

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

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Award #: N0001408C0218
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LONG-TERM GOALS

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

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 of non-spherical natural particles.

APPROACH

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

- *Addition of polarization capability to the LISST-Back instrument;*
- *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles;*
- *Field observations of backscattering of marine particles;.*
- *Modeling of light scattering (Boss).*

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Backscattering and Polarization Properties of Marine Particles -- Instrument Development and Field Work				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Sequoia Scientific, Inc.,2700 Richards Road,Bellevue,WA,98005				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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 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. *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles;* I have completed some observations contrasting backscatter properties of random shaped sediment grains and polystyrene spheres. In results to be reported at the Italian Ocean Optics conference (Oct.6-10, 2008) I shall show 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 angular modulation of near- π scattering that is exhibited by Mie theory is not seen in scattering by random grains. The current work was limited to 25 micron particles. It is to be extended using a settling column for sorting particles by size.
- c. *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.
- d. *Related work:* A related informal collaboration with Dr Emmanuel Boss (U of Maine) continues in these studies. Driven by the same interest, a review paper has been published (Clavano et al., 2007). They have published a manuscript, entitled 'Inherent optical properties of non-spherical marine-like particles—from theory to observation' in "Oceanography and Marine Biology: an Annual Review". In particular, they have extended a method to model the IOPs of individual, randomly oriented, spheroids using a poly-dispersions of spheres (Paramonov, 1994) to model marine-like particles. This permits modeling populations of marine-like particles throughout their relevant size range.

Boss and colleagues have analyzed how phytoplankton shapes affect inversion of VSF into size distribution (Karp-Boss et al., in press). We found that a narrow size distribution of non-spherical particles appear as a poly-dispersion of spherical particles, and that, the mode size of the population of non-spherical phytoplankton is larger than that for spheres of the same volume. Both results are consistent with the theoretical analysis of Clavano et al., 2007.

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). The seaworthy instrument is shown in Fig.1.
2. *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles:* First, we note that the work on small-angle forward scattering by random shaped sediment particles was published (Agrawal, 2008). Here, we have noted that the deep oscillations of the VSF of spherical particles are absent in scattering by random shaped particles. We also showed that equal size random particles of a narrow distribution appear to be equivalent to slightly larger spheres, and of a wider distribution of spheres. The work also showed how interpreting small random particles (<15 microns) as equivalent spheres also invents very fine particles (~1-2 microns).

Switching now to backscatter properties, we are reporting data contrasting scattering by spheres and random grains in scattering angle (θ), and also in azimuthal (ϕ). Figure 2 shows laboratory data and theory showing excellent agreement for spheres. The figures show half of the azimuth plane, corresponding to the size of the CMOS array. The 4 lobes in azimuth arise from considerations of multiple rotations of the reference frame in Mueller algebra, as explained by Yang et al.(2003). The computations are based on their work.

In contrast to spheres, some limited work has been completed with random shaped grains. In Fig.3 are shown the same frames as Fig.2, but for random grains. The azimuthal structure that is so striking in parallel scattering by spheres is completely absent, and furthermore, the magnitude of scattering is also weak by about a factor of 2 or more (beam-c for figures 2 and 3 was 1m^{-1}). Not only is the azimuthal structure gone, the angular structure (i.e. in θ) is not defined. That is, random grains scatter less light in the back direction (smaller cross-section) and do not exhibit significant angular dependence. Even more striking is the absence of measurable scattering in the perpendicular direction, Fig. 3. The contrast between Figs.2 and 3 (backscattering in direction perpendicular to outgoing laser polarization) suggests the possibilities of separating spheres (e.g. bubbles) from sediments.

