Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources

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LONG-TERM GOALS

Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the IOP's of both oceanic and littoral zone constituents. We also want to explore the efficacy of polarimetric time-of-flight lidar techniques in determining salinity and speed of sound in the ocean as well as submersible object detection. We want to continue our collaborative program in ocean polarimetry with the group in Minsk headed by Dr. Eleonora Zege. We are also starting a collaborative program with the NRL Optics Group at Stennis

OBJECTIVES

It is our major objective to find new and innovative ways in which polarimetry can be used to determine not only inherent optical properties but also certain physical properties such as temperature and salinity of ocean water. We also want to develop a new method of imaging which we would like to label "Mueller matrix imaging" (MMI). With this method we want to determine how much more information we can obtain about target features by using elements other than S_{11} (ordinary radiance)of the Mueller matrix

We have begun a collaborative program with the Radiative transfer group in Minsk, Belarus headed by Dr. Eleonora Zege. Our combined objectives for this program are as follows:
a) Simplification of the equations for the elements of the Green's matrix for the VRTE. Development and testing of an algorithm and code to compute the Stokes vector in an atmosphere-ocean using the multicomponent approach (MCA)

b) Computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination employing Monte-Carlo and MCA codes. Comparison of results and Elucidation of ways to improve both codes.

c). Development of the simplified equations for propagation of a linearly polarized beam in order to study the Stokes vector in the on-axis region for both backward and forward directions.

d) Development of the code to compute the Stokes vector in the on-axis region for a polarized narrow beam and compare with experimental data.

e) Improving the codes for computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination. Computation via improved codes. Data comparison.

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APPROACH

We have developed some very sophisticated Monte Carlo codes to handle the following types of problems:

a) Complete Stokes vector calculations for a passive source(the sun) illuminating a plane parallel inhomogeneous atmosphere-ocean system with a wind ruffled dielectric interface. This work is being done by Hatcher Tynes, a Ph.D. candidate.

b) Development of a sophisticated Monte Carlo code that utilizes a new idea we have developed which uses convolution theory to evolve the frequency profile of multiply scattered photons to handle both Raman and Brillouin scattering. This code was developed by former graduate student Dr. Brad Joelson and is presently being worked on by Deric Gray, a Ph.D. candidate.

c) We have developed a higher resolution Monte Carlo code for studying the finer structure in the polarization state of scattered light in an atmosphere-ocean system. Using our bulk Monte Carlo codes which solve the complete polarized equation of transfer for the full observable solid angle at any height above or below the ocean surface we are able to isolate regions of interest and to then apply our Monte Carlo with estimation techniques to these smaller areas. This code was developed by former graduate student Dr. James Adams.

d) We have also applied estimation techniques to the observation of polarization anisotropy in the backscattered light of a laser beam incident on a solution of Mie type scatterers. Our Monte Carlo code has produced images capturing all the qualitative features of observed phenomena so far reported in the literature. Our analysis shows that it may be possible to remotely determine particle sizes and concentrations by use of a system of polarizing analyzers and an active laser source. In the development of our code we have also shown that circularly polarized light has a longer "memory" of its initial polarization state than linearly polarized light and reflects interesting characteristics of the scattering medium. This persistence of circular polarization suggests that circularly polarized sources will allow observers to determine the characteristics of scattering particles deeper in the ocean than is possible with linearly polarized sources. This work is being carried out by Dr. Milun Rakovic, a postdoctoral colleague.

e) We have developed analytic techniques which will calculate the backscattered Mueller matrix from a turbid medium. This work was also carried out by Dr. Milun Rakovic.

WORK COMPLETED

a) Working with colleagues in biomedical engineering we have been able to measure and calculate the backscattered intensity patterns which arise when a turbid medium is illuminated with a polarized laser beam. One paper on this study has now appeared[1] and another will soon appear[2].

b) We have completed a theoretical analysis of the symmetry patterns in the Mueller matrix arising from backscattered polarized laser radiation impinging on a turbid medium. This work has resulted in one publication[3] and another will soon appear[4].

c) The collaborative project with Dr. Neils Højerslev and Dr. Eyvind Aas has been completed. This project involved a comparison of data taken in the Mediterranean in 1971 of the radiance and degree of polarization with Monte Carlo models. A paper on this work has been completed and will soon be submitted for publication.

d) One phase of our collaborative work with Dr. Zege's group in Minsk has been completed which involved a comparison of her multi-component approach method with our Monte Carlo models for a coupled atmosphere-ocean system with an interface with no wind ruffling.

RESULTS

We were able to show that the Mueller matrix patterns obtained from the diffusely backscattered radiation from the illumination of a turbid medium with a polarized laser beam could be explained with incoherent scattering theory. A comparison of actual measurements and our Monte Carlo modeling are shown in Fig. 1.

