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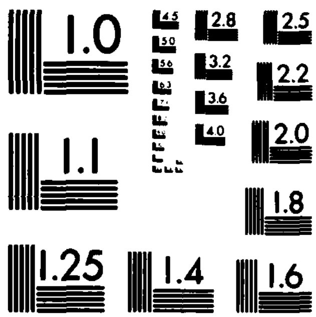

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CHARACTERIZATION OF SCATTERING MEDIA USING NON-GAUSSIAN SPECKLE PATTERNS

FINAL TECHNICAL REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of a research program on non-gaussian speckle are summarized under six sub-headings: dynamic speckle, static non-gaussian speckle, doubly scattered light, quasi-thermal light sources, detection of hidden gratings and space-time analysis camera. Details of the research are given in the eight publications that resulted from this Grant.

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CONTENTS

1 INTRODUCTION

When spatially and temporally coherent light (for example, that from a laser) is scattered by a rough surface or an inhomogeneous random transmitting medium, then one observes a random intensity structure which is called "speckle". If the surface moves or the random medium evolves in time, then the speckle pattern also changes with time, usually in a non-trivial way - this is referred to as "dynamic speckle". Under certain special conditions, the probability density function of complex amplitude in a speckle pattern is a circular complex random process and such speckle is called "gaussian speckle". All other cases of speckle are termed "non-gaussian speckle" - this is the most general type of speckle, and the most interesting.

Gaussian speckle patterns usually arise when a large number of scattering elements contribute to the complex amplitude at any one observation point; the gaussian statistics of the complex amplitude then arise by the central limit theorem and the statistics of the scattering process itself is therefore lost as the complex amplitude is gaussian regardless of the scattering statistics. Thus, as a general rule, static gaussian speckle patterns do not contain any useful information about the scattering medium. Dynamic gaussian speckle can contain interesting information as discussed in Sect 2.1.

Non-gaussian speckle patterns can arise in a number of ways, one of the most interesting being when only a small number of scattering centers contribute to the complex amplitude at any one point. One application of these patterns is to characterizing the random surface or medium responsible for the scattering - although we have made progress in this area, this inverse problem is still unsolved.

A number of problems related directly or indirectly to speckle were investigated under this Grant. It turned out that one of the most exciting had nothing to do with the original goal of characterizing random media; rather, it was a way of characterizing an object "hidden" by a random medium (see Sect 2.5), by means of coherence measurements. We are planning further studies of this problem because of its potential applications in a number of fields.

During the course of the research a total of eight papers were published in refereed journals and these give a detailed account of the results that were obtained. In this final report we simply give a one-page summary for each of six sub-topics, emphasizing our contribution and the scope or need for further study.

2 SUMMARY OF RESULTS

2.1 Dynamic Speckle

Consider the following simple experiment: a random transmitting medium, illuminated by a plane wave, moves immediately in front of a lens perpendicular to the optical axis - what are the spatio-temporal statistics of the intensity at the focus of the lens ? As studied in reference [1], the random medium was the Earth's atmosphere and we were observing at the focus of an astronomical telescope. The motivation for this work was to understand the spatio-temporal behaviour in order to improve the technique of stellar speckle interferometry which hitherto had ignored information in the space-time domain.

It was already well-known that the speckle pattern exactly at the focus had a dynamic behaviour called "boiling"; the implication was that there was no overall translation of the speckle in time (observation was in the Fraunhofer plane, so no translation would be expected) and no overall directionality in space-time. The measurements reported in [1] show that this second implication is incorrect. The boiling speckle has a preferred axis of spatio-temporal change that is parallel to the axis of motion of the atmosphere. In simple terms, a bright speckle disappears from one point and tends to re-appear along an axis defined by the direction of motion of the atmosphere. In technical terms, the spatio-temporal correlation function of the intensity is not cross-spectrally pure (ie does not factorize into space- and time-only parts).

The result is curious, but apparently without application. In subsequent work in our laboratory, O'Donnell [9] investigated the phenomenon in detail in a controlled laboratory experiment which gave excellent agreement between theory and experiment. It was found that the space-time cross correlation function of intensity was a very sensitive indicator of focus position in optical systems - in fact, defocus values as small as 1/40 of a wavelength (measured at the edge of the pupil) can be determined from correlation measurements of this type.

In related work, an academic visitor supported by this Grant, Dr J Ohtsubo, showed how differentiated speckle patterns could be used to determine the velocity of rough object illuminated by coherent light [2,3]. Under certain geometries, the velocity can be obtained directly from the zero crossing rate of the time differentiated intensity in the speckle pattern.

