A New Method for the Measurement of the Optical Volume Scattering Function in the Upper Ocean

MICHAEL E. LEE

Optical Oceanography Laboratory, Marine Hydrophysical Institute, National Ukrainian Academy of Science, Sevastopol, Crimea, Ukraine

MARLON R. LEWIS

Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

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ABSTRACT

A new method to measure the optical volume scattering function (VSF) of seawater is presented. The VSF is a fundamental property used in the calculation of radiative transfer for applications as diverse as upper-ocean heating by solar radiation to laser ranging of the sea bottom. The approach differs from traditional ones and involves use of a special periscope prism that allows the direct determination of the VSF over a wide range of angles (0.6°–177.3°) with an angular resolution of 0.3°. Measurements taken in the laboratory using Barnstead International, Inc., Nanopure water, cleaned seawater, and known additions of defined scatterers indicate close correspondence between experimental data and theoretical simulations based on Mie theory over the angle range from 12° to 170°. Field deployments in the Atlantic Ocean continental shelf water are shown to produce high quality measurements of the VSF in the angle range from 0.6° to 177.3°; such observations have not been available before. The new data show that there is significant environmental variance in the VSF for small angles (from less than 1° to several degrees) in the forward direction and from 170° to 177.3° in the backward direction. The resulting observations are of profound and fundamental importance to the accurate modeling of the propagation of radiation in the ocean.

1. Introduction

The volume scattering function (VSF), which describes the angular distribution of light scattered from an incident beam, is a fundamental inherent optical property of the ocean. The VSF and the absorption coefficient completely determine the inherent optical properties of a medium in the absence of inelastic scattering; coupled with the angular and spectral distribution of the incident radiance field just below the surface, the full radiative flux balance of the ocean can be simulated based on the radiative transfer equation. Such computations are of central importance in areas as diverse as the upper-ocean heat balance, the photosynthetic productivity of the ocean, and the chemical transformation of photoreactive compounds. These analyses are also key to current applications concerning the diagnosis of upper-ocean constituents from inversion of the spectral distribution of upwelling radiance measured from remote airborne and satellite platforms and for the estimation of the efficacy of laser ranging of the sea bottom.

Despite its fundamental nature, little is known about the range of variability in the VSF in the ocean. This is largely due to the extreme difficulty in carrying out the direct measurement of the property. Current radiative transfer models rely on a very limited set of coarsely resolved measurements of the angular distribution of scattering made more than 20 years ago (Tyler and Richardson 1958; Petzold 1972; Kullenberg 1974; see review in Morel 1973), despite widespread agreement on the importance of the variability in the phase function in forecasting the underwater radiance distribution (Morel 1973; Plass et al. 1985; Mobley et al. 1993, 2002; Gordon 1994). As well, the VSF can be inverted to obtain information on the nature of the particulate matter in the oceans, which is of wide interest (e.g., Brown and Gordon 1973; Zaneveld and Pak 1973; Zhang et al. 2002)

Instruments historically used for measuring the VSF across a range of angles (e.g., polar nephelometers; Tyler and Richardson 1958; Kullenberg 1974) are complicated and bulky and have no capability to measure the VSF over the full angular range necessary to solve the general radiative transfer equation. Different devices are available to measure scattering at a few fixed angles, over a narrow range in the forward direction [e.g., Sequoia Scientific, Inc., Laser In Situ Scattering and Trans-

Corresponding author address: Marlon R. Lewis, Dalhousie University, Department of Oceanography, Halifax, NS B3H 4J1, Canada.
E-mail: marlon.lewis@dal.ca

missometer (LISST); Agrawal and Pottsmith 2000], or the total scattering b (integral of the VSF over all solid angles), from which a portion of the VSF can be inferred using models that relate scattering at a given angle to elements of the full angular range in a theoretical sense (e.g., Man'kovsky 1971; Morel 1973; Oishi 1990; Maffione and Dana 1997; Boss and Pegau 2001). Because of the lack of direct measurement, this link is uncertain (but see Boss and Pegau 2001), in large part because the nature of the particles responsible for scattering in the ocean (particularly backscattering) is unknown (Zhang et al. 1998, 2002).

Here, we describe a new approach to the measurement of the VSF in the ocean. We present the theoretical background, the instrument design, and the first volume scattering observations made in the ocean in the last 20 years.

2. Background

The volume scattering function $\beta(\theta)$ is radiometrically defined as the radiant intensity I deriving from a volume element in a given direction θ per unit of incident irradiance E and per unit volume V; that is,

$$\beta(\theta) = \frac{dI(\theta)}{EdV} \quad (\mathrm{m^{-1}\ sr^{-1}}). \qquad (1)$$

The VSF is often normalized by its angular integral to yield the phase function,

$$\overline{\beta}(\theta) = \frac{\beta(\theta)}{2\pi \int_{\theta=0}^{\pi} \beta(\theta)\sin(\theta)\, d\theta} = \frac{\beta(\theta)}{b} \quad (\mathrm{sr^{-1}}), \qquad (2)$$

which provides information about the relative angular distribution of the scattering and where the VSF is assumed to be azimuthally symmetric (e.g., Mobley 1994). The denominator of Eq. (2) is the total volume scattering coefficient b ($\mathrm{m^{-1}}$).

