Backscattering by Non-spherical Natural Particles: Instrument Development, IOP's, and Implications for Radiative Transfer

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LONG-TERM GOALS

(i) Quantify and understand the inherent optical properties (IOP's) of natural particles from a standpoint of measuring size-distribution;

(ii) Understand how the properties of particles (composition, shape, and internal structure) affect their IOP.

(iii) Incorporate these properties into radiative transfer models for prediction of downwelling and upwelling radiances.

SCIENTIFIC OBJECTIVES

- We are developing a version of the LISST-100 forward scatter instrument that will deliver the same high-quality data in backscatter,

- The data will guide analytical light-scattering model development with such observations, and

- The results will be applied to predicting light propagation in the sea by providing as input, the new estimates of IOP's.

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This work is relevant to ONR's Sensor and Systems and Modeling thrust areas. It will contribute to understanding of how the shape of oceanic particles affect backscattering and provide an instrument that specifically addresses backscattering near 180 degree - a crucial parameter to understand, predict, and invert LIDAR signal. The LIDAR signal is proportional to the VSF near 180 degrees.

APPROACH

We describe the distinct tasks in the proposed program, identified with person responsible:

a. *Development of a backscatter version of the LISST instrument* (Agrawal). The instrument development is now complete. Preliminary data with spheres and sediments are being acquired at the time of writing of this report.

b. *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles* (Agrawal, Boss). In a significant advance, the small-angle forward scattering phase function of random shaped natural particles has now been done. This work is to be presented at the Montreal Ocean Optics XVIII conference. Among the findings: random shaped particles appear larger by 20-40% than spheres that pass the same sieves (down to 16 micron sizes); fine random particles below 16 microns continue to exhibit the same effect contrasted with Stokes diameters; in all cases, narrow random shape particles appear as a *distribution* of spheres; and, small particles (<16 microns) appear to be equivalent to similarly large spheres but also additionally particles finer than their main mode (Agrawal, Whitmire and Pottsmith, 2006b), see data (Figure 1,2).

The next task is to make laboratory observations of particles sorted by settling size, as well as quantify the variability of scattering in the back-direction of different phytoplankton (with different morphologies, internal structure, and community structure (e.g. chains).

c. *Field observations*(Agrawal)*:* Since instrument assembly and testing has taken longer than originally planned, field testing will occur in 2006-2007.

d. *Modeling of light scattering* (Boss)*:* Theoretical modeling of light scattering by randomly oriented non-spherical particles have been carried out and a review paper has been submitted (see below).

e. *Modeling of Radiative Transfer* (Mobley): Incorporation of results into radiative transfer calculations. The particle VSF's and cross sections obtained from the laboratory experiments and numerical modeling of non-spherical particles will be used to generate IOPs for use as input to Hydrolight. Hydrolight will then be used to quantify the differences in predicted remote-sensing reflectance spectra for spherical and non-spherical particles.

WORK COMPLETED

Theoretical Development*:* We have submitted a manuscript, entitled 'Inherent optical properties of non-spherical marine-like particles—from theory to observation' to "Oceanography and Marine Biology: an Annual Review". It is our understanding that it will be published as part of the 2007 volume. Besides reviewing the state-of-the-art, we have derived many new results. In particular, we have extended a method to model the IOPs of individual, randomly oriented, spheroids using a polydispersions of spheres (Paramonov, 1994) to model marine-like particles. This allowed us to model populations of marine-like particles throughout their relevant size range.

We are currently assembling a large series of T-matrix runs performed at the Cornell Theory Center supercomputing facility to be available on our web site for all (URL:http://misclab.umeoce.maine.edu/research/research10_data.htm).

Results focusing on backscattering were presented at the Ocean Sciences conference in Honolulu, HI (Clavano et al., 2006). In that presentation we compared measured near backward VSF and its polarization characteristics obtained with the new backward LISST device with theoretical T-matrix results.

