Investigations of Light Scattering by Ocean Waters

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LONG-TERM GOALS

Our overall, long-term goal is to significantly advance our understanding of the light scattering properties of marine particles as well as their general optical properties. Our goal is to study particle optical properties using a unique set of new optical instruments that we have developed on previous ONR funded projects. Observational studies will be conducted at sea in various coastal waters, and careful laboratory experiments of particle optical properties will be performed.

OBJECTIVES

All of the instruments required for us to carry out a thorough investigation of light scattering by marine particles, both in situ and benchtop, are now in our possession, having been developed on a previous ONR funded project (see the annual report, "Light Scattering Properties and Processes of Coastal Waters). We are thus addressing the following major questions in this research program. We expect, of course, that new or related questions will arise in the course of this research and will be addressed as needed. Accordingly, the basic objectives, or problems we seek to address are:

1. What is the range of variability in the shape of the VSF (i.e., the scattering phase function) for oceanic waters, especially coastal waters? How does the phase function relate to other optical property measurements, the nature of the particles, and biological properties such as chlorophyll concentration? And most basically, what are the phase functions for the various endmember classes of marine particles (e.g., phytoplankton, organic and inorganic detritus, sediments, etc.)?

2. How accurate and robust is the conversion to estimate the backscattering coefficient from a measurement of the VSF at a nominal angle in the backward direction? In other words, how variable is χ in the equation $b_b = 2\pi\chi\beta(\psi_0)$, where $\beta(\psi_0)$ is the nominal-angle measurement of the VSF (for the HydroScat, ψ_0 = 140 degrees)?

3. How well can Mie theory be used to calculate the VSF of marine particles based on their measured size distributions with a Coulter Counter? Does the estimated complex index of refraction for obtaining the best match with VSF measurements match the refractive index inferred from that traditional approach of using spectral absorption and beam attenuation measurements (e.g., *Bricaud, Morel and Prieur* [1983])?

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14. ABSTRACT

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4. What are the particles and processes responsible for the shapes and magnitudes of the VSF? For example: Is turbulence responsible for the slope of the VSF near 0 degrees? Are submicron particles the chief source of optical backscattering? Does near-forward scattering depend chiefly on the particle size, as opposed to their shape and/or refractive index?

5. In terms of instrument closure, how consistent are comparisons of various optical properties measured with different instruments and methods? What are the greatest sources of errors and how can they be improved? In terms of model closure, how well do radiative transfer calculations actually match measured AOP's when using measured IOP's as input? Again, what are the greatest sources of errors under various conditions and how can they be improved? In terms of inverse problems, how does the measured VSF, vis a vis measurements of concomitant optical properties, affect inverse relationships such as those between IOP's and AOP's?.

APPROACH

We have been and continue to carry out an extensive program of both field and laboratory research on the nature of light scattering by ocean waters and their constituent particles. This research is unprecedented in its scope, as we seek to address the outstanding questions about light scattering by marine particles as described in our Objectives above. Nearly all of the instruments, equipment and facilities to conduct this research program have already been developed at HOBI Labs. These include the HydroBeta, HydroScat-6, HydroScat-2, a-beta, c-beta, HydroRad and HydroDAS. Other commercial instrumentation that we have and will use in our research on this project include a Coulter Counter, spectrophotometer, PRR600, AC9, and CTD.

HydroBeta is unique among all ocean-optical instruments ever developed and incorporates many impressive capabilities important to gaining a more complete understanding of the VSF of ocean waters. This instrument is designed to measure the VSF at 11 angles *simultaneously* of ambient, *undisturbed* water. What's more, these angles can be set to any 11 angles in the range from 5 to 170 degrees in five-degree increments. With a sampling rate of 1 Hz, the HydroBeta is easily used as a profiling instrument, allowing us to investigate the variability of the VSF throughout the water column concomitant with a full range of optical and physical water-property measurements.