The backscattering coefficient b_b ($\mathrm{m^{-1}}$) is computed as $2\pi \int_{\theta=\pi/2}^{\pi} \beta(\theta)\sin(\theta)\, d\theta$, and the backscattering ratio is defined as b_b/b. A similar computation can be done for the forward hemisphere (e.g., Mobley 1994).

There have been three instrumentation approaches to the measurement of the $\beta(\theta)$. Differences in the approaches relate directly to different problems that arise for VSF measurements in small (e.g., forward), general, and backward angles. The small-angle problem relates to the high level of background light generated by the direct beam, the magnitude of which is several orders greater than that of the measured scattered light. The leading problems of the general-angle scattering (e.g., $10° < \theta < 170°$) are the large dynamic range of measured scattered radiance ($>10^7$) and a very low signal of scattered light at angles in the vicinity of 90°. The problem of insufficient (and difficult to determine) scattering volume is added to difficulties of measurements of the low light level for angles in the range near 180°. In accordance with these differences, different approaches have been used for different angular ranges.

a. Small-angle method of measurements

The most difficult problem of small-angle measurements is the contamination of the scattered signal by light reflected and scattered from parts of the optical unit. The so-called small-angle technique has been developed to avoid this problem. The small-angle technique is based on the illumination of a strictly defined volume of scattering media by a narrow parallel beam and measurement of the scattered light in the focal plane of a receiving objective. The problem faced is the detection of a very weak signal at small angles near the beam center, which interferes with the focal plane because of the imperfect character of the direct beam; for example, the beam can exceed the scattered signal by up to 10^5 in clean ocean waters (Bauer and Morel 1967; Petzold 1972; Agrawal and Pottsmith 2000).

b. Measurements of general-angle scattering

The typical instruments used for measurement of the general-angle VSF have complex mechanical designs because their angular deviation is provided by rotating a bulky light source or photodetector unit around the axis of the scattering volume (e.g., Petzold 1972). Because of interference by stray light, the minimal forward angle is limited to $\sim$10°, and for backscattered light measurements are limited to angles $<$170°, owing to physical restrictions based on the dimensions of the light source and photodetector unit. For such instruments, it is also difficult to provide baffling against ambient light.

Since modern photodetectors measure radiant fluxes, it is more convenient to write Eq. (1) in terms of the exiting and scattered radiant fluxes. The scattered flux $F(\theta)$ can be expressed as a function of the optical assembly parameters of the scattering meter:

$$F(\theta) = I(\theta)\Omega e^{-cr}, \qquad (3)$$

where Ω is the viewing solid angle of the photodetector (sr), c is the beam attenuation coefficient ($\mathrm{m^{-1}}$), and r is the distance between the center of the scattering volume and the photodetector (m). The irradiance E in Eq. (1) is determined by the flux F_0 from the radiant beam, which penetrates into the seawater and is attenuated along the water path r_1 from the light source to the center of the scattering volume,

$$E = \frac{F_0}{S} e^{-cr_1}, \qquad (4)$$

where S is the normal cross-sectional area of the exiting light flux. Combining Eqs. (1), (3), and (4),

$$\beta(\theta) = \frac{F(\theta) S e^{c(r+r_1)}}{F_0 \Omega V(\theta)}. \qquad (5)$$

The necessity will arise for additional measurements of F_0 and c when the determination of absolute values of the scattering coefficient in a given direction is desired, but the opportunity to perform these measurements is not always available. Therefore, the measurements of the angular distribution of scattered light are usually made in relative units. If the polar nephelometer has the additional requirement of measuring the direct beam attenuation for $\theta = 0$ by the same photodetector, then its calibration for absolute values of $\beta(\theta)$ can be carried out (Kullenberg 1968). In this case, in accordance with the Beer–Lambert–Bouguer law, the light received by the photodetector will be determined by

$$F(0) = F_0 e^{-c(r+r_1)}. \quad (6)$$

From Eqs. (5) and (6) we derive

$$\beta(\theta) = \frac{F(\theta)S}{F(0)\Omega V(\theta)}. \quad (7)$$

The simultaneous measurements of scattered and direct attenuated fluxes allow the determination of the absolute values of $\beta(\theta)$, because other variables in Eq. (7) are known from the geometrical parameters of the optical assembly. This equation is strictly true only for a perfectly collimated source and collimated field of view of the receiver, where $V(\theta)$ is very well known and where all scattered light other than into a very narrow detector is rejected. For example, the pure beam attenuation coefficient is difficult to measure given a finite acceptance angle of the receiver in the forward direction, and additional assumptions regarding the magnitude of the rejection of forward-scattered light are required (Pegau et al. 1995).

