

## Laboratory measurements of light scattering from marine particles

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### Abstract

We present an improved technique for measurements of the volume-scattering function (VSF) for marine particles, which include added spectral information, a novel optical design of the sample container, and two new ways of eliminating unwanted reflections. The novel optical design enables us to measure an angular range comparable to the largest angular range previously reported. Our improved setup eliminates the need for an empirically based data correction and reveals interesting characteristics of the VSF for different phytoplankton species. Measurements with our improved setup provide information that is important to understand and simulate radiative transfer in the ocean.

Oceans cover about 70% of the surface of the Earth and represent an important source of food. To obtain information about primary production, propagation of phytoplankton blooms, nutrient status, and temperature, the marine environment is continuously monitored both in situ and from satellites. In this context, in situ optical measurements are indispensable because they are fast and suited for automated routine operation. Among the most commonly measured parameters in situ are the absorption and attenuation coefficients, the diffuse attenuation coefficient for downwelling irradiance, and natural fluorescence. From satellite measurements, one can estimate the water-leaving radiance, and in the laboratory, the chlorophyll concentrations of water samples can be measured by fluorometric or spectrophotometric methods.

The volume-scattering function (VSF) is an important optical property that is not routinely measured. Thus, the measurements of Petzold (1977), which date back to the 1970s, are still commonly used to represent the VSF for seawater. Among the laboratory measurements of the VSF relevant for our study, the data obtained by Privoznik et al. (1978) and Morel and Bricaud (1986) should be emphasized. They conducted their investigation on a suspension of small phytoplankton

cells. Quinby-Hunt et al. (1989), Król et al. (1992), and Witkowski et al. (1993) measured the full Mueller matrix of suspensions of a few phytoplankton species. Voss and Fry (1984) measured the full Mueller matrix for natural ocean water samples from different locations. Lofftus et al. (1992) measured the full Mueller matrix of immobilized single cells, and recently MacCallum et al. (2004) made measurements of narrow-angle scattering from three phytoplankton species. Narrow-angle measurements have been performed in situ on depth profiles by using a LISST-100 instrument (Sequoia Scientific) by Agrawal (2005). Vaillancourt et al. (2004) reported measurements of the VSF for eight different phytoplankton species performed with the commercially available Dawn EOS instrument from Wyatt Technology Corporation. Volten et al. (1998) measured the VSF as well as the  $F_{12}$  element of the Mueller matrix for 15 different phytoplankton species and 2 different ensembles of silt particles. Lee and Lewis (2003) and Zhang et al. (2002) presented a recently developed instrument with the capability of measuring the VSF in the angular range from  $0.6^\circ$  to  $177^\circ$ . This instrument can be used both for in situ applications and laboratory measurements. Most of the reported measurements of the VSF have a limited angular range, either from about  $20^\circ$  to  $160^\circ$  or for a narrow range of forward angles. Only the measurements of Petzold (1977) and those of Lee and Lewis (2003) and Zhang et al. (2002) include both narrow forward angles and intermediate angles.

Many of the measured VSFs for phytoplankton are monotonically decreasing with increasing angle up to at least  $135^\circ$  and show no oscillations. However, one measurement by Volten et al. (1998) and two of the measurements by MacCallum et al. (2004) have interesting features in which there are oscillations in parts of or in the full angular range of the VSF.

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Our experimental setup has some improvements compared to many earlier ones, enabling us to measure the VSF in the angular range from  $3^\circ$  to  $171^\circ$  with excellent agreement between measured and theoretical results. Others have reported measurements with a cylindrical sample container (Quinby-Hunt et al. 1989, Volten et al. 1998), but not with results for angles smaller than  $20^\circ$ . The Dawn EOS instrument has a different design than most setups and provides measurements for angles down to  $10^\circ$  but only in angular steps of  $10^\circ$ . MacCallum et al. (2004) reported forward scattering but their setup prevents them from measuring at intermediate and backward angles. The instrument described in Lee and Lewis (2003) and Zhang et al. (2002) can measure a larger angular range than our setup. However, they have not shown correspondence between experimental data and theoretical simulations for angles smaller than  $12^\circ$ .

