Quantitative imaging through scattering wall and fog using statistical analysis and holography

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By

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Chapter 6

Conclusion

6.1 Summary

This thesis presents advanced methodologies for quantitative imaging through random scattering environments, such as static or dynamic scattering walls and fog, leveraging statistical analysis and holographic techniques. Conventional imaging systems face significant challenges when dealing with such random scattering media due to scrambling of object information, leading to speckle patterns. Although these speckle patterns encode sufficient information about the object, the challenge lies in characterizing these speckle patterns and retrieving the object information from the inherent randomness.

The research presented in this thesis focuses on innovative approaches that utilize the randomness of speckle patterns to develop novel statistical characterization and imaging techniques. By integrating theoretical concepts of Hanbury Brown-Twiss (HBT) based intensity and polarization correlations with holographic methods, this work explores unconventional imaging paradigms. Additionally, the thesis provides novel insights into the polarization properties of spatially fluctuating light and explores polarization correlations as tools for statistical analysis and imaging.

Before moving to the randomness-assisted scheme, in the first chapter, a background of conventional quantitative imaging techniques through homogeneous media is discussed. Different types of iterative, non-iterative phase, and polarization schemes are discussed in detail, including holographic approaches. Later, for imaging through random scattering media, a few techniques such as adaptive optics, phase conjugation, transmission matrix, and wavefront shaping techniques are discussed to tackle the randomness. Later in this section, a brief literature survey of the main content of this thesis i.e., correlation-based techniques, is discussed in detail.

Next chapters present our core contributions of this thesis work, and key contributions are summarized as follows:

In second chapter, for analysis of laser speckle patterns and effective utilization of their randomness, a comprehensive framework was established to analyze spatial polarization fluctuations in laser speckle fields using statistical tools. This includes a novel application of the von Mises-Fisher distribution on the Poincaré sphere to quantify the spatial evolution of the polarization state of the polarization speckle fields. Single-shot Stokes parameters (SPs) measurements were performed using a polarization interferometry setup and normalized SPs and averaged SPs were utilized to map the state of polarization of different polarization speckle using von-Mishes Fisher (vMF) distribution on the Poincaré sphere. Another technique was developed to explore the two-point correlation of the SPs to reveal deeper insights into the spatial variation of polarization states fluctuation of polarization speckle. This technique is robust due to non-interferometric measurement of SPs and free from a separate reference beam. These techniques are validated by numerical simulations, followed by experimental tests.

In the third chapter of this thesis, we developed two new experimental techniques for imaging through dynamic scattering media such as fog and dynamic diffusers, using a high-speed camera. The theoretical framework of the proposed method is established within the realm of HBT-based intensity correlation of the dynamically fluctuating intensity patterns generated from dynamic diffuser as well as through foggy medium. Successful reconstruction of amplitude and phase information of objects hidden behind scattering media showcases potential applications of our technique for quantitative phase imaging under dynamic conditions.

Another major highlight of this thesis is to provide a fresh insight on leveraging polarization correlations for new statistical analysis and imaging methods. A theoretical framework based on two-point correlations of fluctuations in the SPs is established for the statistical characterization and imaging techniques using vector sources. In the fourth chapter, three new experimental techniques for characterizing vector sources using Beam Coherence-Polarization (BCP) matrix are presented. Correlations of fluctuations of the only two SPs, namely S_0 and S_1, are leveraged for the measurement of elements of BCP matrix. To validate the proposed approach, we have designed a compact, stable folded interferometer to facilitate a holographic approach to extract the complex elements of BCP matrix. Desired SPs are measured with double and single-shot, and BCP matrix measurements are performed for spatially and temporally fluctuating vector sources.

In the fifth chapter, we have experimentally demonstrated a new single-shot quantitative full-Stokes polarimetry technique from the scattered random light by capturing dual-channel interferograms. These interferograms are used to compute the desired SPs, S_0 and S_1, and subsequent two-point Stokes correlation enables the recovery of the state of polarization of incident light beam. This technique eliminates the need of mechanical rotation of polarization elements like rotating retarders and linear polarizers to measure the SPs. We have verified the applicability of the proposed technique through experimental measurements of the four SPs for different sources and also characterized by polarization ellipse plots.

A comparison table summarizing the advantages and disadvantages of the techniques presented in this thesis is illustrated in Table 6.1.

	Advantages	**Disadvantages**
Chapter 2	Provides a statistical framework using vMF distribution for the analysis of speckle polarization analysis, first	Experimental constraints like leakage in orthogonal polarization components, optics size, beam

	time to the best of our knowledge. Visualization of vMF distribution on the Poincare sphere provides a deeper understanding of spatial polarization dynamics of different types of laser speckles Non-interferometric, stable experimental approach for evaluating spatial polarization dynamics of different types of laser speckles	profile lead to some discrepancies between simulation and experimental results
Chapter 3	Iteration-free phase retrieval under dynamic scattering conditions Works well for both attenuation-free (dynamic scatterer) and attenuating (fog) scattering medium	Requires high-speed camera Imaging quality depends on the cap of the delta correlation characteristics of illuminating random phases of the intensity patterns
Chapter 4	Compact folded interferometer is designed and developed for the measurement of BCP matrix with fewer measurement than existing techniques and does not require point scanning Free from the mechanical rotation of	Experimentations were performed for statistically stationary vectorial random fields Presence of pinhole aperture with the requirement of uniform reference function can impact the recovery of elements of BCP

	polarization elements	matrix.
Chapter 5	In comparison to traditional polarimetry which require more number of intensity measurements or sophisticated optical materials, our approach leverages the randomness introduced by the diffuser to develop a single-shot Stokes polarimetry technique Mechanical rotation of polarization elements such as a phase retarder and a linear polarizer (LP) is not needed.	Leakage of orthogonal polarization components through polarization optics can attribute to errors in measurement of state of polarization (SOP) of the source

Table 6.1 Comparison table

Overall, the randomness-assisted quantitative imaging methods presented in the thesis have potential applications in characterizing random fields, imaging through scattering media, Stokes polarimetry, biomedical imaging, sensing, etc.

6.2 Future Work

The field of quantitative imaging through randomness remains ripe for exploration, with significant potential for advancing current methodologies. The future scope of this research includes:

- Explore tailored speckle statistics to enhance imaging resolution of conventional diffraction-limited imaging systems. Customization of the speckle statistics play a crucial in imaging through scattering media and improve the resolution of conventional diffraction-limited systems. Instead of illuminating an object with a coherent laser light source, these customized speckle-based illuminations can pave the way for high-resolution imaging techniques.

- Imaging through dynamic scattering media in vectorial domain, specifically non-invasive polarization imaging in challenging environments like fog.
- Non-interferometric geometries for imaging applications using second-order intensity and polarization correlations to simplify experimental setups.
- Stokes polarimetry through scattering layers for biomedical imaging, focusing on real-time applications to establish this technique as a valuable tool in medical diagnostics.
- Higher-order correlations, such as third-order intensity correlations, to develop high-resolution phase and polarization imaging techniques. In addition, we want to develop advanced algorithms to address the computational demands of these methods.
- Adapt the developed techniques for non-line-of-sight (NLOS) imaging and underwater imaging, opening new possibilities for surveillance and environmental monitoring.