Backscattering and Polarization Properties of Marine Particles -- Instrument Development and Field Work

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LONG-TERM GOALS

(i) Develop instruments for near-pi backscattering properties of particles in the near- π region.
(ii) Quantify and understand the inherent optical properties (IOP's) of natural particles with particular emphasis on polarization;
(iii) Present the results in a manner useful to the Optics community.

SCIENTIFIC OBJECTIVES

Modify the LISST-Back near-π backscatter measuring instrument to add polarization measurement capabilities,
Characterize and contrast natural particle scattering with scattering by spheres;
Publish the observed properties in a manner accessible to the optics community.

This work has relevance to interpreting LIDAR measurements of scattering from the coastal seas. The idea is to advance knowledge of backscattering cross-sections and polarization properties particles.

APPROACH

We describe the distinct tasks in the proposed program, including a related research effort of colleague Emmanuel Boss:

- *Addition of* automated *polarization capability to the LISST-Back instrument*;
- *Characterization of scattering from terrigenous size-sorted non-spherical particles*;
- *Field observations of backscattering of marine particles;*.

WORK COMPLETED

a. *Addition of polarization capability to the LISST-Back instrument:* The LISST-Back sensor for measurement of the near- π scattering of particles in-situ has been completed in the period

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preceding this contract period. This device employs a powerful doubled YAG laser and a CMOS array combination as source and detector. The instrument is autonomous, powered by a separate battery pack. It incorporates measurement of beam attenuation as well. The instrument was successfully deployed in a bottom boundary layer experiment at the Martha's Vineyard Coastal Observatory (MVCO) in Aug.-Sept.2007. A paper based on these measurements is now in preparation.

In the current period, a motorized polarization element (an 'analyzer') is being installed in front of the CMOS array detector. By rotating this analyzer to 0, 90, and ± 45-deg., characterization of Stokes vector of light scattering is now possible. These results are to be presented at the Ocean Optics meeting in Italy.

b. *A new method to measure spherical particle size:* As described below in the Results section, it emerges that the azimuthal structure of cross-polarized near-π scattering is similar for all sized spherical particles. The pattern size scales inversely with sphere size. The pattern is relatively insensitive to refractive index over the range investigated, 1.05 to 1.2 (i.e. in water the index of biological and quartz type particles). This property of cross-polarized backscattering can be exploited to size them *in-situ*. A paper is in preparation, Agrawal & Mikkelsen (2009c).

c. *Backscattering of spheres contrasted with randomly shaped grains*; I have completed some observations contrasting backscatter properties of random shaped sediment grains and polystyrene spheres. In results reported at the Italian Ocean Optics conference (Oct.6-10, 2008) I showed the remarkable distinctions between near-π scattering by these random grains, and spheres. The findings to date show (i) that the backscattering by random grains is an order of magnitude weaker, i.e. cross-sections are order of magnitude weaker, than spheres of equal size; (ii) in low concentrations where multiple scattering is not significant, the cross-polarized back-scattering by random grains is nearly zero, being about 2 orders of magnitude weaker than for spheres; and (iii) the azimuthal modulation of near-π scattering that is exhibited by Mie theory is not seen in scattering by random grains.

d. *Field observations of backscattering of marine particles:* The instrument was deployed first for a bottom boundary layer observation in the end of September 2007. Measured volume scattering functions were reported at the Ocean Sciences meeting in Orlando, 2008. Three days of data showed significant variability in the magnitude of the backscattering VSF, though the shape of the VSF curves remained substantially similar. The instrument has not been deployed with polarization discrimination properties yet; such deployment is planned for Spring 2009.

e. *Related work:* (1) We have published the forward angle phase functions of *size-sorted* randomly shaped particles. These data are meant to replace Mie theory when the scattering particles are not spherical. The distinguishing characteristic of randomly shaped particles is the weakening or absence of the resonant oscillations of Mie theory, and a slight narrowing of the main peak. The tabulated data are available to other researchers, Agrawal and Mikkelsen (2009a). (2) We have submitted for publication a paper describing the principles and laboratory test data on ideas for use of shaped focal plane detectors for measurement of particle concentrations and mean particle size in suspensions, Agrawal & Mikkelsen (2009b).