In the backward direction, unwanted specular reflections constitute the major source of error. Volten et al. (1998) discussed a method to correct the measured data for such reflection errors. Their method, however, relies on an empirical correction factor, which may depend on factors such as the optical thickness of the scattering sample and the shape of the VSF. With our method, no such correction is necessary, and therefore, our results are less influenced by methodological artifacts. Our method involves careful redirection of the incident beam and tilting of the detector to avoid the influence from unwanted specular reflections.

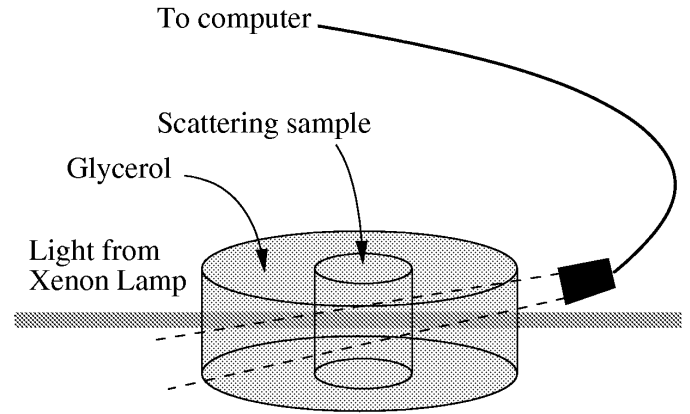
The spectral variation of the VSF for marine phytoplankton has not been systematically studied. Our measurements show that the spectral variation contains valuable characteristics specific to each type of particle.

Most of the previous measurements provide the VSF in angular steps of about  $5^\circ$  or  $10^\circ$ . Our method provides the VSF in angular steps of  $1^\circ$ , which is required in order to capture its full characteristics.

### Materials and procedures

Our experimental setup consists of two concentric cylindrical glass containers, as shown in Fig. 1, each having a refractive index of 1.5. Ordinary glass was chosen instead of Plexiglas because of the birefringent nature of the latter. The outer diameter of the outer cylinder is 315 mm, and the outer diameter of the inner cylinder is 90 mm. The wall thickness of the inner and outer cylinder is 2.8 mm and 6.8 mm, respectively. The space between the two cylinders is filled with glycerol (pro analysis) with a refractive index of 1.48.

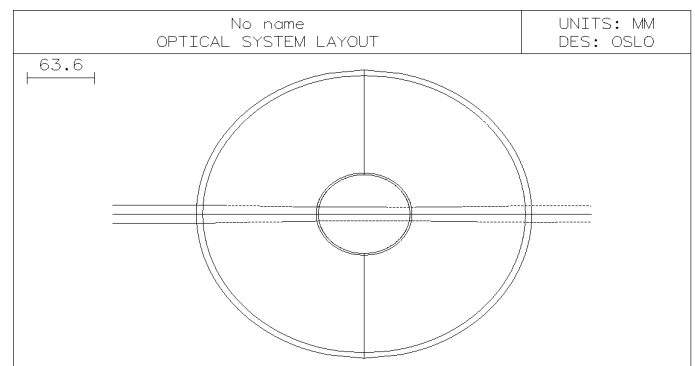
The optical design of the sample container is shown in Fig. 2. A collimated light beam is incident upon the outer cylinder and is refracted toward the optical axis. The refracted beam is incident upon the inner cylinder and is refracted away from the optical axis upon entering it. Large glass cylinders are available in certain sizes, but by choosing an optimum combination of cylinder diameters, we can obtain a system such that an externally collimated incident light beam remains collimated