The extreme forward weighting of the VSF in natural waters results in requirements for high-power light sources with narrow beams and high-sensitivity photodetectors with high angular resolution and wide dynamic range. It is difficult to meet all of the objectives involved in a full determination of the VSF, and little progress has been made in this area since the pioneering studies from the 1950s to 1970s (Tyler and Richardson 1958; Sasaki et al. 1960; Jerlov 1961; Tyler and Austin 1964; Kullenberg 1968; Man'kovsky et al. 1970; Petzold 1972; Afonin and Basharin 1975). Although these instruments allow the acquisition of qualitative data, they do not satisfy current requirements for accurate radiative transfer modeling in the sea. For example, because of low angular resolution, the full VSF cannot be measured, and scattering data for small angles are extrapolated by parabolic (Spilhaus 1968) and other laws (Morrison 1970) or are retrieved from two or three values obtained by the small-angle range technique (Petzold 1972; Kelbalikhanov and Krasovsky 1972; Kopelevich et al. 1975). Other limitations are low accuracy and long measurement cycles. The instruments are bulky and, hence, not convenient for field conditions.

3. New approaches to the measurement of the VSF

A new volume scattering meter, which is free of most of the above-mentioned limitations, has been developed jointly by the Marine Hydrophysical Institute (Academy of Sciences of the Ukraine) and Satlantic, Inc. (Halifax, Nova Scotia). In the following discussion, we first describe the approach to the general-angle scattering problem and then discuss solutions for the near-forward and near-backward angles.

a. *General angles*

The limitations discussed above are overcome by a new measurement approach to determination of the VSF (Fig. 1). The specific feature of the new schematic is the use of a rotating, specially designed periscope prism. The prism rotates around the photodetector assembly axis that extends through the center of the scattering volume. The main advantage is that the light source and the photodetector units are fixed during the measurement process. The special shape of the periscope prism and its precisely adjusted dimensions provide the opportunity to measure scattered light practically over the full angular range, including the case of direct beam attenuation measurements, with an angular resolution of 0.3° achievable with precise knowledge of the prism position.

Since the light source and the photodetector units are fixed, increasing their dimensions (length) does not result in significant design complexity, and the scanning arrangement is significantly simplified and reduced in size as a result.

A halogen lamp with a small-sized filament, which provides a 75-mW light flux, is employed. This lamp, coupled with a 100-mm focus lens, provides a collimated light flux with a divergence of less than 0.1°. This flux penetrates into the water contained in a baffled chamber through the objective window and irradiates the scattering volume; we assume that fluctuations in lamp intensity over the measurement sequence are negligible contributors to the overall uncertainty budget. During measurements of the VSF, the scattering volume varies steadily in a complex fashion, and the precision in the definition of the VSF, especially at small angles and for those close to 180°, depends greatly on the accurate estimation of the scattering volume. With accuracy sufficient for practical applications the scattering volume variation for large angles can be defined as

$$V(\theta) = V(90°)/\sin(\theta), \quad (8)$$

where $V(90°)$ is the scattering volume in the 90° direction, defined by the optical assembly parameters. For small angles near 0° and for backscattered light near 180°, the computation of the scattering volume is more complex, the empirical solution of which defines the accuracy of the VSF retrieval (see calibration below).

The light source, the photodiode for measurements

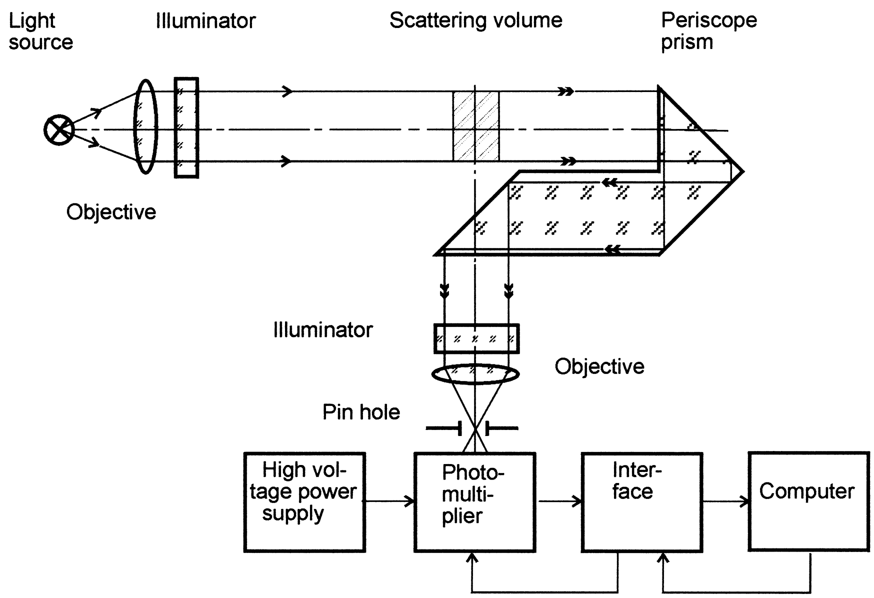

FIG. 1. General schematic diagram of the principle of measurement of the volume scattering function in the ocean. The optical filter (532 nm) is placed before the photomultiplier.