3. *Field observations of backscattering of marine particles*: As of the time of this writing, the data collected by the LISST-Back instrument in the September 25, 2007 deployment are being processed for a paper to be submitted shortly. The key findings are that the VSF varied considerably over the 3-day duration, though not significantly in shape.
4. *Modeling of light scattering* (Boss). The related work of this colleague can be downloaded from (http://misclab.umeoce.maine.edu/publications/review_articles.php). A few notable observations are:
 - a. Non-spherical particles, in general, have peaks in the volume (or mass) specific scattering, attenuation and backscattering which occur for larger sizes than equal-volume spheres. This implies that non-sphericity changes the relative contribution of different size particles to IOPs. For absorption, randomly oriented non-spherical particles are found to absorb more per mass than equal volume spheres, a consequence of them being less packaged, e.g. more of the internal material is available to interact with light.
 - b. In accordance with theoretical predictions randomly oriented particles were found to have volume scattering function which have larger forward peaks in comparison with spheres of the same size. This is consistent with the lab experiment we have derived with random shapes and has been added to the paper through the last parts of its production.
 - c. Polydispersions of particles with constant or varying shape as a function of size, have biases in attenuation, absorption, and scattering, reaching values as high as 270%, generally being within about 50% to that of population of equal volume spheres. While not as large as for monodispersions, these biases are significant and very often overestimate, implying that populations of spherical particles perform poorly as an average, unbiased model.

IMPACT/APPLICATIONS

The ability to understand the impact of shape on marine optical properties will improve our interpretation of optical measurements in general and ocean color remote sensing in particular.

The findings reported here regarding the polarization properties, in particular the absence of a cross-polarized return from random particles, are likely to open avenues for discriminating sediment grains from bubbles in LIDAR observations.

TRANSITIONS

None as yet.

PUBLICATIONS

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.

Clavano, W.R., E. Boss, and L. Karp-Boss, 2007. Inherent Optical Properties of Non-Spherical Marine-Like Particles - From Theory to Observations. *Oceanography and Marine Biology: An Annual Review*, 2007, 45, 1-38.

Karp-Boss, L., L. Azevedo, and E. Boss, 2007. LISST-100 measurements of phytoplankton size distribution: evaluation of the effects of cell shape. *Limnology & Oceanography:Methods* 5:396–406.

Yang, P. Wei, H., Kattawar, G., Hu, Y., Winker, M. Hostetler, C.A., and B.A. Baum (2003): Sensitivity of the backscattering Mueller matrix to particle shape and thermodynamic phase *App. Opt.* v42, n 21, pp 4389-4395.

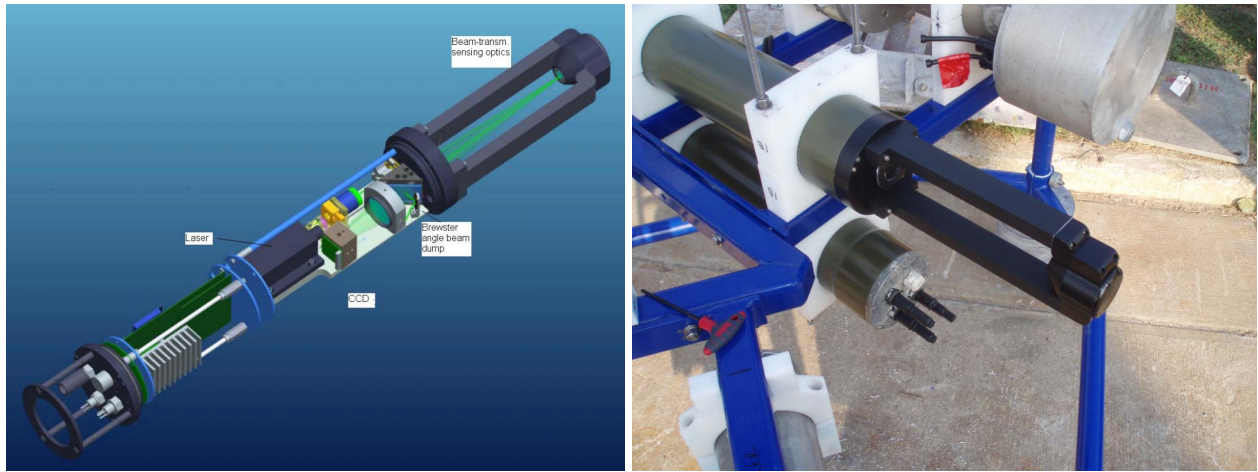


Figure 1: Optics details of the LISST-Back (left) and mounted on a tripod before deployment at MVCO (right). As seen on left, the optical path is set to 20 cm and a beam attenuation sensor is employed. This eliminates need for vignetting correction. The hardware photo shows a separate battery case below the instrument case as well.