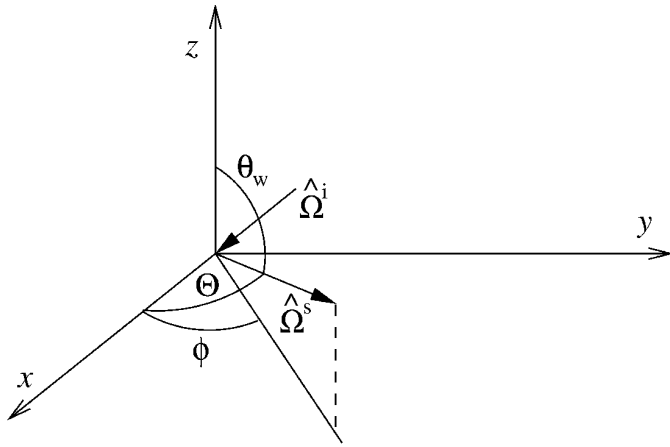
**Fig. 1.** Experimental setup

inside the inner cylinder. Light scattered in a given direction inside the inner cylinder will then have the same direction after leaving the outer cylinder. With this arrangement, we avoid undesirable spreading of the incident beam, which would degrade our measurements. To find an optimal combination of cylinder diameters, we used a commercial lens design program. We note that it would be possible to do this correction by placing a cylindrical lens in the collimated light beam in front of the container or, alternatively, having a flat entrance window combined with a cylindrical lens in front of the detector. Compared to such a method, our method has two advantages. First, we avoid additional reflecting and scattering optical elements, and second, we avoid unwanted specular reflections close to the scattering volume. The second advantage was pointed out by Volten et al. (1998).

Light from a LQX 1000 Xenon lamp is guided through an optical fiber and is collimated before it enters the glass container. The full angular divergence of the light beam leaving the collimator is about  $4^\circ$ . We use interference filters with out-of-band blocking and a bandwidth of 10 nm to obtain almost monochromatic light at wavelengths of 442 nm, 490 nm, 550 nm, and 670 nm. The wavelengths were chosen to correspond to bands 2, 3, 5, and 6 of the SeaWiFS sensor on the Orbview2 satellite.



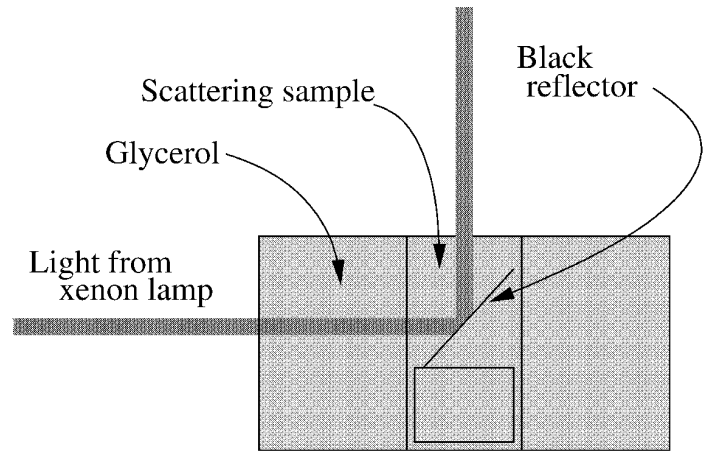
**Fig. 2.** Optical design of the experimental setup



**Fig. 3.** The scattering angle  $\Theta$

An absolutely calibrated silicon photodiode optometer, s370 from Graseby Optronics, is placed on a goniometer ring with a diameter of 62 cm. In front of the detector, a lens with a diameter of 28 mm and a focal length of 30 mm focuses the light onto a 2.0 mm aperture. This means that the full acceptance angle of the detector is  $3.8^\circ$ . We conduct measurements at each  $1^\circ$  from  $3^\circ$  to  $171^\circ$ . At each angle, we conduct approximately 6 measurements and use the average of these. The choice of 6 measurements at each  $1^\circ$  is a tradeoff between data quality and speed. With this configuration, it takes about 2 h to complete measurements for all angles and 4 wavelengths. The noise level of the detector defined as the standard deviation of the dark current measurements, is  $4.6 \times 10^{-12}$  W. Specular reflections may represent a problem in light-scattering measurements, but by carefully designing the setup, one may avoid most of them. Since light is incident normally upon the outer cylinder surface, it will be reflected in directions lying in the plane spanned by the incident light direction and the surface normal. Thus, by raising the detector  $4^\circ$  above this plane, most of the reflections will disappear. The scattering angle  $\Theta$  is related to the azimuth angle  $\phi$  and the polar angle  $\theta_w$  as shown in Fig. 3. Light is incident along the  $x$  axis with unit vector  $\hat{\Omega}_i = \hat{e}_x$ . The detected light is traveling in the direction of the unit vector  $\hat{\Omega}_s = \sin\theta_w \cos\phi \hat{e}_x + \sin\theta_w \sin\phi \hat{e}_y + \cos\theta_w \hat{e}_z$ . The scattering angle  $\Theta$  is therefore given by  $\cos\Theta = \sin\theta_w \cos\phi$ . The angle  $\theta_w$  in water is related to the angle  $\theta_a$  (not shown in Fig. 3) in air through Snell's law.