Experimental: *Field Instrument Development*: The field instrument has been completed. A CCD array is employed to capture not just the angular backscatter, *i.e.* $\beta(\theta)$, but also structure in φ which has been reported earlier by us. We have built-in the capability to observe the Mueller matrix in backscatter, which will only be pursued after the primary objectives are met.

Laboratory Observations: Two preliminary reports describe low resolution (in size) (Agrawal, et al. 2006a) and more recently, high resolution observations of the forward phase function of random-shaped natural particles (Agrawal, et al. 2006b). It has been found that natural sediment grains appear equivalent to larger spheres, and that the finer sediment grains appear equivalent to an additional 'superfine' mode of spheres which diminish in importance as size increases (see Fig. 2). These properties are important to inversion of multi-angle scattering for suspended sediment sizing.

RESULTS

Laboratory: Progress in this field has been achieved through a combination of new technologies and new ideas. For example, in order to find counterparts to Mie theory, one needs to sort random particles by size into narrow size ranges. This is easily done for large grains using standard sieves. In this case, the random particles and spheres (glass) are compared directly for their forward scattering properties, using the LISST-100 instrument, Fig.2. The difficulty with sorting small particles is overcome by sorting particles in a density stratified column, whereby all motion is suppressed. Departure from Stokes settling law for spheres was also quantified for these spheres. The final, resulting phase functions for sizes from 1.7 to 14 microns are now available, and will be published shortly. These data constitute the essential information necessary to account for shape effects in inverting LISST data for size distribution. Figure below shows the equivalent spheres of data from spheres (narrow) and from natural sediments. Clearly, increasingly finer sediment grains appear to invent superfine spheres.

Theoretical: We do not have the space here to detail all of the results we found with respect to the optical properties of non-spherical particles. A few notable ones are:

1. 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 sizes to IOPs (Fig, 3). For absorption, randomly oriented non-spherical particles are found to absorb more per mass than equal volume

sphere, a consequence of them being less packaged, e.g. more of the internal material is available to interact with light.

2. In accordance with the 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 (Fig. 4).

3. 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 larger than one, 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 ability to interpret optical measurements in general and ocean color remote sensing in particular.

TRANSITIONS

The forward phase functions will be available to scientists employing LISST for particle sizing.

PUBLICATIONS

Clavano, W. R., E. Boss and Y. Agrawall, 2006 (Ocean Sciences meeting). Anisotropy in the backscattering of marine-like particles: indications of size and shape. http://dspace.library.cornell.edu/bitstream/1813/2656/1/2006OS36I-06_letter.pdf.

Clavano, W. R., E. Boss and L. Karp-Boss, 2006. Inherent optical properties of non-spherical marine-like particles—from theory to observation', Oceanography and Marine Biology: an Annual Review [in press].