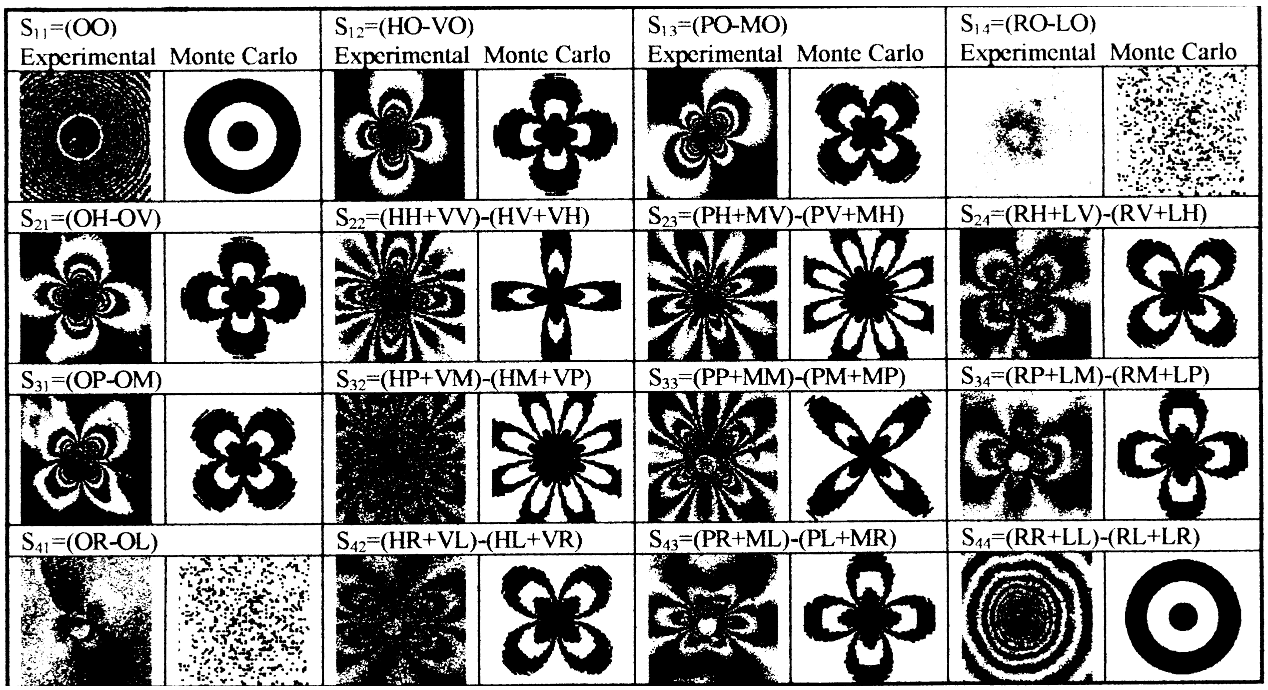

Fig. 1 Experimental and Monte Carlo-simulated diffusely backscattered Mueller matrix for a 2.02-• m polystyrene sphere suspension. The approximate size of each image is 1.6 cm x 1.6 cm. Each of the 16 experimental elements is calculated by addition or subtraction of a series of images. The individual images are represented by a two-letter combination that denotes the input polarization and the output analyzer orientation (i.e., HV denotes horizontal input polarized light and a vertical polarization analyzer). The corresponding symbols denoting polarization are V, vertical; H, horizontal; P, +45• ; M, -45• ; R, right; L, left; and O, no polarization optics.

We were also able to show that if the single scattering Mueller matrix has the following form:

$$M = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{12} & M_{22} & M_{23} & M_{24} \\ -M_{13} & -M_{23} & M_{33} & M_{34} \\ M_{14} & M_{24} & -M_{34} & M_{44} \end{pmatrix}$$

Then the full multiple scattering Mueller matrix **S** has only seven independent elements; namely S_{11}, S_{12}, S_{14}, S_{22}, S_{23}, S_{24}, and S_{44}. The other nine can be obtained from these by simple rotations at most[2,3]. We were also able to show that the shapes of the patterns can be useful in finding the sizes of particles producing them.

We have begun comparisons with Dr. Zege's group to test the validity of the multi-component approach to Mueller matrix calculations from turbid media with an interface. In Fig. 2 we show a comparison of our Monte Carlo calculations with her MCA for the case of a Rayleigh atmosphere-ocean system with a dielectric interface.

