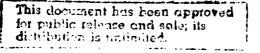Office of Naval Research

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Report for

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Studies of Quantitative Methods for Imaging from Scattered Fields

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1

Report

Summary of overall progress

Since the last report, the following activities have been pursued and are continuing.

1.   A detailed analysis of the differences between first Born and Rytov approximations was carried out. This was done for two reasons; the first to make comparisons for a case in which exact results were known and thereby better model the limitations of each approximation; the second to develop a deeper understanding of the limitations of their distorted wave counterparts, which we have been developing over the last few years. An important result of this work is the effect of range and direction of scattering on the relative merits of the two methods; we believe that these results are new. This work is summarized below and has been submitted for publication to JOSA A.

2.   The analysis of the advantages and disadvantages of the homomorphic filtering technique applied to solve the exact inverse scattering problem has continued. There have been problems with strongly scattering objects due to phase unwrapping. Work has continued to more carefully compare the reconstruction of $\nabla\Psi$ from the backpropagation of simulated data with that predicted for the direct problem, from the same data. This is to verify that the information we wish to recover is indeed present in the form in which we expect it to be. The problems of phase unwrapping and point zeros in the function prior to taking the logarithm have been studied and an alternative approach has emerged which is described below. No further progress can be reported at this stage on relating this method to the Rytov approximation or to obtain useful results from real data but it remains one of our main directions of attack.

3.   The exact method proposed by Ramm has been studied on and off since it does result in a Fourier based inversion scheme, which is appealing. We believe that we have now found a flaw in this approach and may wind down this particular area of work; this too is discussed below.

4.   In anticipation of the next phase of this project, namely to consider the inverse scattering problem for nonlinear medium, we have been studying the writing of structures into nonlinear media, specifically photorefractive crystals. This experimental and theoretical work has been direct toward writing structures with intense beams and reading with weak beams, the partial erasure on reading being a problem. However, we have identified possible methods for storing information more permanently, which is important in its own right because of the widespread interest in these materials for optical data storage. We describe more detail about this work below.

Activities

During the last six-month period M.A. Fiddy participated in the NATO ARW held in mid-April on Inverse Problems in Scattering and Imaging. A paper was presented at a Joint URSI/AP-S Session held in London, Ontario in June and two others at the PIERS meeting held in Cambridge, MA in July. With regard to the problem of imaging from scattered fields and noisy images, M. Fiddy was invited to give a review paper at the O.S.A. Annual Meeting in San Jose, in early November.

Next July, M. Fiddy was invited to chair the Conference on Inverse Problems in Scattering and Imaging, which will be one of several conferences forming SPIE's 1992 International symposium on optical Applied Science and Engineering, to be held in San Diego.

Also during the last 6 months, M. Fiddy joined the Editorial Boards of journal Waves in Random Media (Institute of Physics), Neural Computing Applications Forum (Springer), International Journal of Optoelectronics, (Taylor and Francis).

Papers and conference presentations

Lin, F.C. and M.A. Fiddy, "On the issue of the Born-Rytov controversy: I Comparing analytical and approximate expressions for the one-dimensional case", submitted to J.O.S.A. A.

Lin, F.C. and M.A. Fiddy, "Optimization of the self-pumped phase conjugation in $BaTiO_3$ for optical image storage and readout", submitted to J.O.S.A. B.

Widder, D.R. and M.A. Fiddy, "High performance learning by modified error backpropagation", submitted to Neural Computing and Applications, Springer, (Nov 1991).

Kang, C-C and M.A. Fiddy, "Nonlinear optical properties of suspensions of microparticles; electrostrictive effect and enhanced backscatter", submitted to Optics Letters (Nov. 1991).

Fiddy, M.A., "Quantum-limited image restoration", Proc. Optical Society of America Annual Meeting, San Jose, November 1991, (invited review paper).

Fiddy, M.A. "Multidimensional processing: nonlinear optics and computing", Multidimensional Systems and Signal Processing, 2 (1991) 359-372.

Li, G., F.C. Lin, M.A. Fiddy and Y.Y. Teng, "Fanning effects in photorefractive barium titanate", Bull. Am. Phys. Soc. (to appear).