2.2 Static Non-Gaussian Speckle

The probability density function of intensity in a gaussian speckle pattern is a negative exponential function:

$$p(I) = 1/\langle I\rangle \exp[-I/\langle I\rangle] .$$

The normalized moments of this distribution are:

$$m_j = j\,! ,$$

and in particular the second moment is 2. When only a small number of scatterers form the speckle pattern then the intensity no longer has the simple negative exponential probability density function and indeed there is still no satisfactory theoretical formulation for p(I).

Jakeman and collaborators at RSRE, Malvern, UK have developed a theory that predicts the moments for a non-gaussian speckle pattern produced by illuminating a small area of a rough surface whose height fluctuation has a gaussian probability density and also a gaussian autocorrelation function - it is also assumed that the rms surface height fluctuation is greater than one wavelength and that the correlation length is much greater than a wavelength (this second assumption is required for the scalar diffraction theory to be valid). Several groups, including ourselves, found no agreement between their theory and measurements made using ground glass surfaces and this motivated two further studies.

Ohtsubo [4] performed a computer simulation of non-gaussian speckle and found that, in one dimension, the results were closer to the experimental results for ground glass than to Jakeman's theory. However, a simple consideration of the focusing characteristics of caustics suggests that in two dimensions the computer simulations would yield larger moments and hence be closer to the theory; we are currently doing the two dimensional computer simulations.

Using carefully fabricated random surfaces of known and controlled surface characteristics, which exactly obey the theoretical assumptions, we have shown [5] that there is excellent agreement between theory and experiment. The earlier disagreement is probably due to the fact that ground glass is a fractal-like surface and does not have a gaussian correlation function. Experimental studies in this area are continuing.

2.3 Doubly Scattered Light

Another way in which non-gaussian speckle can arise is when light is scattered twice, ie "speckled-speckle". Consider the following simple experiment: light from a laser illuminates a diffuser, forming gaussian speckle which is then allowed to illuminate a second diffuser. What is the probability density function of the intensity in, say, the far-field of the second diffuser? This problem was investigated by O'Donnell [6] who developed the theory; we are currently trying to verify the theory through experiments.

The probability density function of intensity turns out to depend critically on the speckle "diameter" d incident on the second diffuser relative to the diameter D of that diffuser (in practice a clear aperture of diameter D was taped to the second diffuser). If $d/D << 1$, ie many speckles illuminate the second diffuser, then the intensity in the far-field of the second diffuser has a negative exponential probability density function. However, if $d/D >> 1$, then the intensity has a one-parameter K-distribution, and for intermediate cases, defining $N = d/D$, it can be shown that the intensity is <u>approximately</u> K-distributed, where the order of the K-Bessel function is N-1.

The K-distributions seem to arise in a number of non-gaussian speckle problems, although it should be stressed that this is one of the few cases in which it can be shown formally that they should exist. Experimental verification of these results is difficult as few photons remain after a double scattering process; we are currently using an Argon laser and photon counting techniques to measure the histogram of photon counts. Recently, we have developed a stable method of inverting the Mandel or Poisson transform based on a minimum norm criterion in a suitably chosen Hilbert space [10] and will use this to estimate p(I) from the histogram of photon counts.

2.4 Quasi-thermal Light Sources

The coherence time of a thermal source depends inversely on its bandwidth; in practice however it is difficult to produce a thermal source with a coherence time longer than about a nanosecond. When studying coherence, it is sometimes convenient to have a source with a longer and more controllable coherence time, and Martiennsen and Spiller showed that a rotating ground glass placed in a laser beam can fulfill this task - this is the so-called "quasi-thermal" source. The field produced by a quasi-thermal source is simply a dynamic speckle pattern and it is well-known that there is a very close analogy between speckle and coherence theory.

Physically, of course, there is a great difference between a true thermal source, such as a blackbody, and a secondary (scattering) quasi-thermal source. Because of the deterministic motion of the diffuser, we might expect the differences to be apparent when we consider the spatio-temporal coherence properties in each case. There is indeed an important difference, as pointed out by Gonsiorowski and Dainty [7]. Light from a blackbody is cross spectrally pure; that is, the spatio-temporal coherence equals the product of the spatial coherence and the temporal coherence. This means that the shape of the spatial coherence function is invariant of time integration and vice versa, and this fact was implicit in the classic intensity interferometer of Hanbury-Brown and Twiss. They measured the spatial coherence of light integrated over many coherence times and their subsequent analysis based on the van Cittert-Zernike theorem assumed cross spectral purity of the light. This was a perfectly valid assumption for blackbody radiation.

