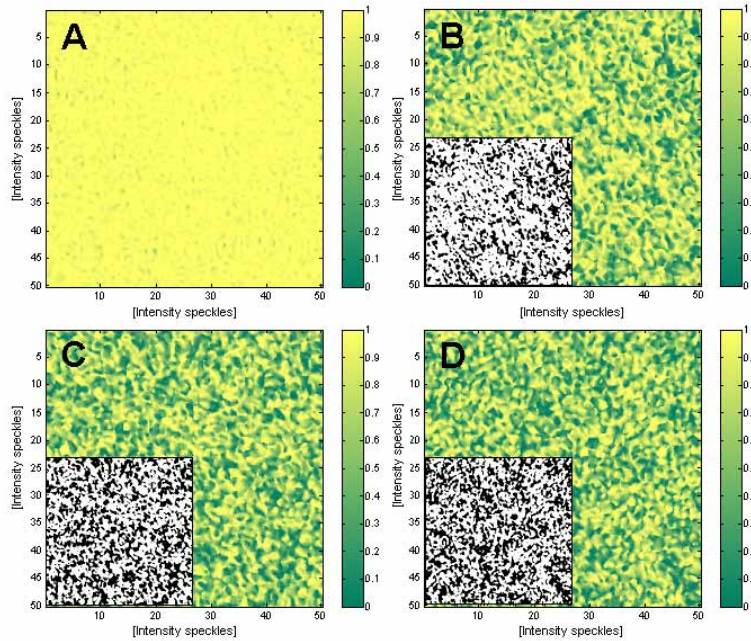


Fig. 4. CDMP maps of the REF in Fig. 1 calculated with respect to incident state of polarization. Insets show binary images of corresponding maps thresholded at CDMP=0.5.

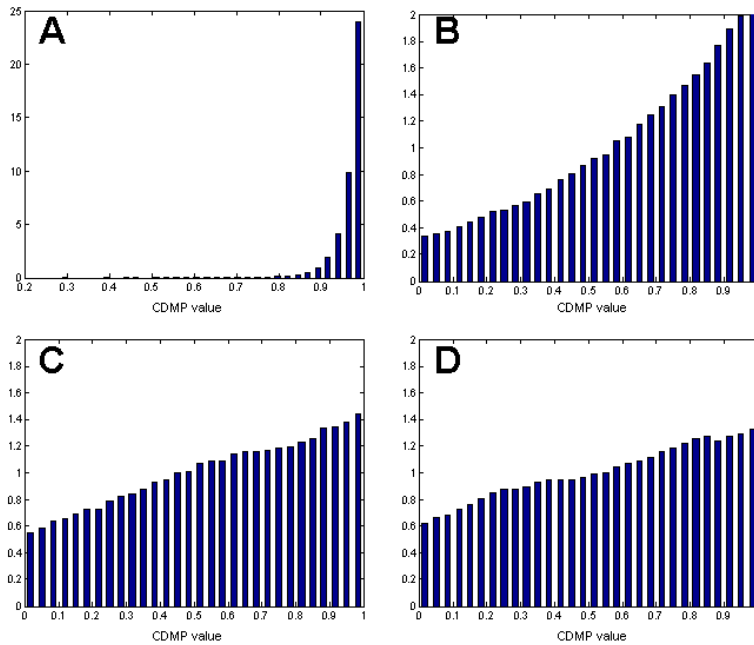


Fig. 5. Probability density functions for the CDMP distribution maps shown in Fig. 4.

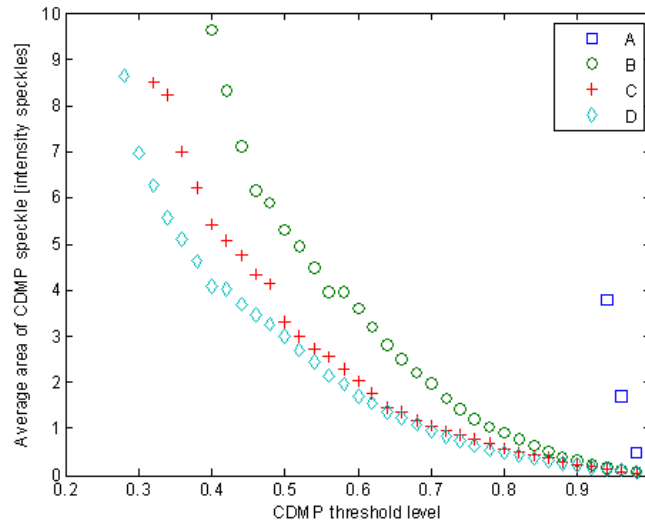


Fig. 6. Size of CDMP speckle in units of intensity speckles as a function of CDMP threshold level. Different decay rates are evident for the four samples examined.

toward higher CDMP values means that the diffusive scattering behavior has not been reached. In the present case this is a consequence of the backscattering geometry where the low-order scattering events are always dominant.