RESULTS

1. *Development of a backscatter version of the LISST instrument*: Two key developments have been completed – incorporation of low-power electronics to ensure longevity of submerged operation, and the preliminary testing of polarization properties using a non-automatic rotating polarizer (see results below). Details are shown in Fig.1.

2. *Preview of elements of Mueller Matrix:* As shown in Fig.2 below, our data with the LISST_Back have shown the quantitative and qualitative difference in backscattering between spheres and randomly shaped grains. Clearly, shape information in revealed with polarization discrimination in backscattered light. With this in mind, a rotate-able polarizer has been inserted in front of the light-sensing CCD array. The data of Fig.2 are from such a set up, and can be modeled for spheres following the work of Yang et al.(2003). At the time of a mid-year stop in work due to funding deferral, the polarized set up and data collection and storage software had been completed. Work will continue in FY 2010.

3. *A new method based on cross-polarized backscattering to size spherical particles:* We have stumbled on a new method for spherical particle sizing. The pattern shown in Fig.2 (*top right*) shows cross-polarized light scattering in the near-π region, over the 360^o azimuth. In Fig.3, it is shown that for particles 10:10:50 micron in sizes, the same pattern persists, only it becomes smaller inversely with size, analogous to aub unrelated to Airy diffraction for forward scatter. The pattern is also seen to be insensitive to refractive index from 1.05 to 1.2. Thus, observations at the 45^o azimuth will be a linear superposition of patterns due to different sized particles, Fig.4. This becomes a relatively simple inverse problem of particle sizing. A paper on this is in preparation (Agrawal et al., 2009c). The attraction of this method is that it is one-sided (mono-static in LIDAR parlance). The limitation is that it applies only to spherical particles, including bubbles (but probably also to other *regular* particles), but not to random particles.

4. *Forward scattering Phase Functions of Randomly Shaped Particles*: Phase functions of **size-sorted** randomly shaped particles were computed from the data of Agrawal (2008). These were published both in graphical and tabulated form this year, Agrawal and Mikkelsen (2009b). Light scattering by random shapes is a problem of fundamental interest. The data shown in Fig.5, we hope, begin to fill the need. Such data, given its size-sorted nature, replace Mie theory when dealing with randomly shaped particles.

5. *Shaped Detectors for measuring particle concentration and size:* In a recent paper, Agrawal and Mikkelsen(2009b) describe the principles and practice of shaped focal plane detectors to measure total concentration and mean sizes or concentration and mean sizes in size sub-ranges. Tests with random shaped particles show excellent results.

PUBLICATIONS

Y. C. Agrawal and O. A. Mikkelsen, 2009a: Shaped Focal Plane Detectors for Particle Concentration and Mean Size Observations, (*subm.*) Optics Express.

Y. C. Agrawal and O. A. Mikkelsen, 2009b: Empirical Forward Scattering Phase Functions from 0.08 to 16 deg. for Randomly Shaped Terrigenous 1-21 μm Sediment Grains, Optics Express, v 17, n11, pp8805-8814.

Y. C. Agrawal, E. Boss, and O. A. Mikkelsen, 2009c: Polarization based particle sizing in backscatter; Optics Express (*in prep*.)

Agrawal, Y.C., Amanda Whitmire, Ole Mikkelsen, and H.C. Pottsmith, 2008: Light Scattering by Random Shaped Particles and Consequences on Measuring Suspended Sediments by Laser Diffraction; JGR v213, C04023.