Yang, T., G-J Leu, F.C. Lin, M.A. Fiddy and Y.Y. Teng, "Temperature dependence of diffraction efficiency and response time of volume gratings in barium titanate", Bull. Am. Phys. Soc. (to appear)

Lin, F.C., D. Sun, G. Leu, M.A. Fiddy, T. Yang and Y.Y. Teng, "Stability of information readout by self pumped phase conjugation in barium titanate", Proc. O.S.A. Topical Meeting on Photorefractive Materials, Effects and Devices, July 1991.

Steriti, R., M. A. Fiddy and J. Coleman, "Regularized matrix inversion on a neural network architecture", Proc. Int. Joint Conference on Neural Networks, Seattle, pp , 1991.

Alavi, A., R.V. McGahan, F.C. Lin and M.A. Fiddy, "New interpretation to inverting scattered field data from strongly scattering targets", PIERS'91, 2A5, Cambridge, July 1st - 5th.

Lin, F.C., R.V. McGahan and M.A. Fiddy, "Quantitative imaging of strongly scattering objects at 10GHz", (Invited) PIERS'91, session 4A3, Cambridge, July 1st - 5th.

McGahan, R.V., F.C. Lin and M.A. Fiddy, " Inversion of 10GHz scattered field data from strong scatterers", 1991 North American Radio Science Meeting and International IEEE/AP-S Symposium, June 24th-28th, London, Ontario, IEEE/AP-S.

Abbiss, J.B., B.J. Brames and M.A. Fiddy, "Super-resolution algorithms for a modified Hopfield neural network", IEEE Trans on Signal Processing, 39, pp1516-1523, July 1991.

Kalkan, A. and M. A. Fiddy, "Neural network co-ordinate transformer", Proc. Neural Networks for Vision and Image Processing, Wang Institute of Boston University, p36, 1991.

Steriti, R., M. A. Fiddy and J. Coleman, "A neural network matrix inversion algorithm used for regularized image reconstruction", Proc. Neural Networks for Vision and Image Processing, Wang Institute of Boston University, p60, 1991.

Widder, D.R. and M.A. Fiddy, "Handwriting character recognition on a compact neural network", Proc. Neural Networks for Vision and Image Processing, Wang Institute of Boston University, p63, 1991.

Kang, C-C and M.A. Fiddy, " Nonlinear optical properties of suspensions of microparticles: electrostrictive effect and enhanced backscatter", Proc. SPIE Vol 1497, Nonlinear Optical Materials, 372-381, 1991.

Steriti, R., M.A. Fiddy and J. Coleman, "Image reconstruction and regularization: SVD and a neural network based matrix inversion algorithm", Proc. Third Biennial IEEE Acoustics Speech and Signal Processing Conference, p F121-122, 1991.

Fiddy, M. A., "Linearized and approximate methods for inversion of scattered field data", Proc.. NATO ARW on Inverse Problems in Scattering and Imaging, April 1991, Ed. M. Bertero and E.R. Pike, Plenum Press, to appear.

Progress since last report.

The following issues were raised in the last report and have been addressed:

1   Data sets from targets have now been taken using the bistatic procedure. This is much faster and avoids having to rotate the target to change the incidence angle and data are now available on concentric circular loci in k-space. This allows the data to be more uniformly spread in the Fourier domain and leads to improved interpolations of that data onto a Cartesian grid prior to taking the inverse Fourier transform. However, we are finding that the lack of data near the k-space origin leads to increased error in the interpolation, compared to data on arcs.

2   The backpropagation algorithm, useful for all of the methods for inversion is now working and has been checked and tested against known scattered field data and k-space data.

3   We can simulate the scattering from two concentric cylinders of arbitrary radius and permittivity. By selecting either the inner or the outer cylinder to be the stronger scatterer, we can verify the performance of the DWBA inversion method for the case when either is the stronger known *scattering component*. This has not been taken further in the last 6 months because of the work described below which had priority.

4   Data have been collected from a styrofoam block with a square cross section; this has been done both using monostatic and bistatic data collection. The motivation for using a block as the scatterer was to allow incorporation of a very tight support constraint on the reconstructed image and to obtain a maximum improvement in resolution using the PDFT. Data were also collected from this target with a small strip of different permittivity attached to the side. These data allow us to complete one of the initial tasks of the work which was to verify the DWBA method, knowing the background scattering potential. Small features such as this strip were not observed in the early reconstructions done with cylindrical objects, mainly because of the poor resolution of the reconstructed image. This has not been taken further in the last 6 months because of the work described below which had priority.