of the directly attenuated beam, and the motor for the angular scanner are placed in three separate hermetic cases, mutually oriented at 90° with respect to the working volume of the device. The working volume is contained within a light-trap assembly consisting of two coupled cups of light-absorptive material (flat black paint) enclosing a volume of approximately 1 L, with provision for free exchange of ambient fluid. The water is slowly stirred within the chamber by rotation of the periscope; complete rotation about the axis is normally set to 1.5 min.

As the scanning motor rotates, scattered light is continuously directed by the periscope prism into the hermetic case of the photodetector assembly, where it is focused by an objective into the center of the field stop and then is directed onto a photomultiplier photocathode. For all of the experiments reported here, the output was filtered to provide a Gaussian spectral band centered at 532 nm with a bandpass of 10 nm at full width, half maximum. The filter set can be adjusted if desired. The acceptance angle of the photodetector, determined by both the objective focus and the field-stop dimensions, is chosen to be somewhat greater than that of the source collimation. The VSF measurement is performed under continuous rotation of the periscope prism. The intensity of the directly attenuated flux is measured at 0°.

Because of the elongated shape of the VSF, the required dynamic range can reach seven or more orders of magnitude. We have developed a logarithmic mode operation to address this, using negative feedback through the photomultiplier power source (Bogushevsky et al. 1973) and a series of automated gain ranges. As a result it is possible to establish a linear working mode for the photomultiplier with high accuracy over a dynamic range encompassing 12 orders of magnitude in a routine, automated fashion.

b. Small angles

After successful testing of the first variant over the general-angle range in the laboratory, efforts were undertaken to extend the angle range to 0.3° in the forward direction and to >178° in the backward direction. For this goal, a new shadow method for small-angle scattering measurements was developed. For this approach, the periscope prism was designed with a parallel shift such that the prism boundary matches the optical axis of the system (Fig. 2). In this case, the direct beam is not able to move into the receiving objective, and scattered light will reach the photomultiplier without interference. For angles near zero, the beam edge slides along the prism boundary, but no direct light is received. With this design, the amount of interference decreased by several orders of magnitude. For an ideal parallel beam, this approach fully avoids interference from background light. Unfortunately, real collimated beam sources have small spatial sidelobes, which pass to the receiving objective. This was addressed by means of narrowing the beamwidth to a very small size for small-angle measurements. For this, a shifted aperture was introduced that changed the beamwidth synchronously with the prism rotation. The aperture is shifted such that from 0° to 30° the beamwidth was minimal and for the other angles it was maximal. Accurate measurements to 0.6° have been successfully made with this new approach.

The second significant problem involved the provision of adequate conditions for scattering determination in angles near 180°. For most designs, the dimensions

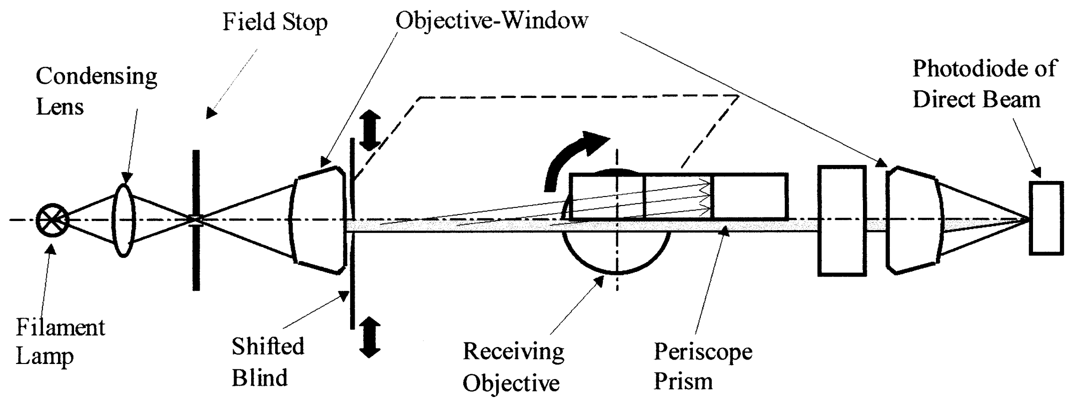

FIG. 2. A schematic diagram of the shadow method for small-angle scattering measurements. This is a top view, with the rotational axis of the prism and the translational path of the stop indicated.

of the light source and the photodetector unit restrict measurements in the near-backward direction. Furthermore, accurate determination of the appropriate scattering volume becomes difficult, as does specular scattering of the forward beam from the instrument surface into the backward direction. We addressed this problem by introducing two polished absorbing glass plates fixed at an angle of 45° to the primary optical axis (Fig. 3), which resulted in a decrease in specularly scattered light by more than 10^9.