Let us now turn our attention to the spatial characterization of the CDMP maps in Fig. 4. As can be seen, these maps reveal areas of more uniform polarization. One can interpret these areas of spatial variation of the CDMP values as determining some sort of polarization or CDMP “speckles”. This spatial correlation over the CDMP maps is more obvious in the binary images included as insets in Fig. 4. The binary distributions were obtained by thresholding all the points having a CDMP value greater than 0.5. The field in A is clearly dominated by single scattering, where the incident state of polarization is largely maintained. In the binary images corresponding to the other samples, the different extent of clearly defined areas with similar polarization is evident, which can be understood as different levels of spatial correlations between the CDMP values. This is akin to defining an average size of the CDMP “speckle”.

When considering the distributions in the binary map shown in Fig. 4(B), we found that the average size of correlated areas is about 5.3 times larger than the average size of an intensity speckle. The size of the correlation areas clearly decreases for samples C and D where it is 3.3 and 3.0 intensity speckles, respectively. Of course, the number of clusters and their size depend upon the threshold level. As the threshold decreases, the total number of points that lay above this level increases and the size of these correlated areas increases as shown in Fig. 6. However, the areas increase at different rates as clearly seen in Fig. 6, indicating different structures in the CDMP maps and, moreover, a distinctive dependence on the level of scattering in each sample. We should reiterate that both the distribution of CDMP values in Fig. 5 and the extent of the two-dimensional CDMP correlations in Fig. 6 are obtained from one single realization of the random fields shown in Fig. 4. Thus, this analysis constitutes the point and the point-pair characterization of the polarization properties of the scattered electromagnetic field in a manner similar to the intensity distribution $p(I)$ and the average intensity-intensity correlation $\langle I(r)I(r+R) \rangle$ in a scalar speckle pattern.

Finally, we would like to briefly comment on the information contained in these REF prop-

erties. It is known that a number of polarization memory effects are present at different levels of scattering [4, 20, 21]. There is an intimate dependence between the medium's structure and the polarimetric properties of the scattered field and, therefore, one can anticipate that the distribution of polarization states and their spatial correlation in a REF should reflect some of the morphological properties of the scattering media. Let us consider again the two samples that, in average, depolarize the light at essentially the same level, $\text{DoP} \approx 0.32$, yet their structural morphology is quite different. From Figs. 5 and 6, one can clearly see that both the PDF of the corresponding CDMP maps and the sizes of the CDMP speckles are different for these samples. This is because the structural differences lead to different scattering strengths in these two media. To assess these differences we performed typical ensemble average measurements of enhanced back scattering (EBS) [22]. These measurements yielded different values of the transport mean free path: 8 and 7 μm for media C and D, respectively, as estimated from the full width at half maximum of the enhancement peaks.

Being a measure of polarization similarity at different spatial locations, the size of the CDMP speckle reflects the extent of the interaction volume necessary for the wave to depolarize, or, in other words, to lose memory of its initial polarization state. In a specific geometry, the magnitude of this characteristic length scale depends on the number of transport mean free paths [15, 16]. Therefore, scattering media characterized by small values of l^* are also expected to generate, at their surface, scattered fields with smaller values for the CDMP speckles. This is exactly what our experiments show; the lowest value of the CDMP speckle corresponds to the strongest scattering in sample D. Remarkably, one single realization of the scattering process is sufficient to provide information similar to that acquired through an ensemble average measurement.

In conclusion, we examined properties of random electromagnetic fields resulting from scattering processes of different strengths. We have found that the spatial variability of the vectorial properties can be markedly different even when the random fields have similar global properties. The point and point-pair correlations of the complex degree of mutual polarization provide means to identify the origins of scattered fields. We demonstrated that the extent of these spatial correlations is determined by the magnitude of the transport mean free path characterizing the scattering process. Spatially resolved measurements of the polarization properties in one realization of the scattered field allow recovering information otherwise available only through ensemble averages.