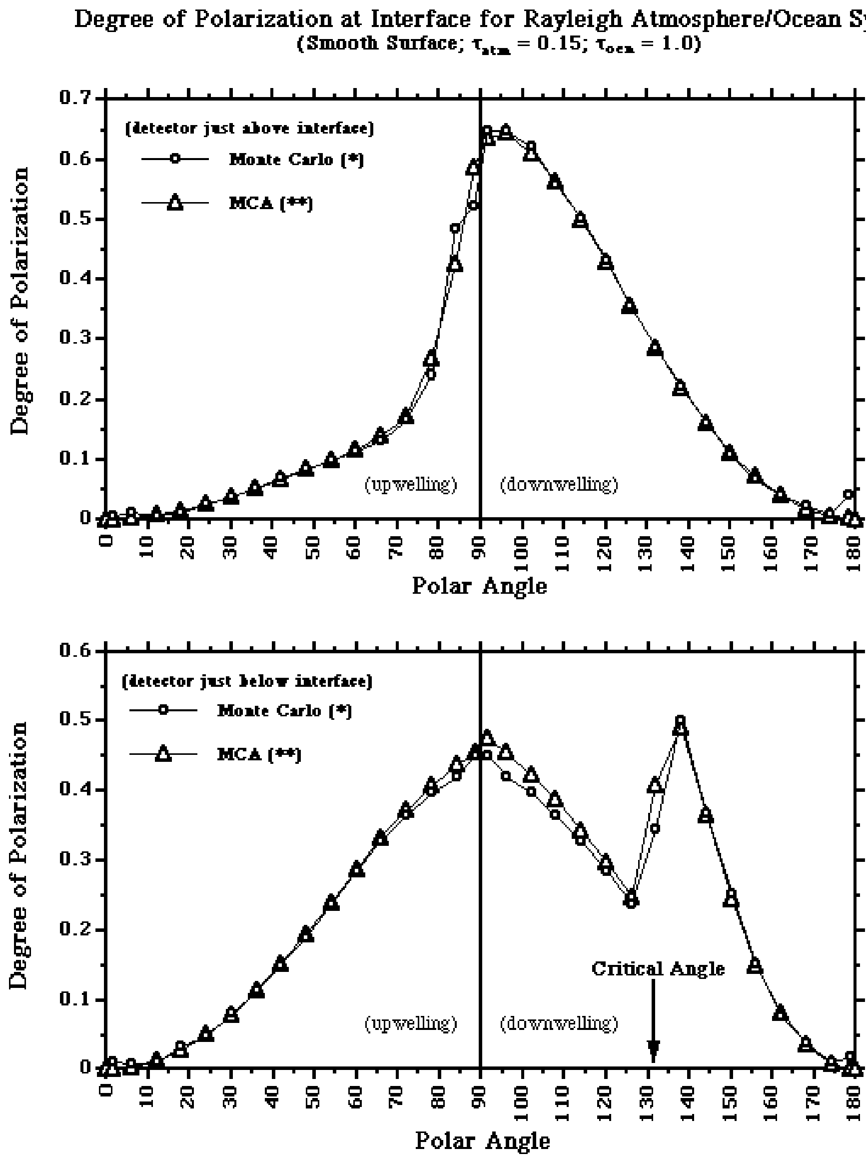

Fig. 2 A comparison between the multicomponent approach (MCA) of Dr. Zege's group with the Monte Carlo approach of the author and graduate student Hatcher Tynes. The model used is a Rayleigh Mueller matrix for both atmosphere and ocean layers. The solar zenith angle is zero degrees (defined to be directly overhead). The atmosphere has an optical thickness of 0.15; the ocean has an optical thickness of 1.0 (so the total thickness is 1.15). The index of refraction of the ocean is taken to be 1.338 and conservative scattering is used throughout. The upper graph is a comparison of the degree of polarization versus polar angle for both upwelling and downwelling radiation just above the ocean interface. The lower graph is for the same parameters except for radiation just below the interface. It is interesting to note the symmetry in the degree of polarization for this radiation from the horizon up to the critical angle since this is the region of total internal reflection.

IMPACT/APPLICATION

We now feel that the new techniques of Mueller matrix imaging will open up new avenues for remotely sensing the atmosphere-ocean system. We also believe that it will lead to better and more comprehensive target detection mechanisms.

Our Monte Carlo programs for laser scattering from turbid media are presently being used to study light scattering from living tissue. In some very preliminary experiments it has already been shown that cancerous skin lesions may be detected by polarimetric methods since it provides a way to “see” further beneath the surface layers of skin.

We feel that polarization spectroscopy in the ocean may be a way to extract both temperature and salinity profiles in the ocean.

TRANSITIONS

Our Monte Carlo passive source Stokes vector programs are being used to check a different method for solving the equations of transfer with full Stokes vector treatment developed by Dr. Eleonora Zege and her group in Minsk, Belarus. We have a CRDF grant for this work

We have also given our Stokes vector program to Dr. Vladimir Haltrin at NRL, Stennis Space center so the group there can use it to develop their own programs for polarization calculations.

RELATED PROJECTS

Our inelastic scattering code is being used in a joint project with Dr. E. S. Fry to study the feasibility of using Brillouin scattering to measure the speed of sound as a function of depth in the ocean. This project is funded by the Texas Advanced Technology Program.

We are working closely with colleagues in the Bioengineering Department as well as the M.D. Anderson Cancer Center to determine the feasibility of using polarimetry to detect pre-cancerous skin lesions. This project has partial funding by the NIH.

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