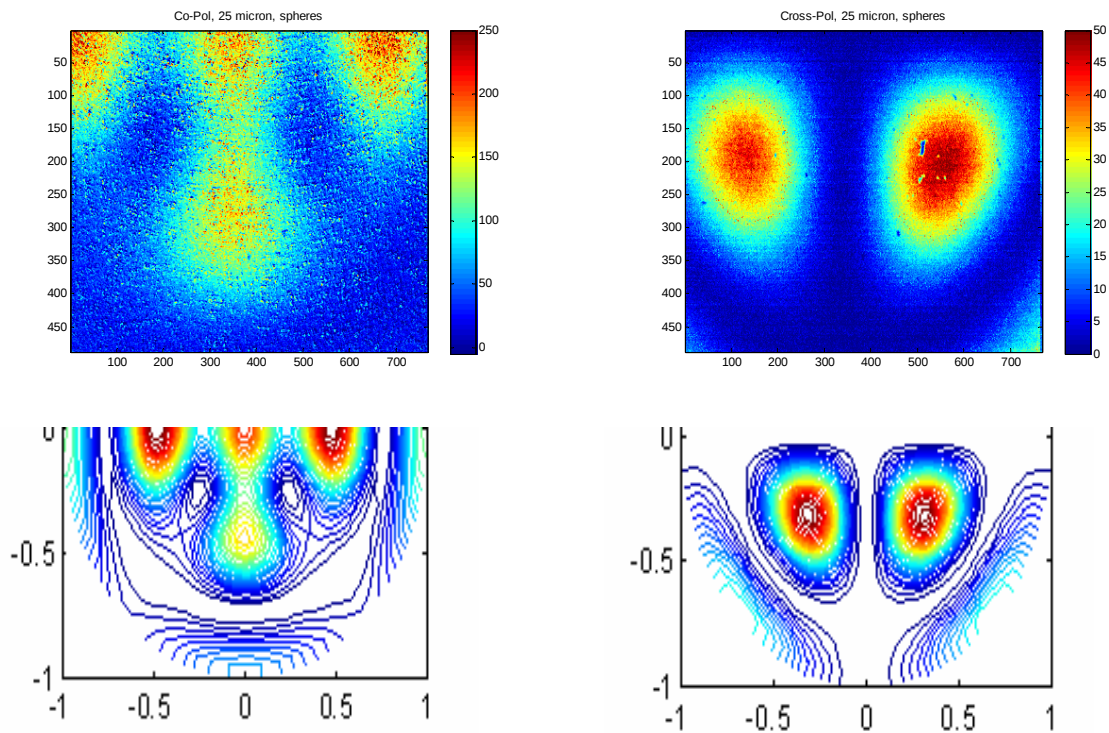


Figure 2: Backscattering in the two directions, parallel (left) and perpendicular (right) to the outgoing beam, by spherical particles and azimuthal dependence of scattering. The measured co-polarized and cross-polarized backscattering is compared with Yang et al. (2003).