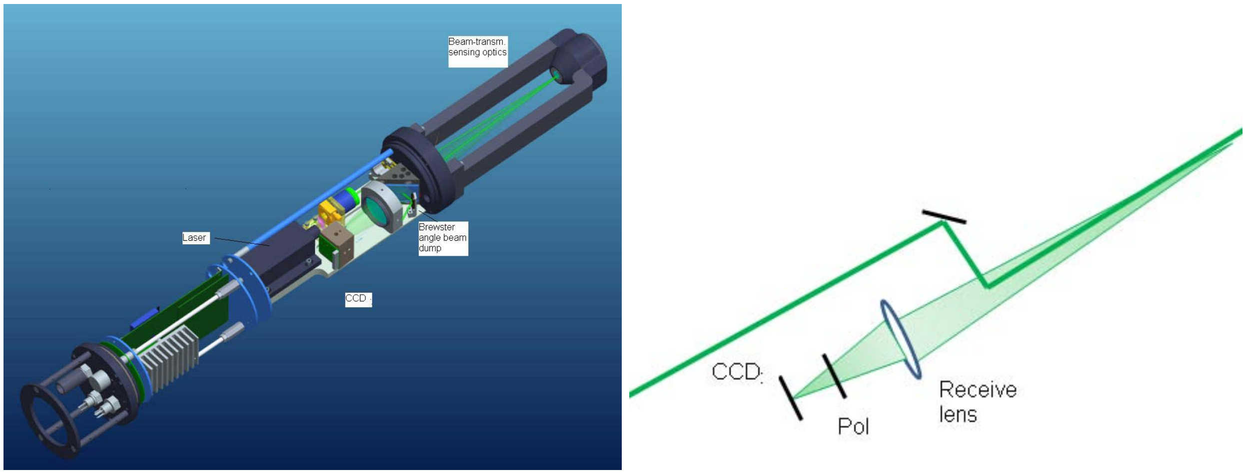

Figure 1: Optics of the LISST-Back (left), and (right) location of the polarization filter in receive optics behind the lens. The polarizer is computer controlled to any angle, 0 to ±90^{o}.

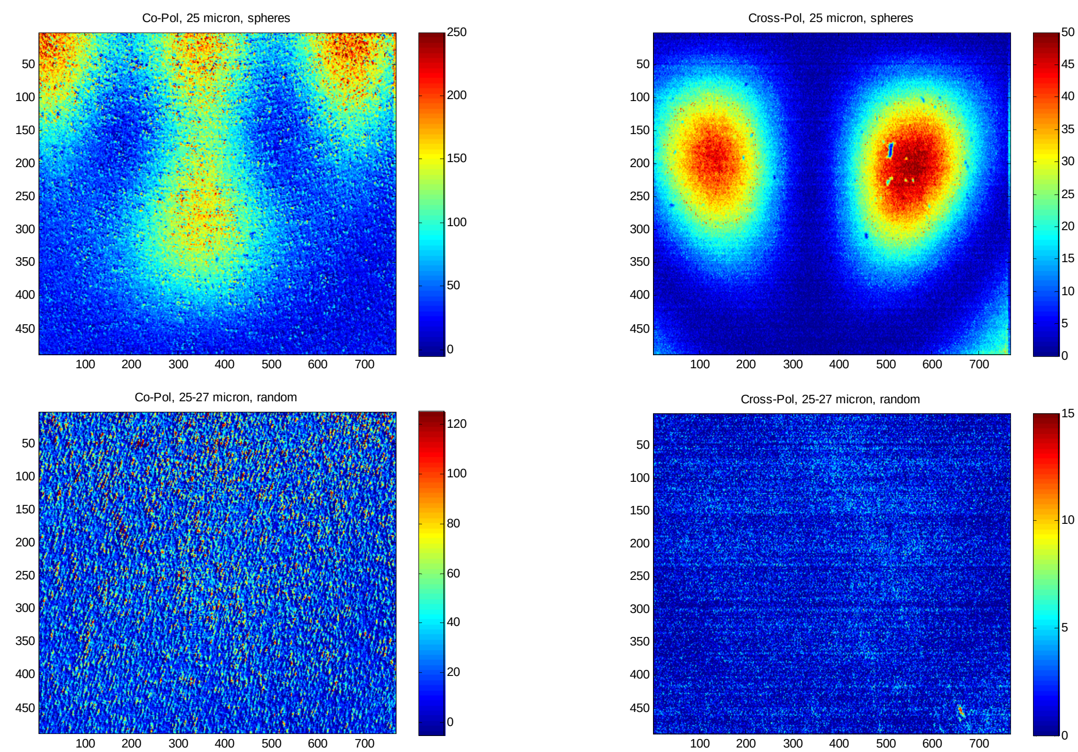

Figure 2: CCD view - Azimuthal dependence of backscattering by particles in two directions, parallel (left) and perpendicular (right) to the outgoing beam. Top pair is spheres, bottom is random shape. Note the weaker backscattering by randomly shaped particles and the absence of structure. The data are for identical beam attenuations.