5.   The separation of V from $V\Psi$ by homomorphic filtering techniques is proceeding well. The requirement for phase unwrapping has been resolved, by considering a differential cepstrum. Rather than dealing with $\log V\Psi$ and the

problems of point zeros in the function and a discontinuous phase, one can filter the derivative of this, i.e.

$$\frac{\partial \log G}{\partial x} = \frac{\frac{\partial G}{\partial x_1} + \frac{\partial G}{\partial x_2}}{G}$$

where multiplication top and bottom by $G*$ allows easy regularization to avoid the point zeros of a function G. The differential cepstrum will retain the spatial frequencies of the field added to those from V, to allow filtering and recovery of V. This is being pursued at the moment, using the internal fields associated with targets consisting of concentric layers of differing permittivity.

6. The inversion techniques can be used for quantitative imaging of optical structures or for synthesis of optical elements. In the last report we mentioned on-going work on computer generated hologram (CGH) fabrication which was presented at the 1990 OSA Annual meeting. The distorted wave methods combined with the PDFT to constrain the structure of the object, lends itself to the design of stacked CGHs which can exhibit high diffraction efficiencies. The student who was working on this left in May and no further work has been done, unfortunately. Discussions had been held with the Director of Corporate Relations at the National Nanofabrication Facility at Cornell and this was mentioned in the last report. A proposal was written in order to get some small optical elements fabricated based on our CGH programs; this was not funded. Our attention therefore returned to our own facilities and there remains a chance of modifying a electron microscope for writing purposes, but more attractive is the writing of structures directly into photorefractive media.

7. Although only indirectly related to this program of work, two other areas of work have seen some progress and are mentioned in the list of publications above. With regard to imaging from limited Fourier data, which we anticipate will be the requirement from our inversion methods, a neural network processor was evaluated for image reconstruction. Both the recovery of an image from low pass filtered image data and limited Fourier data have been studied and it was found that the neural inversion method was intrinsically regularized, providing better reconstructions than the usual algorithmic procedures. Secondly, work has been submitted for publication on the effect of enhanced backscatter from multiple scattering media when the medium is optically nonlinear. The enhanced backscatter is a result of reversible multiple scattering paths and has similarities to weak localization phenomena. This may prove to be important in several ways, one of which is that there has been recent evidence to suggest that imaging of objects through strongly scattering media might be possible because of this

enhanced backscatter effect and its consequences for the complex degree of coherence of the backscattered light. This may assist with our desire to image in and through strongly scattering media, whether nonlinear or not.

8.   We have been trying to understand how to implement, numerically, the "exact" inversion algorithm of Ramm's for some time. The scattered field from an effectively bounded scatterer is measured for all scattered field directions, θ', and all incident illumination directions, θ. These scattering amplitudes, $A(\theta',\theta)$ are analytically continued under the constraint that, for complex θ, $\theta'.\theta'= 1$ and $\theta - \theta' = p$ but $|\theta'|$ and $|\theta|$ tend to infinity. It is necessary that the values of p span the Fourier domain of the scattering object at values which permit the inverse Fourier transform to be performed. However, in order to satisfy the constraints of the theorem on which this inversion method is based, one can show that p cannot be arbitrary, but is confined to a manifold which would not allow the scatterer to be found by inverse Fourier transform. If $\theta = a + ib$ and $\theta' = c + id$, then $p = a - c$ but $a.b = c.d = 0$, and $|a| = |c|$, necessarily. Only an unreasonably optimistic use of analytic continuation to retrieve information at other p seems possible; indeed the simple Fourier inversion proposed may reduce to nothing more than a disguised form of the first Born approximation. We hope to expand on this further in the next few months.

9.   We have reconsidered the validity of the Born and Rytov approximations by comparing successive terms of the Born and Rytov series with exact solutions. We have shown that the (first-order) Rytov approximation is superior to the (first-order) Born approximation because the Born series suffers nonuniformity in convergence when $Vk_0z > 1$. We also show that to approximate the scattered field (or the reflected field) in free-space when the target is a dielectric half-space, the Born approximation is more suitable than Rytov, although both have the same domain of validity. In the dielectric-slab case, both Born and Rytov methods have the same (and very narrow) domain of validity. However, when $Vk_0d > 1$, these two methods are inapplicable because the Born and the Rytov series diverge. Despite of the fact that the principle of limiting absorption provides a self-consistent way of deriving the exact total fields for both 1-D deterministic cases, it is unable to eliminate the secular terms occurring in the Rytov series for the dielectric-slab case when d becomes very large such that $Vk_0d > 1$.