Corrections were made for attenuation in the scattering volume [see Eq. (7)] either by using the instrument itself (laboratory measurements) or by using measurements from an AC-9 instrument (WET Labs, Inc.).

4. Calibration, testing, and deployment methodologies

a. Laboratory experiments with known scattering agents

The first unit designed for general-angle scattering observations was used for initial testing under controlled conditions. Measurements were carried out first using Barnstead International, Inc., Nanopure freshwater and then using filtered and cleaned seawater. The volume scattering meter was initially submerged in a large (1 m $\times$ 1 m) tank with Nanopure water, and measurements were taken of the VSF. The tank was subsequently filled with seawater that had been filtered (0.2 μm) and purged

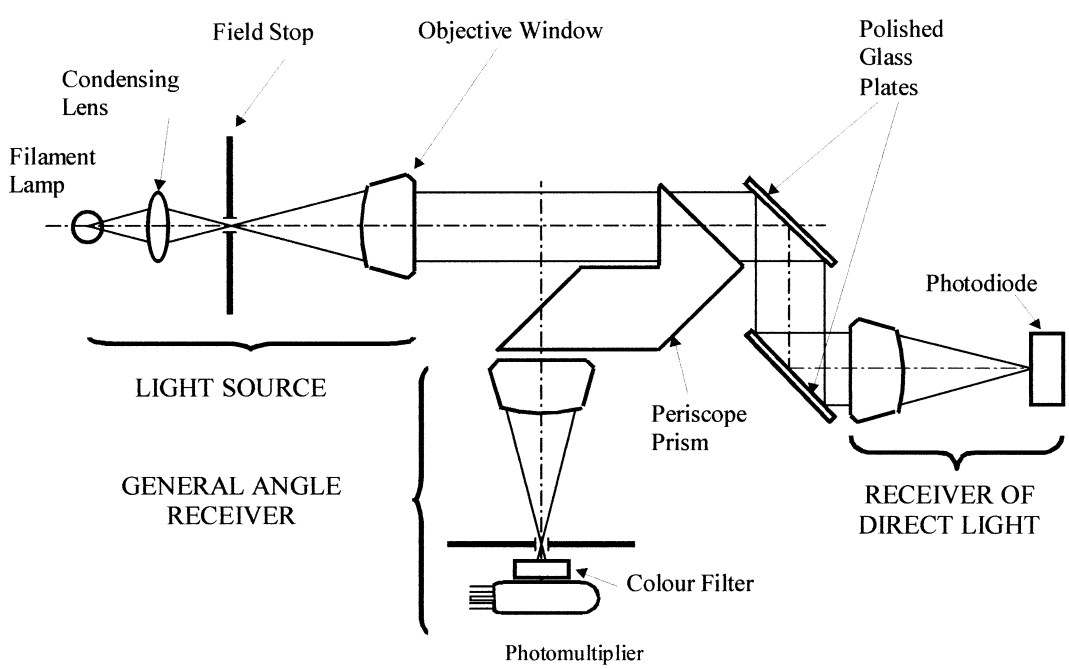

FIG. 3. A schematic diagram of the approach to the solution of specular reflection for the measurement of scattering in the near-backward direction. The rotation axis of the prism is in the plane of the diagram.

of most surfactants by means of adsorption on a stream of bubbles introduced from filtered air (0.2 μm and activated charcoal), and the VSF was determined.

The VSF of natural marine waters was then determined in the same fashion, using surface seawater collected from the Northwest Arm, a semienclosed marine inlet adjacent to Halifax, Nova Scotia, Canada.

Last, measurements were made of clean seawater, to which polystyrene microspheres had been introduced. These particles are monodisperse latex beads of precisely known size and refractive index. Six different sizes of beads were used, spanning diameters from 0.064 to 87.9 μm. The smallest-size beads did not appear stable, and the data were discarded. The manufacturer's size determination was verified by Beckman Coulter, Inc., Coulter-counter measurements. Because the particles are nearly perfectly spherical, their VSF can be predicted to high accuracy using Mie theory (Bohren and Huffman 1983) and thus provides a means to calibrate the functioning of the instrument. Because of the limited number of these particles, a new measurement technique was used whereby the testing fluid was introduced directly into the working volume by means of a siphon. This method was used initially with the same fluid used in the larger tanks, and results were indistinguishable. This was used as a background control, and the known number of particles were then mixed with a volume of the same water and were introduced into the working volume of the instrument for the measurement.