Successfully developing a multi-angle VSF instrument is only the first, though quite difficult step in measuring the VSF of ocean waters. The next, though equally important step is the accurate calibration of the instrument. This latter step historically has been a controversial and unresolved issue, bringing into question all previously reported VSF measurements. Petzold, for example, used a purely analytical calibration technique that he himself acknowledged in his famous 1972 report contained many unresolved questions. More recent VSF makers and users of VSF instruments have attempted to use spherical particles and Mie theory calculations of the VSF to calibrate their measurements. The problems with this approach are myriad and this approach is far from being proven or accepted. We have developed a method for calibrating HydroBeta with a method that relies only on the Lambertian properties of a diffusely reflecting target. Errors in the Lambertian target assumption are at most a few percent. The method is similar to the thoroughly documented and well tested technique we developed for calibrating the HydroScat backscattering instruments [Maffione and Dana, 1997]. This method involves measuring each receivers response to a Lambertian target, illuminated by the instrument's light source, over the receivers complete field-of-view. The result is a complete, absolute, in-water calibration that involves a bare minimum of assumptions, all of which can be independently verified.

WORK COMPLETED

This past year we conducted four research cruises around the Monterey Bay area aboard the R/V Pt. Sur. During these cruises we measured profiles of a complete set of inherent and apparent optical properties with our HydroProfiler system (Figure 1), along with total suspended solids (TSS) and chlorophyll concentrations from bottle samples. These measurements added to our long-term seasonal database of optical properties and processes in this region. A considerable amount of effort was expended processing our vast optical datasets and arranging them in a form that can be downloaded from our website, understood, and used by other investigators. Indeed, our in-situ optical measurements, which are all made simultaneously, cover an unprecedented range of optical properties and most importantly includes the volume scattering function. We expect our VSF database, which includes associated optical properties, to quickly supplant the VSF measurements of Petzold that have been widely used for three decades. In addition to our sea measurements, we conducted a number of laboratory measurements of the optical properties, including the VSF, of known assemblages of particles, including bubbles and microspheres. One purpose of these laboratory measurements is to validate our calibration methodology as well as check it against other methods of calibration.

