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

Yogesh Agrawal
Sequoia Scientific, Inc.
2700 Richards Road
Bellevue, WA 98005
phone: (425)867-2464     fax: (425) 643-0595     email: yogi@sequoiasci.com

Award Number: N0001408C0218
http://www.SequoiaSci.com

LONG-TERM GOALS

(i) Develop instruments for near-pi backscattering properties of particles in the near-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

• Field observations of backscattering in the water column,
• 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

Addition of polarization capability to the LISST-Back instrument: The LISST-Back sensor for measurement of the near-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 several field efforts (see later). A paper describing the instrument and field observations is shortly to be submitted.

a. A new inverse method to solve for few of the Mueller matrix elements for particle scattering: Azimuthal backscattering from particles contains information about elements $p_{11}, p_{12}, p_{22}$ and $p_{33}$. Measurements by this instrument permit inversion of the azimuthal scattering patterns into these elements, each of which is a function of scattering angle. A paper describing this idea is in preparation.

b. Spherical Particle Sizing from observation of $P_{11} + P_{33}$: As described below in the Results section, it emerges that the azimuthal structure of cross-polarized near-scattering is similar for all sized spherical particles. The pattern represents $P_{11}+P_{33}$, and its 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, Boss & Mikkelsen (in prep).

c. Backscattering of spheres contrasted with randomly shaped grains; We have reported in the past that backscattering by terrigenous random shaped particles is featureless near. It this follows that the backscattering VSF can be replaced by a single value near 10-degrees. This has profound consequences. The conventional method of prediction backscattering VSF from particle size distribution measurements by invoking Mie theory can be replaced by weighted sum of measured near-pi VSF of randomly shaped particles.

d. Field observations of backscattering of marine particles: Two new field experiments were carried out for instrument testing and as a cross-comparison with a LIDAR.

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). (3) We have also built an instrument to measure the depolarization of scattered light in very small forward angles. This work is a collaboration with Drs. Anni and Fraser Dalgleish of Harbon Branch Oceanographic Inst.
RESULTS

1. **Development of LISST-Back instrument**: The incorporation of polarization capability into the instrument has been done. An automated rotating polarizer in front of the receiving CCD enables observation of the full azimuthal structure of scattered light with an analyzer at 0, +/- 45 and 90 degrees. Details are shown in Fig.1.

2. **Solving for the elements of Mueller Matrix**: It is known that the Mueller matrix of scattering depends on particle shape and other characteristics. The cross-polarized backscattered view, e.g. Fig.2 (which represents spheres and randomly shaped grains) can be modeled for spheres following the work of Yang et al. (2003). The same theoretical basis can be exploited to predict the Mueller matrix for other types of particles. Ongoing work is attempting to solve for the elements p11, p12, p22 and p33 from the azimuthal structure. Notably, irregular particles do not permit this approach due to the generally featureless scattering in the 180-degree region.

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° 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° 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. 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. However, the featureless scattering of random grains may permit solving for bubbles in the combined bubble-sediment environment.

4. **Backscattering by narrow-size random grains**: Work is continuing on generating the near-pi phase functions of randomly shaped sediment grains. Once completed, prediction of backscatter will be possible from the simpler measurement of forward scatter (say, with a LISST-100). The method replace the old method – forward VSF to size distribution– then Mie theory to back-VSF; with forward scatter to grain size distribution to back VSF, without use of Mie theory.

5. **Forward scattering Phase Functions of Randomly Shaped Particles**: Phase functions of size-sorted randomly shaped particles 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 begin to fill the need. Such data, given its size-sorted nature, replace Mie theory when dealing with randomly shaped particles.

6. **Field Observations of**

Two field experiments were performed, one in Commencement Bay, Tacoma, WA and another in Eastsound, WA, in conjunction with a LIDAR campaign in May 2010. The Commencement Bay data are shown in Fig. 6. The measured VSF were again flat, with only a 2:1 variation in the water column. The estimates of in Eastsound were consistent with estimates by Dr Churnside (data shown at Ocean Optics XX).
7. **Depolarized forward scattering at small angles:** No data exist on the small-angle forward scattering and its depolarization. The nearest such data is reported by Quniby-Hunt (2000), but it covers angles larger than about 10 degrees. We report the mild depolarization observed by us in the near-forward region, in our collaborative work with HBOI, Fig. 7. These data are from the new instrument LISST-Stokes.

**PUBLICATIONS**


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.*)

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°.
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-\(\pi\) 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° 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(blue), 20(green), 30(red), 40(cyan), and 50(black) 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 function 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)
Fig. 6: Near-\(\pi\) VSF measurements in Commencement Bay, Washington.

Fig. 7: Depolarization at small forward angles.