Calibration of the instrument is facilitated by the use of a single detector with a high degree of stability. The principal uncertainty arises from uncertainties in the estimated scattering volume, as discussed above, when the total scattering coefficient is relatively low, and the single-scattering albedo is near 1. We used measurements of monodisperse bead populations performed at 90°, combined with Eq. (8), to provide a first-order estimate of the scattering volume. The measured VSF was adjusted slightly ($<3\%$) based on comparison with the corresponding Mie computations for angles between 30° and 150° to fine-tune the instrument characteristics. No measurements of bead scattering were taken after introduction of the techniques to enhance near-forward and near-backward scattering, and the scattering volume estimation was derived by analysis using known instrument geometry.

b. Field experiments in coastal waters

Experiments were made to evaluate the variation in the VSF in the nearshore waters off New Jersey, in association with the U.S. Office of Naval Research's Hyperspectral Coastal Dynamics Experiment (HyCode) during July/August 2000. The work was carried out on board small research vessels based at the Rutgers University Marine Field Station in Tuckerton, New Jersey.

Measurements were made at a number of locations ranging from immediately adjacent to shore to 20 km offshore on the continental shelf. Measurements were also made over a range of depths. A total of 423 determinations of the VSF were made, and, for many of the stations, concurrent observations of the beam attenuation coefficient and absorption coefficient were made (Mobley et al. 2002; Boss and Pegau 2001). In general, the water was highly turbid (attenuation coefficients ranged from 0.47 to 8.8 m^{-1}). Further details of the VSF environmental variability are reported elsewhere, and we confine ourselves here to an analysis of the performance of the instrument.

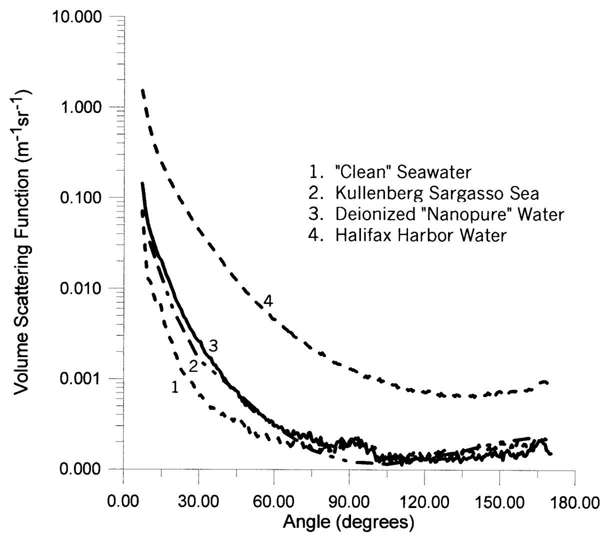

FIG. 4. Laboratory measurements of the VSF of 1) ''clean'' seawater, 2) Sargasso Sea water (Kullenberg 1968; shown for reference), 3) deionized Nanopure freshwater, and 4) Halifax Harbor surface water.

During this experiment, there was opportunity to compare the results from the new device with additional instruments for the measurement of the total (e.g., integral VSF) scattering coefficient (AC-9; WET Labs, Inc.), with the backscattering coefficient, and with advanced numerical models of radiative transfer (''Hydrolight''; Sequoia Scientific, Inc.) used for comparison with high-precision measurements of the radiance and irradiance fields from profiling packages (Satlantic, Inc.; Mobley et al. 2002; S. Pegau and E. Boss 2001, personal communication).

5. Results and discussion

a. Laboratory observations

The laboratory measurements were carried out with the general-angle-scattering version of the instrument over the angular range 12°–170°. The measured VSFs for both Nanopure and cleaned seawater were comparable to observations for the open ocean over this range (Fig. 4) (e.g., Kullenberg 1968). The lack of correspondence to theoretical values of pure seawater (e.g.,

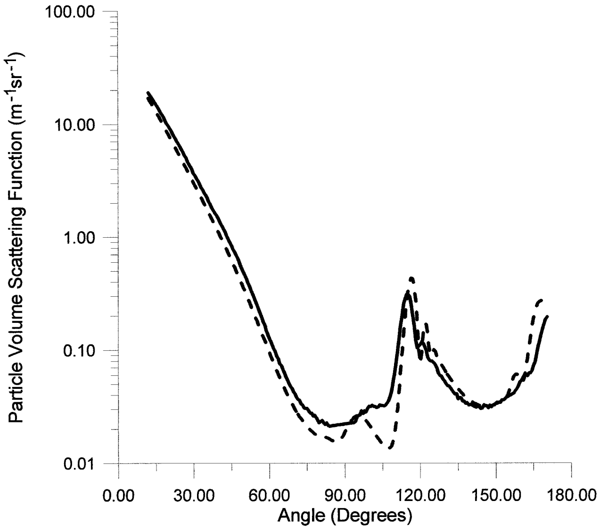

FIG. 5. Comparison of theoretical Mie calculations (dashed curve) and direct measurements (solid curve) of the VSF of latex microspheres with a diameter of 45.6 μm.