However, there is still a problem with light that is first scattered and then reflected and light that is first reflected and then scattered. This problem is most severe for scattering angles larger than  $90^\circ$ . When measuring at such angles, we introduce a black Plexiglas plate with a glossy surface inside the scattering volume. It reflects light vertically out of the container (see Fig. 4). The material giving the black color of the Plexiglas plate must not contain scattering pigments. We found that a black permanent marker fibertip pen from Penol gave the most absorbing and least scattering black color. It also



**Fig. 4.** A black reflector is absorbing and reflecting the incident light beam.

gave a glossy surface which specularly reflected that part of the incident beam, which was not absorbed. However, the black color degraded with time, so that we had to renew it before each series of measurements. It may also cause problems that the upward reflected beam scatters light in the direction of the detector. To predict the influence of this unwanted scattering contribution, we calculated the reflection coefficient. We assumed that the refractive index of the ink was about the same as that of glass, ie,  $n_g = 1.5$ , and that the refractive index of water was  $n_w = 1.33$ . The light was incident upon the plate at an angle of incidence  $\theta^i$  of  $45^\circ$ . According to Snell's law, the corresponding angle of transmission  $\theta^t$  is  $38.9^\circ$ . Thus, from Fresnel's formulae (Born and Wolf 1997) for unpolarized incident light the reflection coefficient  $R$  is

$$R = \frac{1}{2} \left( \frac{\tan^2(\theta^i - \theta^t)}{\tan^2(\theta^i + \theta^t)} + \frac{\sin^2(\theta^i - \theta^t)}{\sin^2(\theta^i + \theta^t)} \right) = 0.0058,$$

which shows that scattering contribution due to the reflected beam is less than 1% of the scattering contribution due to the direct beam. Therefore, we may neglect this effect.

The volume viewed by the detector changes with the scattering angle  $\Theta$ . Also, the scattering volume  $V_{\Theta < 90^\circ}(\Theta)$  for scattering angles smaller than  $90^\circ$  is different from the scattering volume  $V_{\Theta > 90^\circ}(180^\circ - \Theta)$  for scattering angles larger than  $90^\circ$  because of the black reflector used in the latter case. Relative to  $V_{\Theta < 90^\circ}(90^\circ) \approx 12 \text{ cm}^3$ , the scattering volume for angles between  $29.1^\circ$  and  $90^\circ$  is equal to  $1/\sin\Theta$ . For angles smaller than  $29.1^\circ$ , the scattering volume monotonically increases to its maximum value  $V_{\Theta < 90^\circ}(0^\circ)$ , which is defined as the scattering volume seen by the detector as it looks into the direction of the incident beam. In the angular range from  $0^\circ$  to  $29.1^\circ$ , we interpolate to get a smooth curve for  $V_{\Theta < 90^\circ}(\Theta)$ . The volume  $V_{\Theta < 90^\circ}(0^\circ)$  and the angle  $29.1^\circ$  where the  $1/\sin\Theta$  relation is no longer valid are chosen to minimize the difference between the measurements and the calculated values of the VSF for Dynospheres. The Dynospheres were manufactured by Dyno Particles AS, and the concentration and diameter of the spheres were  $1.38 \times 10^{11}$  particles per milliliter and  $2.0 \mu\text{m}$ , respectively.

Without the black reflector, the scattering volume is symmetric about  $90^\circ$ . However, the black reflector approximately halves the scattering volume, implying that  $V_{\theta > 90^\circ}(180^\circ - \theta) = C(\theta) + V_{\theta < 90^\circ}(\theta)/2$ , where the extra term  $C(\theta)$  is small and varies little with the scattering angle  $\theta$  so that we may put it equal to a constant  $C$ . To determine the value of  $C$ , we force the VSF to be continuous across  $\theta = 90^\circ$ :  $VSF_{\theta > 90^\circ}(90^\circ) = VSF_{\theta < 90^\circ}(90^\circ)$ .