These statements concerning the Born and the Rytov methods are also valid for the situation when the dielectric half-space or the dielectric slab has a permittivity

of the form $\varepsilon_1(1 + V)$ where $\varepsilon_1 > \varepsilon_0$, i.e. the distorted wave cases. Here we derive the Born and the Rytov series from inhomogeneous Fredholm equations of the first kind with a set of appropriate Green's functions which satisfy the boundary conditions at the planar interfaces. We have shown that with assistance of these sets of Green's functions for 1-D deterministic cases, we are able to develop the correct integral representations, which are beneficial to both direct and inverse scattering theory, for the exact total fields in different regions. This work is summarized in Appendix A, our paper submitted to JOSA A. The sequel to this paper is now in preparation in which the nonlinear case is considered. The restrictions on the applicability of the first Born and the Rytov approximations is the same whether the medium is linear or nonlinear, because of the necessary constraint on the field within the scatterer being the incident field; however differences emerge for distorted wave and higher order approximations.

10. We have been studying the properties of photorefractive media, for the storage of diffracting patterns which could be used for optical information processing. In such nonlinear media, one can write structures in (near) real time since a refractive index modulation results from the local change in charge density caused by the photoconductive effect. While one can write information holographically, i.e. through the use of a reference beam, one can also image structures directly into the medium and a refractive index modulation will result. It is important to model the mechanisms responsible for this effect because other phenomena occur which may or may not help the desired effect.

Our work is directed toward the storage of patterns within a photorefractive in order to write scattering structures whose permittivity can be usefully altered as a function of the intensity of the incident light. This will permit some useful and high efficiency optical devices to be developed. There are two issues to be considered in this regard, namely whether one wants to write a specific permittivity structure which generates the required scattered field, or whether any scattering structure which serves this purpose. Through the mechanism of beam fanning in photorefractives and the associated phenomenon of self-pumped phase conjugation, SPPC, we have studied how to store information about a desired output wavefront in the photorefractive.

Our results are presented in the accompanying paper which has been submitted for publication in J.O.S.A. B. Our experiments suggest that the temporal behaviour of the SPPC reflectivity depends on several parameters. There is a strong temperature dependence and cooling can restore stability. Also, the SPPC can be optimized when an optimal incidence condition for an individual

4

photorefractive crystal can be specified; the information to be stored is focused onto the crystal face at this optimal position and angle. Finally, the stability of the SPPC reflectivity is improved as the spatial frequency content of the incident beam is increased.

For multiple-image storage and readout, we used the vertical height of the crystal, storing information in adjacent horizontal layers within the body of the crystal. There is minimal overlap between these layers and we have successfully stored distinct images in this way, with a separation between input locations of 20 μm. We project that in a 5 mm cube of material, one could store approximately 200 high resolution images in this fashion.

Summary of work to be carried out in the next period.

The following areas will be pursued in the next few months:

The further development of numerical methods to invert scattered field data to determine the permittivity profile is of prime concern. In particular we will focus on the application of homomorphic filtering techniques to the inverse scattering problem, applied to both simulated and real data. In all cases, application of inversion methods to real data, and their evaluation, is a priority.

We include in this inversion work the recovery of nonlinear permittivity profiles, with the expectation that we can design permittivity structures from nonlinear media such as photorefractives, which demonstrate a predictable and useful change of scattering pattern as a function of the incident beam's intensity. This assists with the general topic of the characterization of nonlinear materials and provides a test for the inversion methods. In addition, we wish to develop inversion procedures which incorporate constraints on the profile such as a layered structure, for fabrication purposes.

The computing resources and back-up software are already available to support this program of work and the PDFT which can incorporate specific constraints will play a role in this. We have available in our optical computing laboratory, photorefractive materials and holographic processing capabilities; this permits permittivity profiles to be written optically in real time and to provide a scattering structure for a probe beam. By varying the intensity of the writing and reading beams, an ideal platform is available to study both the effects of nonlinearity on scattering, in order to verify the models developed and to construct permittivity patterns that generate desired scattered field patterns.