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Optical signal processing: Holography, speckle and algorithms

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Abstract: Modeling the propagation of light through free space and simple paraxial systems continue to be enduring, and practically important topics in optics. Is there anything new or interesting that remains to be said? Given the pervasive use of digital cameras and numerical algorithms, examples are given indicating that the answer is yes. Satisfactory modeling requires the interactions of the whole optical information processing system (optics, optoelectronics and software) be included.

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1. Introduction

In this paper I briefly introduce and review some topics which I, collaborators and several current and former graduate students have been tackling over the past several years. Most of the issues have resulted in recent publications [1-24], but my discussion will primarily involve the recent work presented in [26-32]. I wish to emphasis the importance of treating optical system as systems which must be analysed and designed in their totality. Some of what I will say will no doubt strike some readers as obvious; however I will discuss very specific problems in topical areas of research which I believe have benefited from our approach. Therefore this paper might most charitably be characterised as an attempt to describe the causes and remedies to some of my own confusion in the forlorn hope that some benefits may result from the resulting public airing.

The context for much of what is discussed is Optical Signal Processing, (OSP) and specifically Fourier Optics. It has been very strongly influenced by work over the past 20+ years involving the Collins ABCD matrix formalism, the Linear Canonical Transform (LCT), and the Wigner Distribution Function (WDF), i.e., Phase-Space Optics (PSO), [1]. This work has placed the discussion of paraxial systems in a broader and I believe more structured context. Importantly the resulting framework has also supplied a set of mathematical modelling tools, which have provided some insights into the operation of such systems. Some of the applications examined by my group include metrology systems [2-6, 25], and optical encryption [18-24, 31]. The work has included significant experimental work with speckle based and holographic systems [4-11, 32].

What has become obvious in the context of this work, in both understanding the physics and defining the performance of such systems, is the absolutely critical significance of the digital elements (optoelectronic hardware and algorithmic software) of these systems. However the motivation to perform this work is not only to develop good software to model or design these systems. The numerical algorithm used in fact play a central role in processing or interpreting the experiments performed. Clearly the performance of a software tool, i.e., its efficiency, necessitates that the algorithms themselves are developed to ‘fit the physics’. But significantly, in trying to achieve such an optimum fit interesting insights into the systems being examined and the models themselves emerge.

Thus a unifying picture emerges: ray matrices, paraxial wave optics and the numerical simulation of optical Quadratic Phase Systems (QPS) to be brought together in a systematic and insightful way with the PSO providing the simple insights that allows operational insights to be accessible even in quite complex situations.

2. Free Space Propagation and the Space Bandwidth Ratio

The Space Bandwidth Product (SBP) is the product of a length (area: \( L_xL_y \)) and a spatial frequency extent or bandwidth (\( f_x = 2/D_x \) and \( f_y = 2/D_y \)). If you have a camera or SLM and you know the device area and the pixel pitch (size: \( D_x, D_y \)) you know the maximum amount of information that can be captured or displayed, \( 4L_xL_y/D_xD_y \). If you draw a Phase Space Diagram of a 1D signal, typically a box in the plane, then the area inside the box indicates the number of samples needed to represent the signal, i.e., \( 2L_y/D_x \). If you pass the signal through an optical system you
transform the shape of the area of this box. So what does all of this mean when we wish to efficiently simulate the process taking place? Two things are critical: (i) The number of samples used, and (ii) The actual algorithm used. Based on the number of papers published in the literature both issues are of great interest and non-trivial. To answer (i), i.e., how to choose the fewest sufficient number of samples, it turns out it is best to pre-process the signal before performing the calculation. In terms of the SBP this involves finding the most suitable PSD starting area shape [16].

What about question (ii): How do you identify the best algorithm? This question has been answered in two ways, either (a) Use an integrated fast algorithm we have developed a Fast LCT [12] which is directly analogous to the Fast Fourier Transform (the ubiquitous FFT); or (b) Using a new parameter we have proposed, the Space Bandwidth Ratio (SBR), choose when to apply the Direct Method (DM) or Spectral Method (SM) of calculating Fresnel propagation. Both the DM and SM rely on numerically simulating the system using a FFT [26].

One final remark about efficient calculations: As noted The LCT describes propagation of a signal through any lossless QPS. But real systems have apertures. Do fast sampling rules and fast algorithms exist for such lossy systems? Yes they do, and the development of such algorithms and their physical significance is discussed in [27].

3. Speckle Longitudinal and Lateral Speckle Size

Understanding and using speckle is important in a large number of situations, how important is best illustrated by the commercial significance of the optical mouse, which is a truly extraordinary piece of everyday technology. The standard mouse records motion in 2D. Is a 3D optical mouse possible? For an optical engineer the question might involve identifying displacements by performing correlations in a controlled 3D speckle field.

What has any of this to do with the topic of our discussion? Applying the SM and DM to simulate the propagation of a speckle field and then using the results to estimate speckle sizes will typically result in different speckle size dimensions. Why? Having analytically modelled speckle size experimentally measured speckle size using a digital system and then compared the results to the numerical simulations we find the DM is best and this is intimately linked to the speckle correlation characteristics [28, 29].

3. Digital Holography – 2.5 Dimensional Imaging

Using a digital camera (CCD) to capture a speckle field, or indeed a holographic field, has significant consequences for the resulting digital representation of the field. Matching the post capture digital processing to the input optical signal and/or optical system used to process the field before capture, is critically important if one wishes to maximise the quantity and quality of the data captured. Manipulation of the field before capture has enabled such very fruitful avenues of research as super-resolution and computational imaging. But technology and the digital holographic technique itself, while providing real opportunities also imposes limitations. In [30] these limitations are discussed and rules are presented which permit the total system performance to be quantified.

4. Conclusion

The work to date has raised many questions which have lead to fruitful insights into possible applications of OSP.

5. Acknowledgements: The work has been support by Enterprise Ireland, Science Foundation Ireland, and the Irish Research Council for Science Engineering, and Technology under the National Development Plan.

6. References

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