Before each scattering experiment, we measured the background signal. For Dynospheres, the background was  $0.22 \mu\text{m}$  filtered MilliQ-water, and for phytoplankton it was  $0.22 \mu\text{m}$  filtered seawater. The background signal was subtracted from the scattering measurement, where after the remaining signal was divided by the scattering volume to yield the VSF.

We followed a procedure similar to that of MacCallum et al. (2004) to ensure that the optical thickness of the scattering sample was less than 0.1 (van de Hulst 1957), so that we may ignore multiple scattering. To keep the particles (Dynospheres or phytoplankton) suspended with uniform concentration, we used a magnetic stirrer.

The alignment of the setup was done in several steps. First, we made sure that the incident light beam propagated in a direction normal to the surface of the outer cylinder and that the axis of the incident light beam passed through the common axis of the cylinders. We then put the detector into the scattered light beam and rotated its viewing direction horizontally until we obtained maximum intensity. Next, we rotated its viewing direction vertically to obtain maximum intensity. The experimental setup includes a system of stepper motors by which one can vary the viewing direction of the detector both vertically and horizontally in predefined angular steps.

We cleaned the container between each measurement by first flushing it with MilliQ water. We then flushed it with ethanol to clean the glass surface and to remove remaining phytoplankton, and finally we flushed it once again with MilliQ water to remove the ethanol.

We used batch-cultured cells of the diatoms *Chaetoceros calcitrans* and *Phaeodactylum tricorutum*, of the dinoflagellate *Protoceratium reticulatum*, and of the blue-green algae *Synechococcus* sp. The algal cultures were preadapted to a light intensity of about  $100 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , provided by 40W fluorescent light tubes. With the exception of *P. reticulatum* that was grown at a temperature of  $15^\circ\text{C}$ , the algal cultures were grown at  $20^\circ\text{C}$ . All cultures were grown in nutrient-enriched  $0.22 \mu\text{m}$  filtered natural seawater. Cell density and size were monitored using a Coulter counter (Beckman Coulter, Multisizer™ 3), and the cell counts were verified against microscopic cell counts in Fuchs-Rosenthal counting chamber. The cultures were harvested at mid-exponential growth, and the optical measurements were commenced immediately. The size and volume of the Dynospheres were verified by using the Coulter counter. In addition to the VSF, we measured the absorption and attenuation coefficients of the algal cultures with an AC9 instrument from Wetlabs. The temperature in the optics laboratory varied between  $20^\circ\text{C}$  and  $23^\circ\text{C}$ .

**Table 1.** Size and concentration of the four species of phytoplankton investigated

Name	$r$ [ $\mu\text{m}$ ]	$std$ [ $\mu\text{m}$ ]	Concentration [ $\mu\text{m}$ ]
<i>Chaetoceros calcitrans</i>	1.82	0.22	$1.7 \times 10^4/\text{ml}$
<i>Phaeodactylum tricorutum</i>	1.72	0.23	$5.9 \times 10^4/\text{ml}$
<i>Protoceratium reticulatum</i>	12.1	2.7	$5.7 \times 10^3/\text{ml}$
<i>Synechococcus</i> sp.	0.85	0.12	$2.2 \times 10^4/\text{ml}$

$r$  and  $std$  are the mean radius and the standard deviation of the radius as measured with a Coulter counter. The mean radius of *Protoceratium reticulatum* is the average of three light microscopy measurements.

To analyze the influence of fluorescence and Raman scattering from microalgae, we placed a Ramses ARC Hyperspectral radiance sensor at a scattering angle of  $90^\circ$ . In this case, we used the haptophyte *Isochrysis galbana*, the dinoflagellate *Karlodinium micrum*, and the diatom *P. tricorutum*. When measuring the VSF at 670 nm, we may neglect these inelastic scattering effects (Mobley 1994).

