# Exploiting speckle statistics in random media beyond the diffusion limit

**Chen Bar**[a] **Marina Alterman**[a] **Ioannis Gkioulekas**[b] **Anat Levin**[a]
[a]*Department of EE, Technion, Israel.* [b]*Robotics Institute, CMU, USA.*

**Abstract:** Using a new MC simulator, we study statistics of speckle fields in scattering media. This allows understanding the Memory Effect limits and using speckle correlations to improve our ability to see through random media 

**OCIS codes:** 030.6140, 030.6600, 290.0290.

## 1. Introduction

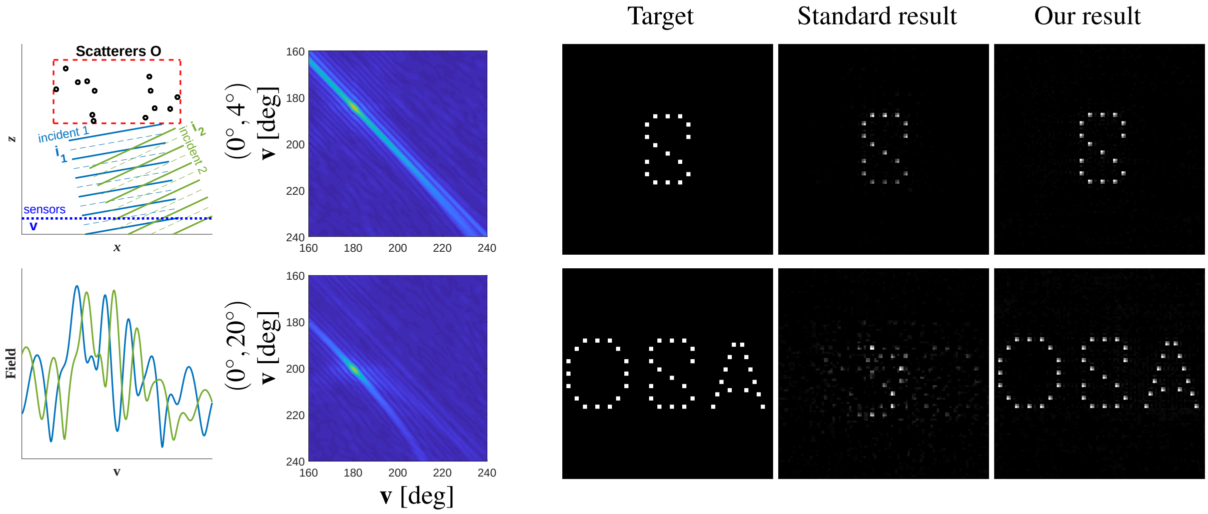
Coherent waves propagating through random media lead to high fluctuation patterns known as speckles. These noise-like patterns are characterized by strong statistical properties, which are at the core of imaging techniques for applications as diverse as tissue imaging, motion tracking, and seeing around the corner [1]. They allow seeing through scattering media [1,2] in microscopic resolution, far beyond what can be achieved by incoherent diffusive techniques. The most common form of speckle statistics is the so-called memory effect (ME), implying that within a small angular difference, two illumination directions propagating through the same set of particles lead to speckle fields that are shifted versions of each other. Due to its wide applicability, there have been many efforts to study the extent of the memory effect for different materials [3]. Available theoretical results only apply under restrictive assumptions, such as diffusion and the Fokker-Planck limit [3]. Given the limited theory, there have been many experimental lab efforts [4] measuring the range of the memory effect for tissue and other materials. The empirical evidence from these experiments suggests that the angular range of the memory effect can, in practice, be order of magnitudes larger than the theoretical predictions derived under the diffusion approximation. Moreover, other types of speckle correlations beyond the angular range of the memory effect are not well studied. In a recent research [5], we suggest a computationally efficient Monte-Carlo (MC) simulator that can evaluate speckle statistics as a function of bulk material parameters, whose accuracy was verified against an exact yet computationally heavy wave solver. Here we show how such a numerical approach opens the door for new ways of studying speckle statistics. In particular it allows a quick evaluation of the memory effect beyond the diffusive models as well as the ability to predict new types of speckle correlations that were not explored in the past. Moreover, it allows extending the angular range under which previous strategies for seeing through scattering layers are applicable [2].