Suppose one tries to repeat their experiment in the laboratory using a quasi-thermal light source. As shown in reference [7], the shape of the spatial coherence function now depends on the degree of time integration, because the field is not cross spectrally pure. In fact, the coherence areas (speckles) slightly increase in size on time integration. The theory of quasi-thermal sources is not only interesting in its own right but also is relevant to the reduction of speckle in conventional and holographic imaging systems.

2.5 Detection of Hidden Gratings

Suppose that a diffuser consists of a random phase plate in front of a phase grating and we are interested in detecting the presence of the grating that is "hidden" by the random phase part of the diffuser. Let the grating have a period b and let the autocorrelation width of the complex amplitude transmittance of the random diffuser be L. Simple inspection of the grating/diffuser combination in incoherent light will not reveal the presence of the (phase) grating. If $L/b \gg 1$, then the far-field diffraction pattern will consist of narrow speckle clouds centered on well-separated diffraction orders; in fact, a more detailed analysis [8] shows that the speckle clouds are separated for values of $L/b > 0.33$. For values $L/b < 0.33$, the grating is "hidden", at least as far as simple-minded intensity measurements are concerned.

However, as first shown by Baltes and collaborators, the presence of the grating can be revealed by coherence measurements in the far-field. We have made a complete experimental study of this theory [8,11] and shown that the grating can be detected provided that $L/b > 0.15$; there is thus a small region of L/b between approximately 0.15 and 0.33 where the grating is hidden to conventional measurement but detectable to cross correlation or coherence measurements. This principle governs the operation of the Phonocard system in widespread use in Europe and could be used in optically encoded credit cards, giving much greater immunity to counterfeiting then magnetic encoding.

The experiments described in references [8] and [11] used photon correlation methods and during the course of these experiments we discovered by accident that if the diffuser is allowed to move with respect to the grating, then the presence of the grating can easily be detected for any L/b by recording the autocorrelation of the intensity recorded with a single photomultiplier. Whilst this is not relevant to the Phonocard type of application, it is highly relevant to seeing objects obscured by moving fogs and other diffusing media. We are currently extending this work to the detection of objects that are more complicated than simple gratings. The basic principle is to use spatio-temporal correlation or coherence measurements in the far-field, rather than simple intensity measurements, to detect fixed objects "hidden" behind moving diffusers.

2.6 Space-Time Analysis Camera

During the period covered by this Grant, we have made many measurements of the spatio-temporal correlation of dynamic speckle patterns (partially coherent optical fields). These have been made using a pair of photomultpliers separated by a distance x and time cross correlating the photon counts from them; by repeating this for many separations x, the space-time intensity cross correlation can be measured. As outlined in previous sections, the spatio-temporal behaviour of light fields can carry alot of useful information about scattering media. However, the two photomultiplier approach to the measurements is too slow to be valuable in any real application and a new measurement system is currently under construction.

In the new system, called the Space-Time Analysis Camera, or STAC, the space and time coordinates of detected photons are recorded on a 256 by 256 spatial array with a deadtime of about 600 ns. The spatio-temporal cross correlation function is then computed on line for a range of spatial and temporal lags, thus yielding results in real-time. This instrument will be completed by mid-1984.

3 PUBLISHED PAPERS

Supported by Grant

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2. J Ohtsubo, "Exact solution of the zero crossing rate of a differentiated speckle pattern",Opt.Commun.,42, 13-18 (1982).

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8. J C Dainty and D Newman, "Detection of gratings hidden by diffusers using photon correlation techniques", Opt. Lett., December 1983.

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9. K A O´Donnell, "Correlations of time-varying speckle near the focal plane", J.Opt.Soc.Am., 72, 191-197 (1982).

10. C L Byrne, B M Levine and J C Dainty, "Stable estimation of the probability density of intensity from histograms of photon counts", in preparation.

11. D Newman and J C Dainty, "Detection of gratings hidden by diffusers using intensity interferometry", submitted to JOSA A.

4 PERSONNEL, DEGREES AWARDED

Personnel Supported

J C Dainty	Associate Professor of Optics, Principal Investigator
T Gonsiorowski D R Hennings B M Levine D Newman K A O´Donnell	Research Students

Degrees Awarded

K A O´Donnell	PhD - January 1983

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