## Assessment

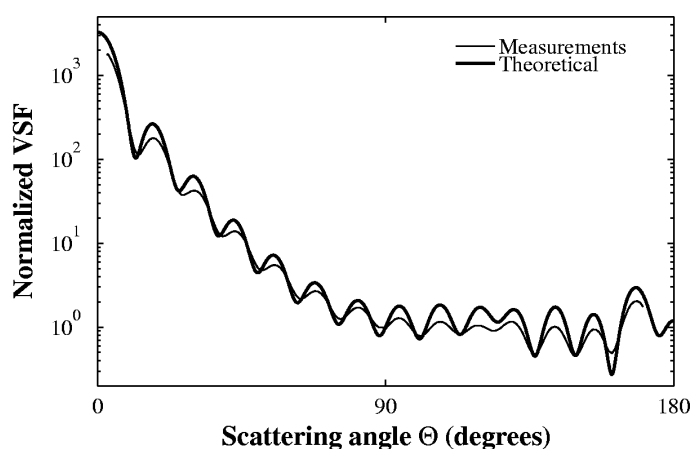
Now we present measurements at four different wavelengths of the VSF for the four selected phytoplankton species as well as for the Dynospheres (see Material and procedures). The mean radius, the standard deviation of the radius, and the concentration of the four species are listed in Table 1.

These four species were chosen because they have different optical properties, which are expected to influence the VSF. Factors that are expected to influence the VSF are cell size and composition of the cell envelope. All of our main test algae have a wall (Table 2). In the case of diatoms (e.g., *Chaetoceros calcitrans* and *Phaeodactylum tricorutum*), the wall mostly consists of polymerized silic acid; in the case of the dinoflagellate *Protoceratium reticulatum*, it consists of cellulose; and in the case of blue-green algae (e.g., *Synechococcus* sp.), it consists of murein (a peptidoglycan) and lipopolysaccharides. Haptophytes (e.g., *Isochrysis galbana*), on the other hand, are don't have a wall, but the surface of the cell is covered with tiny organic scales. In addition, there are calcified scales in the case of coccolithophorids. Also some of the dinoflagellates are without (e.g., *Karlodinium micrum*).

According to Aas (1996), the water content of microalgae is one of the main factors determining its refractive index. Besides

**Table 2.** Shape and composition of the four species of phytoplankton investigated

Name	Cell wall	Vacuoles	Shape
<i>Chaetoceros calcitrans</i>	$\text{SiO}_2$	Liquid	Cylindrical
<i>Phaeodactylum tricorutum</i>	$\text{SiO}_2$	Liquid	Needle
<i>Protoceratium reticulatum</i>	Cellulose	Not present	Spheroidal
<i>Synechococcus</i> sp.	Murein, lipopolysaccharides	Not present	Spherical



**Fig. 5.** VSF of Dynospheres, theoretical and experimental values. Theoretical values are computed with a diameter of 1.96  $\mu\text{m}$ .

this, an algal cell contains many different organelles, which possess their own membrane systems (e.g., chloroplasts, mitochondria, golgi bodies, endoplasmic reticulum, eyespot). It also contains support structures (e.g., microtubuli, flagellar apparatus) and storage products (e.g., starch grains, lipid droplets). All these constituents may influence the refractive index. Also, liquid vacuoles, in general, and gas vacuoles among some blue-green algae will cause the effective refractive index of phytoplankton species to differ from that of the surrounding medium (water). *Synechococcus* sp., however, does not have gas vacuoles, and liquid vacuoles are not prominent among blue-green algae and dinoflagellates (Table 2). Shape also affects the VSF, and it is of interest to determine whether the external shape of a species is sufficient to explain its VSF or whether one has to take into account also its complex internal structure.

In our study, we chose to conduct measurements on phytoplankton species that have different values for some of these parameters to determine whether they influence the VSF. From Table 1, we see that for three of the four phytoplankton species being investigated, the size was relatively equal, but *Protoceratium reticulatum* was one order of magnitude bigger.

Figure 5 shows experimental and theoretical results at 550 nm for the VSF for Dynospheres. The theoretical values are computed with Mie theory. According to the manufacturer (Dyno Particles AS), the diameter of the particles was  $d = 1.98 \mu\text{m}$ , but a diameter of  $d = 1.96 \mu\text{m}$  gave better agreement between experimental and theoretical values for the VSF. The root-mean-square error between the measurements and the calculated values using Mie theory was 15% to 17%. The refractive index at 550 nm is 1.5959 in pure water. We used a concentration of  $4.15 \times 10^6$  particles per milliliter.