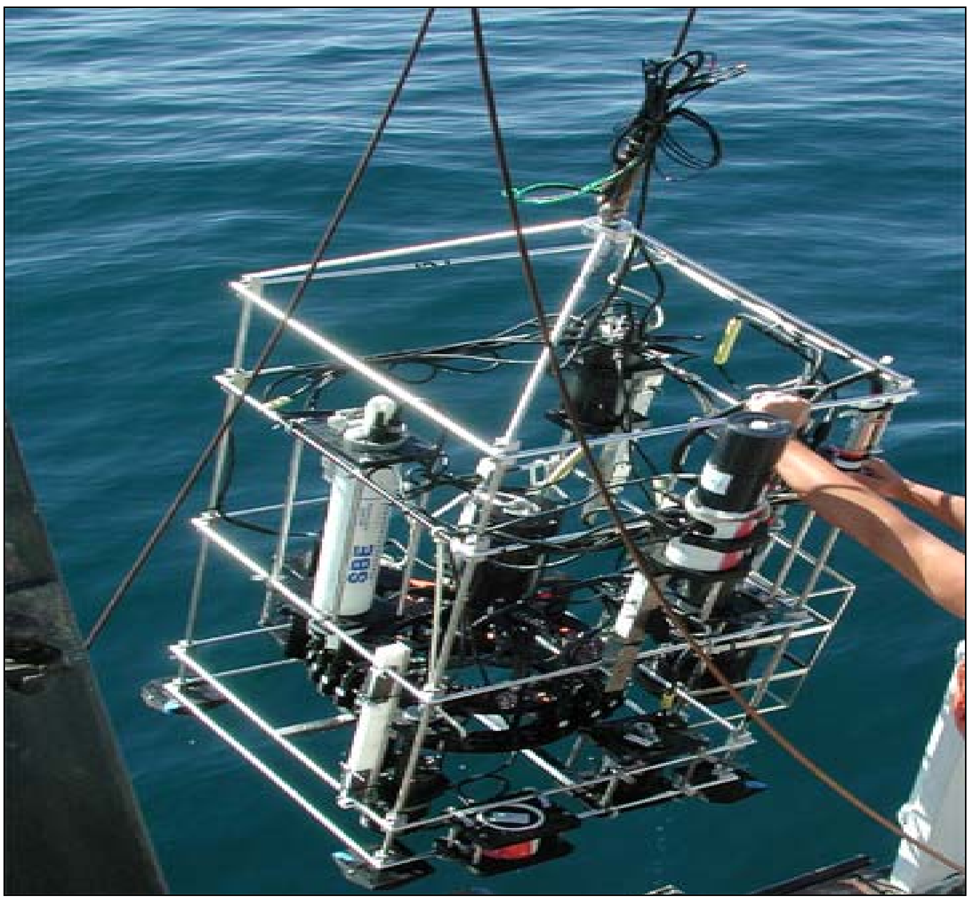

Figure 1. Photograph of the HydroProfiler aboard the R/V Pt. Sur. Instruments on this package include the HydroBeta, a-beta, c-beta, a HydroScat-2 and HydroScat-4, AC9, PRR600, and a Seabird CTD. All instruments are integrated into a HydroDAS, a multi-instrument data integration system that collects data from all instruments and sends it up a two-conductor cable in real time while also supplying power to all the instruments.

To enhance our research on light scattering, we complemented our in-situ IOP measurements with surface hyperspectral measurements of remote-sensing reflectance (RSR) using a new instrument we developed called WALRUS (WAter-Leaving Radiance Unison Spectrometer). This unique instrument, modeled after the HydroRad, is a tethered buoy that measures upwelling radiance both above and below the water's surface, and both downwelling irradiance and sky radiance. It also contains pitch/roll and compass sensors so that the orientation of the light sensors is known during data collection. We used the WALRUS to conduct several types of experiments on RSR and its relationship with the complete set of IOP's we measured with the HydroProfiler. One type of experiment involved generating a plume of bubbles around the WALRUS by making short bursts of thrust from the ships aft propellers. The tether attached to the WALRUS would be played out to allow the instrument to follow the decaying bubble plume, all the while making repeated measurements. This technique allowed us to determine the effects of bubbles on the upwelling radiance (Figure 2). This past year we also began a collaboration with the Naval Postgraduate School and investigators at UCSC on mapping hyperspectral RSR of Monterey Bay from an aircraft mounted with a HydroRad that measures upwelling radiance, downwelling irradiance and downwelling sky radiance. Flights were conducted during our cruises, with flightlines covering our cruise track.

Figure 2. Photographs of the WALRUS. Left photo shows the WALRUS in a bubble plume created by the ship's thrust, and right one shows its position after the plume had dissipated

RESULTS

The HydroBeta is the first in-situ instrument that measures the VSF at 12 angles simultaneously in undisturbed water (i.e., it is not a flow-through system). Because the sampling rate is 1 Hz, this instrument is well suited for mounting on profiling packages. Thus in a single profile we obtain more data on the VSF than were published in the seminal report by Petzold (1972). Moreover, the vertical variability in the particle distributions, common to Monterey Bay, allowed us to obtain, in a single profile, measurements of the VSF that cover the full range of VSF's published by Petzold, from clear oceanic waters to turbid near-shore waters. Considering the number of profiles obtained in a single cruise, we are rapidly expanding our knowledge of the VSF of ocean waters, which was a virtual desert over the past 30 years. This past year we have invested a considerable amount of effort collating the VSF data, along with simultaneous measurements of associated optical properties into a database that can be accessed from our website.

One of the many problems in ocean optics that our measurements are allowing us to investigate is the effect of the shape variability in the VSF on estimating the backward scattering coefficient from a single measurement of the VSF (Maffione and Dana, 1997, 2003). Our original conjecture, based on Mie calculations, was that a single measurement of the VSF anywhere in the range from 120 to 140 degrees could be used to estimate the backward scattering coefficient with an error of 10% or less. The results shown in Figure 3 confirm this conjecture from actual measurements of the VSF made with the HydroBeta. Moreover, it appears to show that "best" angle for this determination is around 135 degrees, the angle at which the HydroScat measures the VSF to estimate the backward scattering coefficient (Maffione and Dana, 1997). Another problem we're investigating with our VSF measurements is how best to invert these measurements to obtain information on the nature and distribution of suspended particles (Maffione, 2003). We are pursuing a number of other problems that space does not allow us to expand on here, including the effects of bubbles on water optical properties and upwelling radiance, relationship of the shape of the VSF of RSR, and the variability of the phase function in relation to various particle distributions. Our laboratory measurements have been directed towards validating our calibration methodology, and we have definitively shown that our plaque method is significantly more accurate than attempting to use microspheres to calibrate VSF and backscattering sensors.