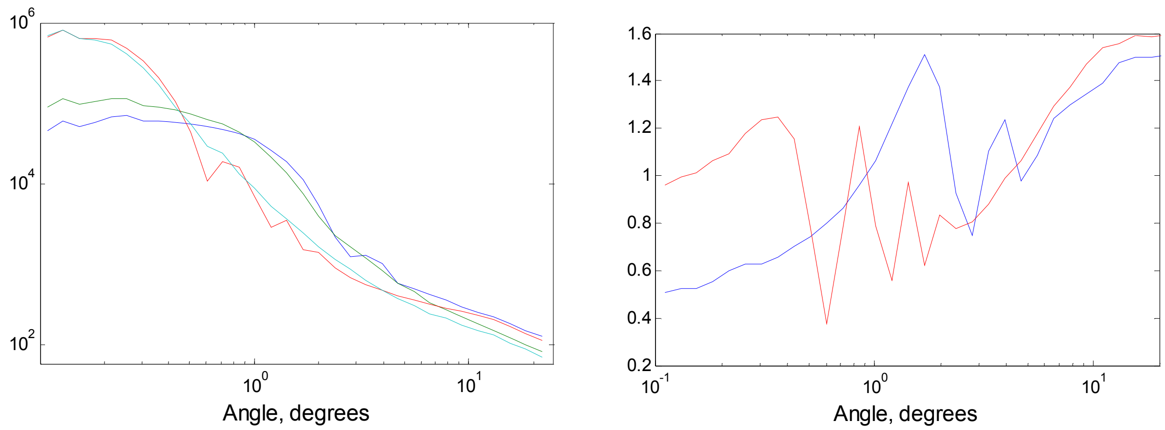

Figure 1: Relative scattering for 2 sizes of spheres (red lines) and natural particles (Colorado river sediments), 16-20 micron fraction (blue line and 75-90 micron fraction (gray line, top). On the bottom, the ratio of phase functions: spheres/random shapes (red for the 75-90 micron fraction and blue for the 16-20micron fraction).

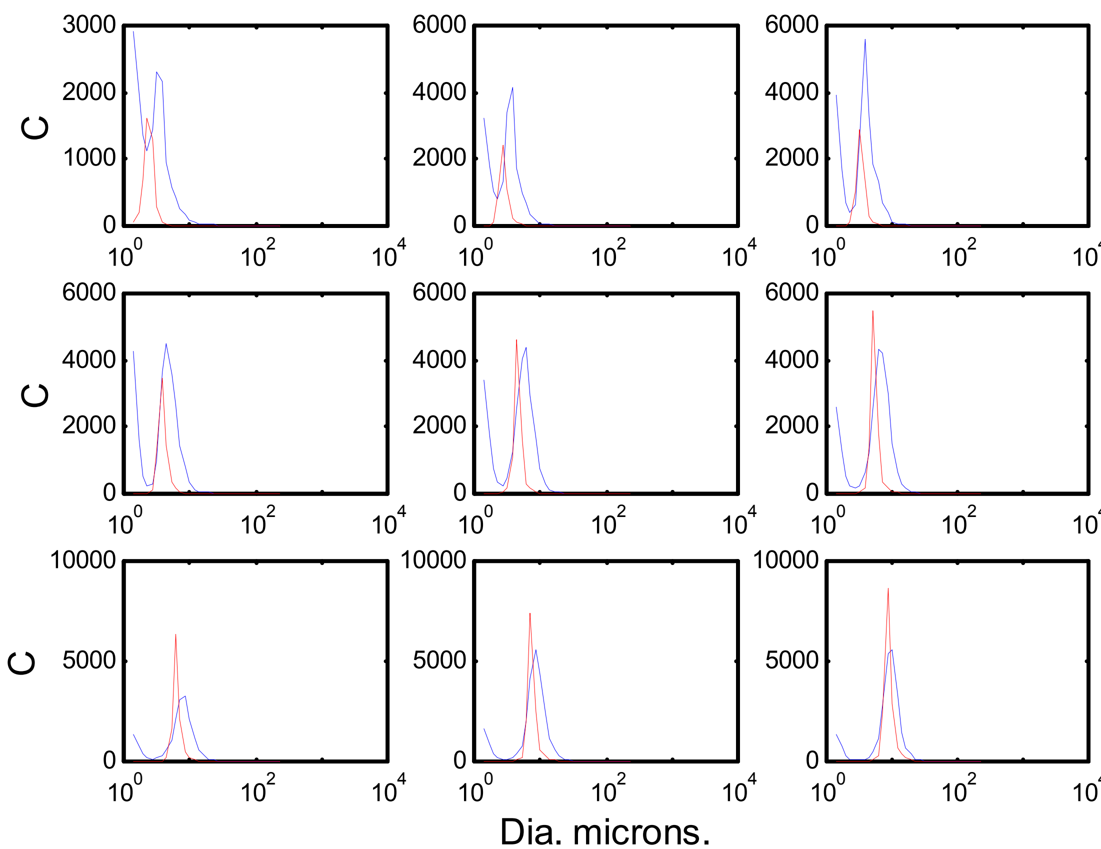

Figure 2: Equivalent sphere size distribution of spheres (red) and sediment grains (blue). Spheres naturally appear to be of narrow single size. Grains appear broad, larger. In particular, the finer sediment grains, the more they invent a 'superfine mode' of non-existing spheres. Diameters (from l to r, top to bottom: 2.3, 2.7, 3.2, 3.8, 4.4, 5.2, 6.1, 7.2 and 8.5 microns).