The agreement between theoretical and experimental values is good, except that the experimentally obtained maxima and minima are less pronounced than the theoretical maxima and minima. These discrepancies have two possible explanations. First, they may be caused by the finite detector accept-

ance angle of  $3.8^\circ$  and the divergence of incident light beam of  $4^\circ$ . Second, we inspected the spheres using a microscope and found that some of them were forming aggregates. From Coulter counter measurements we found that the fraction of bispheres was 22%, whereas the fraction of trispheres was less than 10%. From Mie theory calculations we have seen that the presence of aggregates lead to a smoothening of the VSF. The agreement is good for angles in the range from  $3^\circ$  to  $171^\circ$ , which is a quite large range to cover in one single experiment.

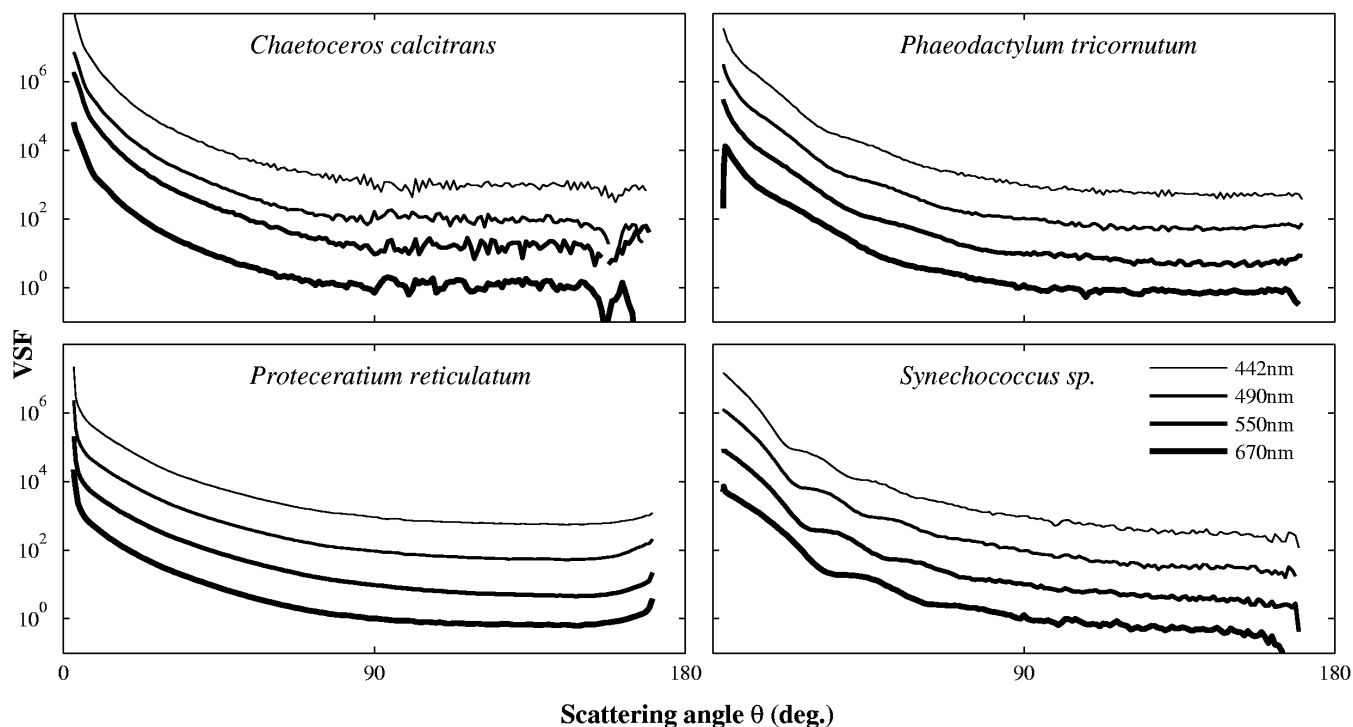
Figure 6 shows VSFs at four different wavelengths for the four different phytoplankton species investigated. The VSFs for *Chaetoceros calcitrans* and *Phaeodactylum tricorutum* show little wavelength dependence, whereas the VSFs for *Synechococcus* sp. depend strongly on the wavelength. The VSF is more forward peaked at the shorter wavelengths, and the positions of the shoulders of the VSF also change with the wavelength. This is probably due to the fact that the size parameter of a given phytoplankton species increases as the wavelength decreases. It is therefore expected—and in agreement with experiments—that the VSF at shorter wavelengths should be more forward peaked than at longer wavelengths.