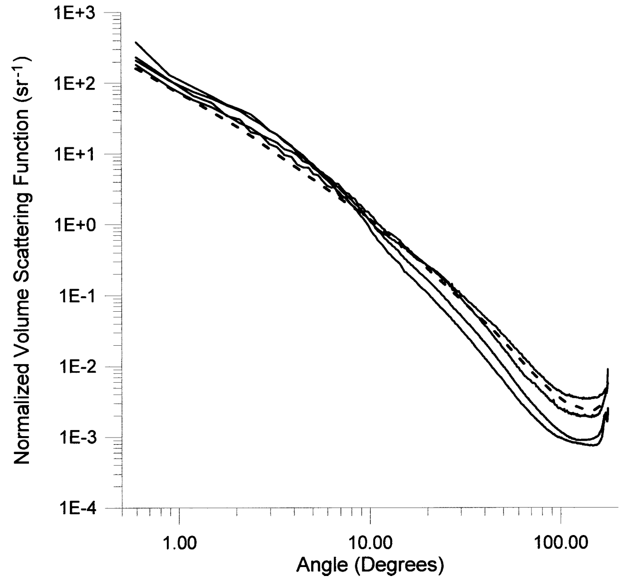

FIG. 6. Spatial variation of the measured normalized VSF (similar to phase function—see text) in surface waters off the New Jersey coast. In order of decreasing backscatter, the curves represent a transect of four stations from inshore to offshore (from 39°33′N, 74°25′W to 39°21′N, 74°05′W). The Petzold phase function (Mobley 1994) is provided for reference. On ordinate, 1E − 4 is 1 × 10^{-4}, etc.

Morel 1974) reflects the general inability to purge seawater of all small particles, particularly bubbles.

The VSF of natural surface water from a eutrophic environment (Northwest Arm) was also measured (also shown in Fig. 4). This moderately turbid water shows elevated scattering of approximately one order of magnitude more than the clean seawater and lacks much of the angular scattering structure seen in the purer water.

The observations of the VSF of precisely defined monodisperse spheres compared well to theoretical Mie calculations (Fig. 5). For particles with a central diameter of 45.6 μm, the theoretical Mie values (dashed curve) and laboratory determination (solid curve) can be seen in Fig. 5. Both the amplitude and much of the angular structure were retrieved well; similar results were obtained for particles of different diameters. For this experiment, the departure of the integral over the full angular range (the total scattering coefficient less those values for angles less than 12° and greater than 170°) is 19%; for the integral over the backward direction, the error is −8%.

Based on these observations under controlled conditions, we conclude that the performance of the instrument is sufficient for the accurate determination of the VSF with angular resolution of 0.3° and over the general scattering angle range from 12° to 170°.

b. Field observations

We made improvements to the instrument for the field study that permitted the measurement of angles as small as 0.6° and as large as 177.3°. The variation observed in the VSF, even over a restricted geographical range, is high, particularly in the backward direction (Fig. 6). For clarity, these curves have been normalized as in Eq. (2), but with the integral taken only over the range 0.6°–177.3°. To the extent that the near-forward (0°–0.6°) and near-backward (177.3°–180°) scattering contribute strongly to the integral, these curves will depart from the ''true'' phase function. Although this is likely a small effect, given the sine θ weighting, we have designated these as ''normalized volume scattering functions'' to distinguish them from the true phase function. Scattering by water has not been subtracted from these curves.

The primary mode of variability observed is a tilting around a region from 7° to 8° where little variance was observed. Strong variations thus appeared in the near-forward and near-backward directions. The relative backscattering decreased with increasing distance offshore, with computed backscattering ratios (over the defined angular range) from 1.2% to 0.3%. The Petzold phase function, derived by Mobley (1994), is shown for reference; only in the stations closest to shore was this function approached in the backward hemisphere.

This is also evident in the vertical sections, where variation in the VSF over the small-angle range was most prevalent at a site where upwelling of deep water fueled growth of phytoplankton, particularly large cells that could potentially contribute strongly to the forward scattering and that were in greatest abundance at a depth of 4 m at this station (Fig. 7a). All depths showed backscattering probabilities less than the Petzold phase function, with the deeper stations showing the largest departure (b_b = 0.53% at the sea surface and 0.39% at 4 m). A pronounced ''glory'' in the near-backward direc-