## 2. Speckle statistics and their information

Let $u^{\mathbf{i}_1}_{\mathbf{v}_1}, u^{\mathbf{i}_2}_{\mathbf{v}_2}$ denote two speckle fields generated by the same scattering material under two illumination directions $\mathbf{i}_1, \mathbf{i}_2$. Fig. 1(b) visualize speckle covariances $\mathbb{E}[u^{\mathbf{i}_1}_{\mathbf{v}_1} \cdot {u^{\mathbf{i}_2}_{\mathbf{v}_2}}^*]$ for two fixed illumination directions and a wide set of viewing directions $\mathbf{v}$. The matrices demonstrate the non trivial statistics of speckles. In particular, the covariance has a dominant diagonal that is offset from the center. This shift is essentially the memory effect: two illumination directions propagating through the same set of particles lead to speckle fields that are highly-correlated and shifted versions of each other. When the angle difference is larger, the classical version of the memory effect no longer holds, but one can still observe some correlation along a curved set of viewing directions. To the best of our knowledge, such correlations have not yet been explored, and thus, point to ways of expanding the angular range of computational imaging applications relying on the memory effect.

## 3. Evaluating the memory effect

There have been many attempts to understand the exact extent under which the memory effect holds. The main theoretical results were derived under diffusion assumptions. However, empirical evidence suggests that, in practice, the decay is slower than theory predicts, as long as the optical depth (that is, the average number of scattering events) is lower than the diffusion regime. This difference becomes more pronounced in volumes with high absorption, because absorption attenuates multiply-scattered paths, and especially in volumes with a very forward-scattering phase function. Both of these cases are important in practice, as they match the scattering properties of tissue. Given the difficulty of predicting the memory effect in these situations, the angular extent of the memory effect for materials of interest is often measured empirically in the lab [4]. Our MC algorithm can relax this experimental burden, as it allows for the numerical evaluation of speckle correlation as a function of many material




(a) (b) (c) (d) (e)

Fig. 1: (a) Setup of a 2D target illuminated by two plane waves and sensors measuring the backscattered field. Below it, a typical pair of fields generated by two different illumination directions: the blue and green fields are nearly shifted versions of each other, demonstrating the memory effect. (b) speckle covariances for two pairs of illumination directions. (c-e) Reproducing seeing through random media by [2]: (c) Two targets where illuminators are spread over different angular ranges. (d) As the memory effect range is limited the standard phase retrieval succeeds at the top where the illuminator spread is narrow, and fails at the bottom where the spread is wider. (e) Our algorithm exploiting more accurate statistics can recover both illuminator arrangements.

and imaging parameters. Our simulator takes as input only bulk parameters such as the extinction coefficient, the absorption and the phase function. In particular it shows that for the highly forward scattering phase functions that we can find in tissue, the memory effect can be orders of magnitudes wider than diffusion theory predictions.

## 4. Seeing through scattering layers

To demonstrate how speckle statistics can improve computational imaging techniques based on speckle correlations, we re-implemented the algorithm of Katz *et al.* [2], which attempts to recover a set of incoherent light sources located behind a scattering layer. Remarkably, due to the memory effect, the auto-correlation of the speckle image should be *equivalent* to the auto-correlation of light source positions. Thus, given the seemingly random speckle image, one can recover the position of light sources behind it by applying an iterative phase retrieval algorithm. The success of this algorithm highly depends on the validity of the memory effect at the angular range and for the material of interest. In Fig. 1(d) we show the result of this reconstruction applied to speckle images rendered with our algorithm [5] with two illuminator arrangements. As the angular range used in the second simulation is wider than the range at which the classical memory effect is valid, the reconstruction fails. However, utilizing our accurate modeling of speckle correlation, we can exploit richer statistical information and get a better phase retrieval result through this wider range (Fig. 1(e)).

**Acknowladgment:** This work was supported by ERC 635537, ISF 1046-14, Ollendorff Minerva Center of the Technion, DARPA REVEAL HR0011-16-C-0028 and NSF Expeditions CCF-1730147.

## References


1. M. Batarseh, S. Sukhov, Z. Shen, H. Gemar, R. Rezvani, and A. Dogariu, “Passive sensing around the corner using spatial coherence,” Nature Communications (2018).
2. O. Katz, P. Heidmann, M. Fink, and S. Gigan, “Non-invasive single-shot imaging through scattering layers and around corners via speckle correlation,” Nat. Photonics (2014).
3. G. Osnabrugge, R. Horstmeyer, I. N. Papadopoulos, B. Judkewitz, and I. M. Vellekoop, “Generalized optical memory effect,” Optica (2017).
4. S. Schott, J. Bertolotti, J.-L. Léger, L. Bourdieu, and S. Gigan, “Characterization of the angular memory effect of scattered light in biological tissues,” Opt. Express (2015).
5. C. Bar, M. Alterman, I. Gkioulekas, and A. Levin, “A Monte Carlo framework for rendering speckle statistics in scattering media,” arXiv 2546969 (2019).