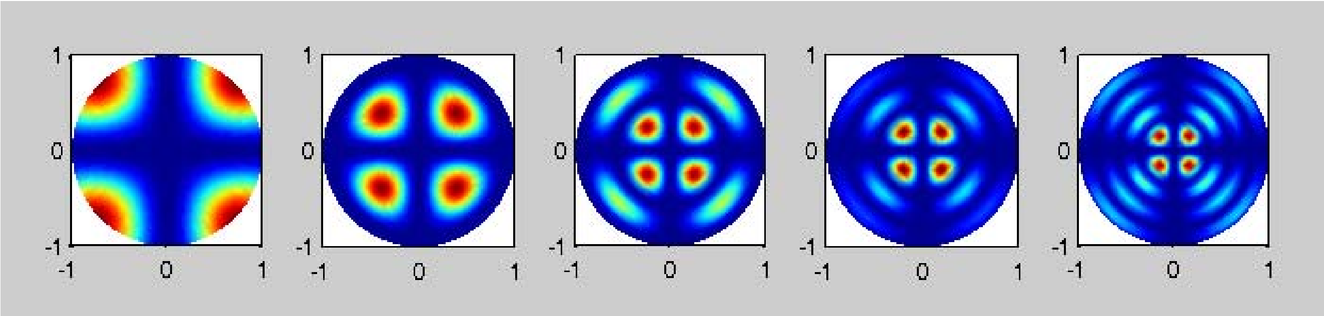

Figure 3: Illustration of the use of cross-polarized near-π scattering for particle sizing. Each frame shows the azimuthal structure of backscattering. Left to right, particle sizes 10:10:50 microns. Center of each frame is exact 180^{o} scattering, radial distance from center is scattering angle, identical to Fig.2 Note the identical pattern is compressed with increasing size.

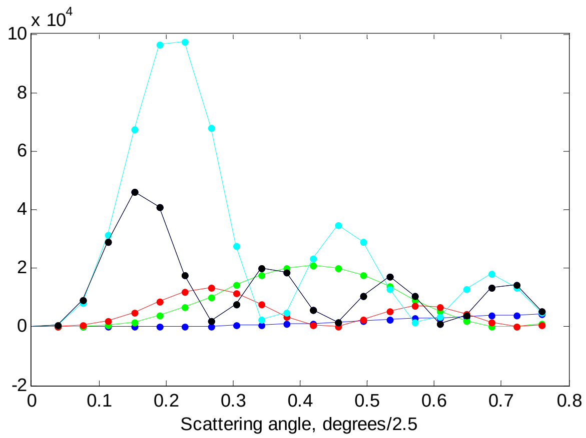

Fig. 4: Cross-polarized backscatter along a diagonal of Fig. 3 from 10(blu), 20(grn), 30(red), 40(cyn)and 50 (blk) micron particles showing distinct signatures. It is clear that this provides a basis to invert such data to recover size distribution.

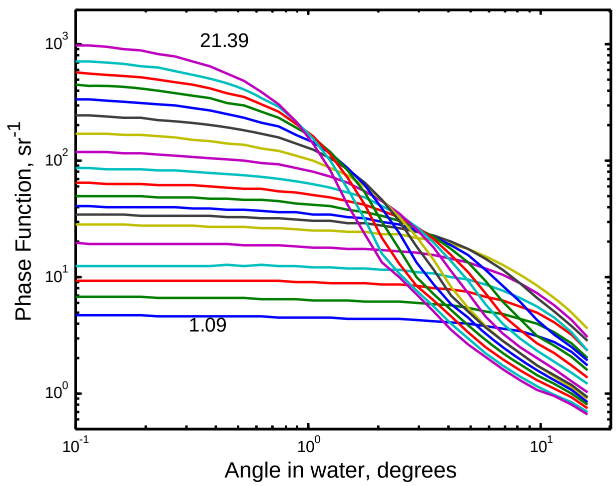

Fig.5: The small angle phase functions of randomly shaped grains determined empirically for particles from 1.09 to 21.4 microns in 18 log-spaced narrow sizes (from Agrawal & Mikkelsen, 2009b)