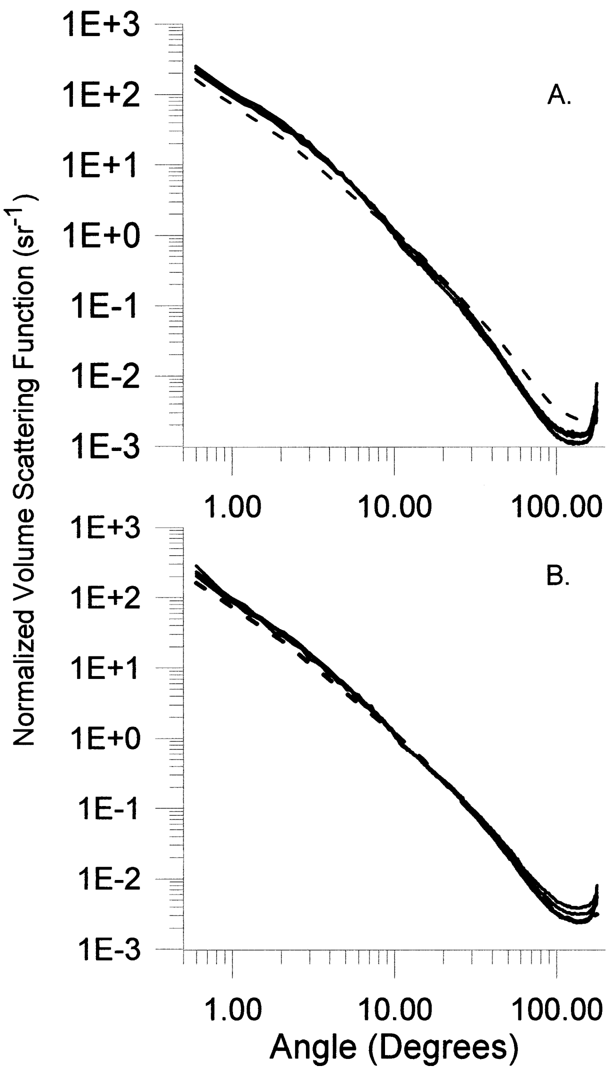

FIG. 7. Vertical variations in the normalized VSF (similar to phase function—see text) in waters off the New Jersey coast. (a) Variations at an offshore station (39°28′N, 74°15′W); depths of 0.5, 2, 3, and 4 m are represented. The smallest relative backscattering is found at depth. (b) Variations at a shallow (4-m water depth) station (39°30′N, 74°17′W); depths of 0.5, 1.5, 2.5, and 3.5 m are represented. The highest relative backscattering is found at depth. In both panels, the Petzold phase function (Mobley 1994) is provided for reference (dashed line).

tion was observed. Another case, wherein measurements were made in very shallow water (<4 m) over a sandy bottom, is shown in Fig. 7b. From the curves demonstrated in this figure, one can see a small but regular increase of backscattering with depth (b_b = 0.90% at the sea surface and 1.35% at 3.5 m) that may have resulted from resuspension of particles toward the bottom. In this case, the measured values approached those of Petzold (~1.8%).

The full VSF (and associated true phase function) can be obtained by extrapolation of the observations in the near-forward direction to 0° through a power-law dependency and to the full-backward (e.g., 180°) direction by assuming constant values of the VSF between 177.3° and 180° (e.g., Mobley et al. 2002). The angular integrated values of the total scattering coefficient b and the backscattering coefficient b_b thus derived were found to be in excellent agreement (within 8%) with independent measurements of the particulate scattering coefficient and backscattering fraction (Mobley et al. 2002); use of the directly measured volume scattering coefficient in advanced radiative transfer models provided close agreement with direct measurements of the radiance distribution and other apparent optical properties, such as the diffuse attenuation coefficient and the reflectance (Mobley et al. 2002).

It is clear that, for the near-forward, general, and near-backward regions, the volume scattering coefficient is not a conservative property in either amplitude or angular dependence, even over this limited geographical region, and, based on scattering theory, not in the spectral domain either. In particular, because of the great variability of the VSF in small-angle ranges and near 180°, it is difficult to describe the shape of the VSF by a single model, or even a family of parametric models, over the full angular range.

6. Conclusions

1) We developed and implemented new principles for the measurement of the volume scattering function of the ocean that are capable of measuring the angular scattering over the full angular range of 0.6°–177.3° and to a resolution of 0.3°.
2) We successfully tested the instrument under controlled conditions, using scattering suspensions of known properties; results are consistent with theoretical scattering estimates based on Mie theory.
3) We deployed the device in the coastal waters of the North Atlantic and made some of the first measurements of the entire VSF of natural oceanic waters since the early 1970s. A high degree of environmental variability was found in the VSF, particularly in the near-forward and near-backward directions. These measurements clearly show that the use of a single (or even a family of) volume scattering function(s) for the modeling of radiative transfer will introduce error.
4) These results are of high and perhaps profound significance for the understanding and prediction of the propagation of radiation in the sea and have implications for applications as diverse as determinations of the upper-ocean heat balance and laser ranging of subsea conditions.

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