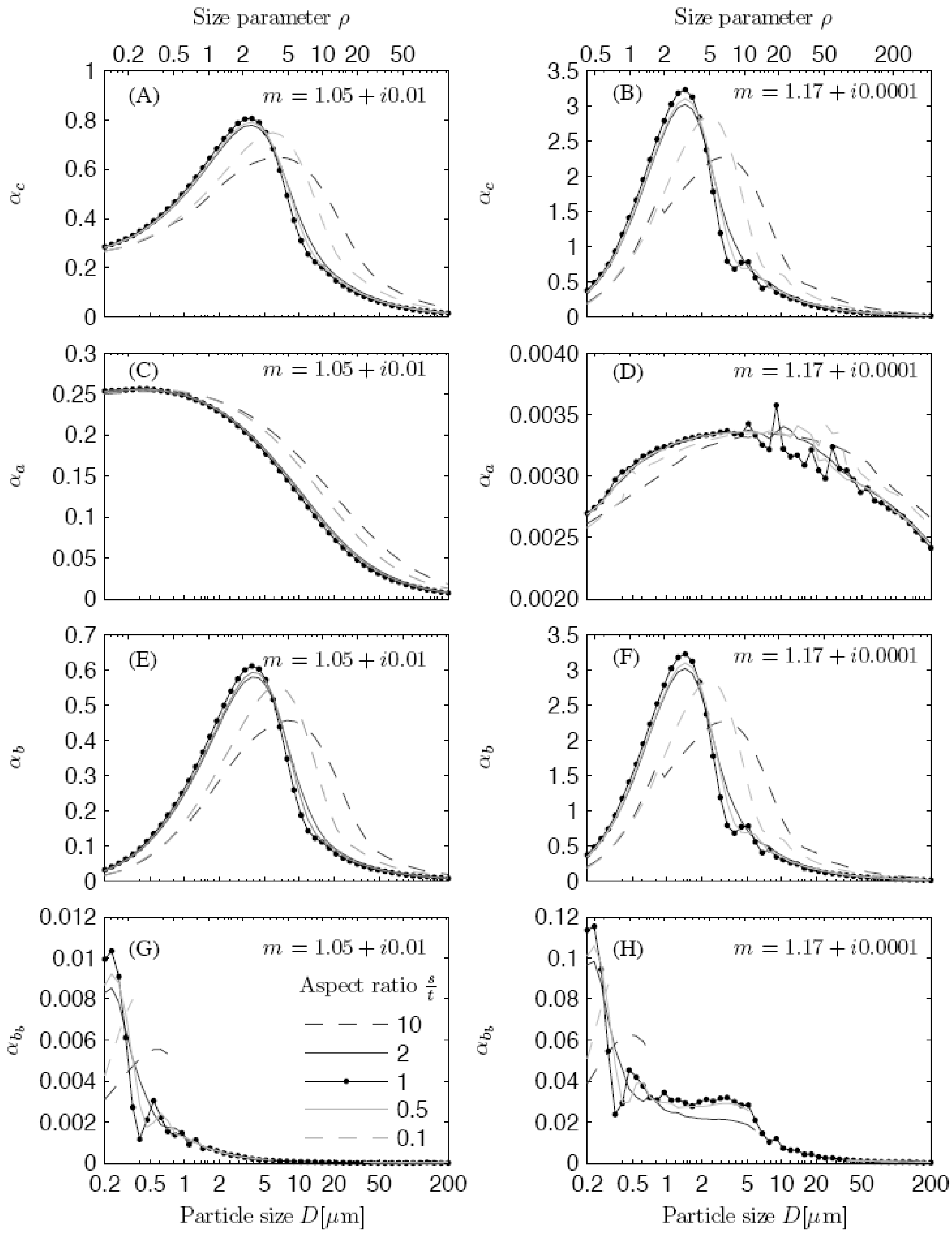

Figure 3. Volume-normalised cross sections for attenuation, _c ((A,B)), absorption, _a((C,D)), scattering, _b ((E,F)), and backscattering, _bb ((G,H)), for spheroids as a function of size, D [μm] (primary x-axis, bottom), with corresponding size parameter, ρ (secondaryx-axis, top). Each line represents a different aspect ratio, s/t (legend is shown in panel (G)). Results were derived for two different types of particles: a phytoplankton-like particle with refractive index m = 1.05 + i0.01 ((A,C,E,G)) and an inorganic-like particle with m = 1.17 + i0.0001 ((B,D,F,H)).

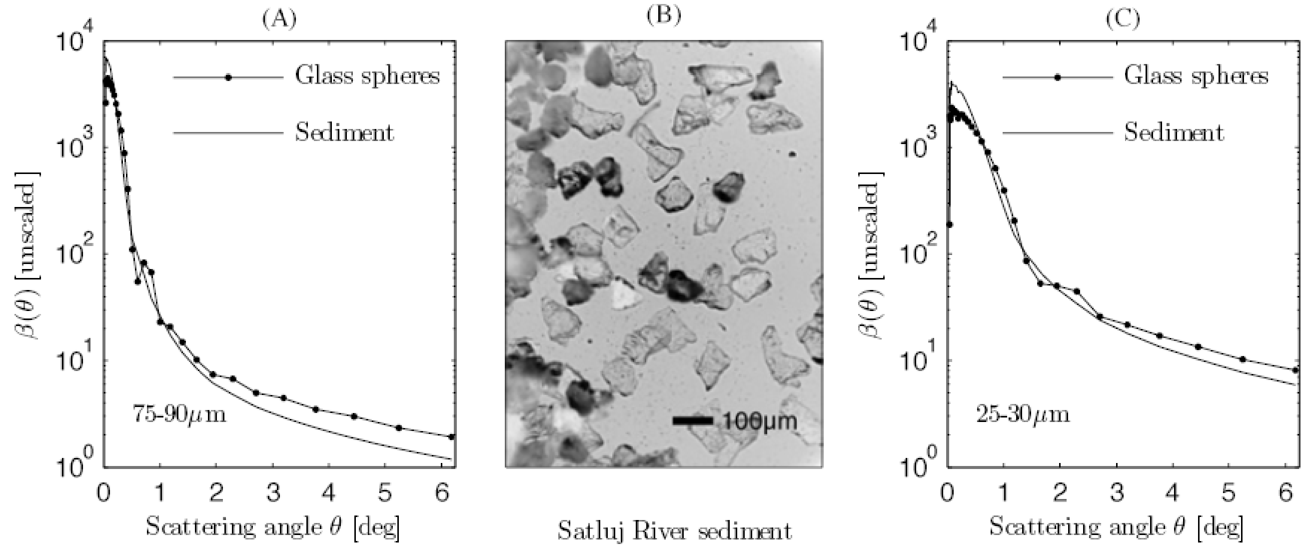

Figure 4. Measurements of near-forward scattering. (A) is a comparison of the shape of the near-forward scattering between sorted particles (Satluj River sediment; solid line) and glass spheres (line with dots) 75-90μm in size. An image of the particles used in the measurement of the sediment in (A) is presented in (B). (C) is a comparison between sediment (solid line) and glass spheres (line with dots) 25-30μm in size. Note the narrowing of the scattering pattern and absence of secondary maximum for the non-spherical natural particles (solid lines) compared to polydispersions of spheres sieved similarly (lines with dots). Scattering measurements were performed with the LISST-100 instrument

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