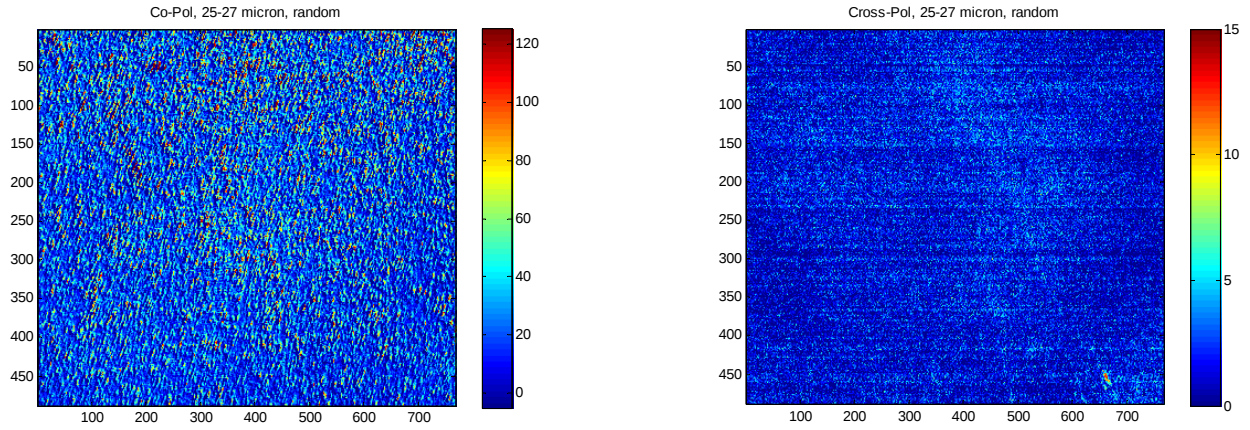


Figure 3: The co-polarized (left) and cross-polarized scattering(right) by random shaped grains, $25\mu\text{m}$ diameter. Note the absence of structure and weak scattering in contrast with spheres, Fig.2.

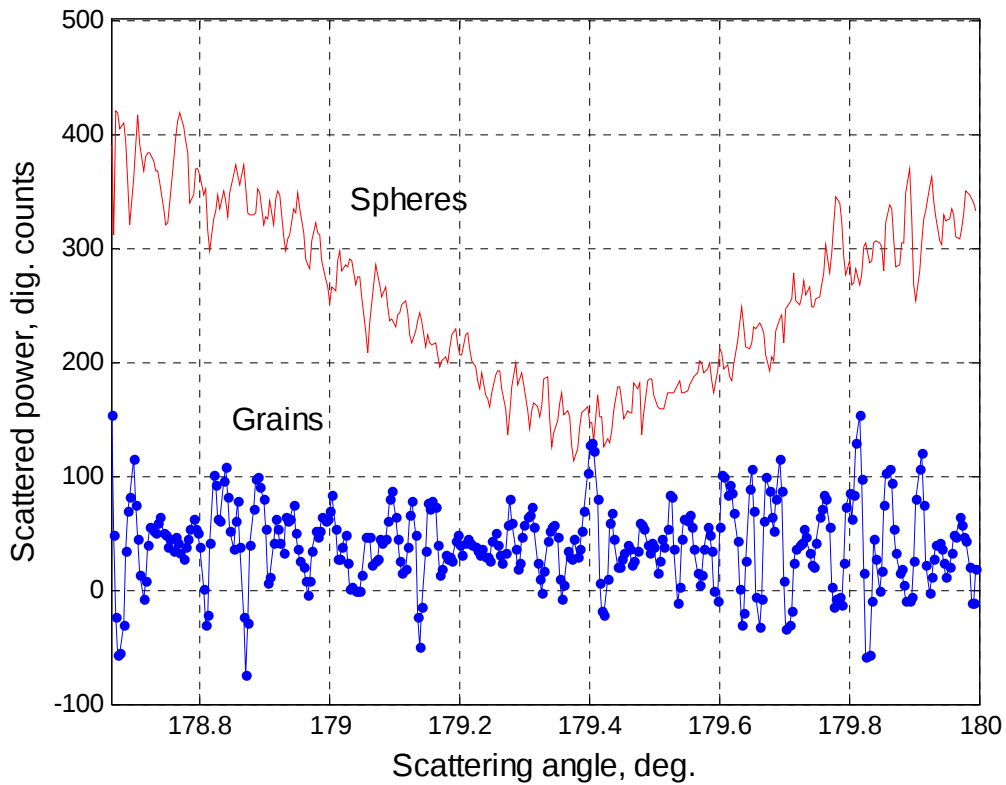


Figure 4: Comparison of the shape and magnitude of near- π backscatter in the co-polarized (left) analyzer, 25 micron spheres vs 25-27 micron sediment grains show the weaker and featureless character of the latter.