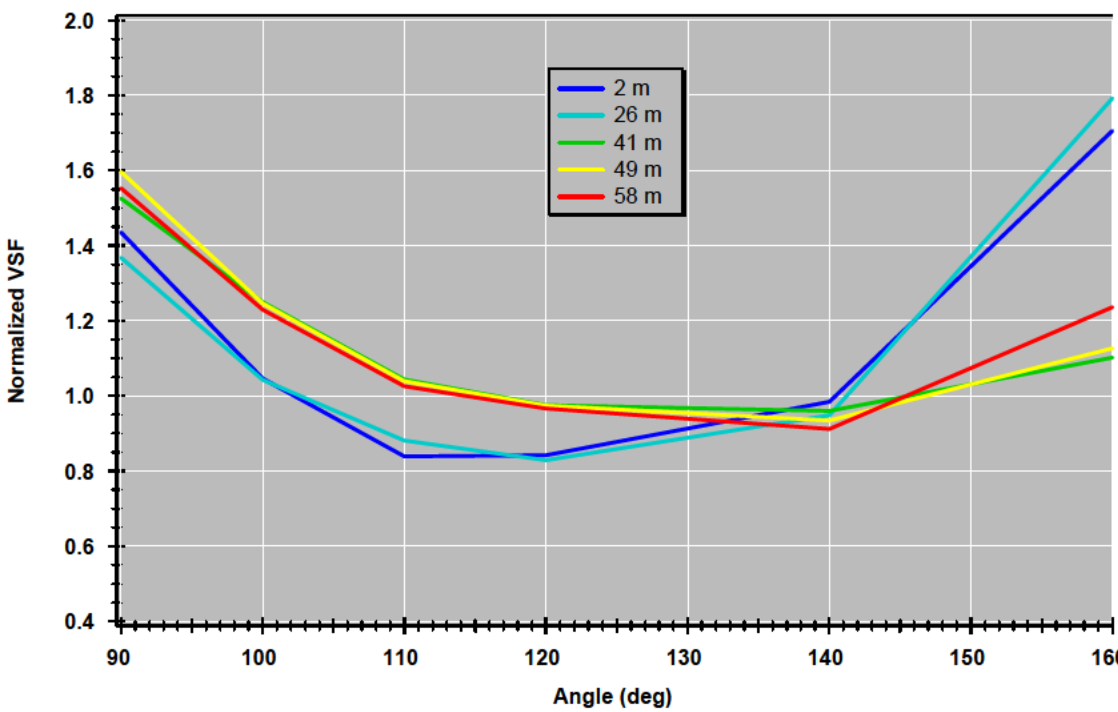

Figure 3. Graph of the normalized VSF in the backward hemisphere as measured by the HydroBeta, illustrating the variation of the shape of the VSF in the back hemisphere.

IMPACT/APPLICATIONS

We expect that our measurements of the complete VSF will have an enormous impact on nearly all areas of optical oceanography. No measurements of the kind we plan to obtain have ever been made. Indeed, the nearest data of this type were obtained over 25 years ago. This lack of systematic and complete VSF measurements has greatly hampered our understanding of light scattering by marine particles, the testing and refinement of optical models, and the calibration of ocean-optical systems. Our extensive collection of optical property measurements in various coastal environments will be a critical aid in developing bio-geo-optical models of coastal waters.

TRANSITIONS

Our results, especially the VSF measurements, are being utilized by others in optical modeling and radiative transfer efforts in the investigation of remote sensing, underwater visibility and ocean lidar.

RELATED PROJECTS

The research we are conducting on this project is closely related to the research we are conducting on two ONR DRI's, CoBOP and HyCODE. Both of these DRI's benefit from, and contribute to this project. Our DRI projects also involved the study of water optical properties and their effect on radiative transfer. We anticipate that work being conducted at NRL-Stennis by Dr.'s Robert Arnone and Alan Weidemann will also benefit from our research. Our VSF measurements are also being used by groups doing optical modeling of ocean lidar.

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