Some of the measurements on phytoplankton in Fig. 6 suffer from noise in the angular range from  $90^\circ$  to  $171^\circ$ . This is because the noise level of the detector is  $4.6 \times 10^{-12}$  W, and the intensity of the measured light can be as low as a few times this value. For samples with very low backward scattering, such as the measurements on *Chaetoceros calcitrans*, one can therefore question whether 6 measurements on each angle is enough to adequately average out the noise.

Dynospheres have a higher refractive index than phytoplankton and, therefore, a higher degree of backscattering. Hence, Dynospheres give a stronger signal than phytoplankton in the angular range between  $90^\circ$  and  $171^\circ$ .

The VSFs for *Chaetoceros calcitrans* and *Phaeodactylum tricorutum* are strongly forward peaked and very similar to the VSFs reported by Petzold (1977) for natural seawater. It is somewhat surprising that the VSFs for these two phytoplankton species are so similar, bearing in mind their different shapes. *Chaetoceros calcitrans* has a cylindrical shape and a more or less equal extent in all directions, while *Phaeodactylum tricorutum* is needle-shaped. In contrast to the VSFs for these two species, the VSF for *Synechococcus* sp. at, for example, 442 nm has a specific “signature” with a pronounced shoulder from  $25^\circ$  to  $30^\circ$  and another less pronounced shoulder from  $40^\circ$  to  $50^\circ$ . It is definitely a necessity to sample in angular steps of 1 in order to identify and describe the extent of these shoulders. *Synechococcus* sp. is about half the size of the other two phytoplankton species, and this is probably the main reason for the observed differences between the VSFs.

Figure 7 shows the intensity measured with a Ramses ARC Hyperspectral radiance sensor at a scattering angle of  $90^\circ$ . The measurements are normalized to the maximum intensity. The highest peak is at 490 nm, which is the wavelength of the incident light. For one of the phytoplankton species, *Karlodinium*



**Fig. 6.** VSFs for the four species of phytoplankton investigated at four different wavelengths. The VSFs for the different wavelengths are multiplied with constant factors of 1000, 100, 10, and 1 to make them distinguishable.

*micrum*, we see a less pronounced peak at about 680 nm, which corresponds to fluorescence from chlorophyll. However, this peak is only about 10% of the main peak at 490 nm due to elastically scattered light, even at a scattering angle of 90°, where the elastically scattered light has its lowest value.

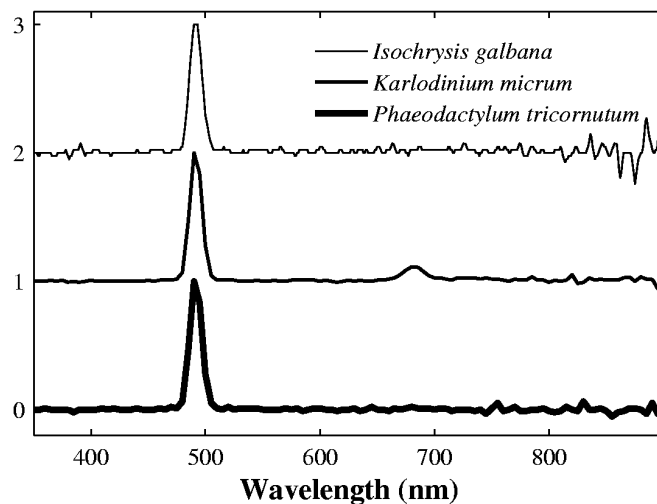
In order to find out whether the VSF changed over time, we performed a repeated measurement on *Heterosigma akashiwo* (not shown) and *Chaetoceros wighamii* (not shown) on the angular range from 3° to 90°. The time between the measurements was 1 h and 1 h 50 min, respectively. The corresponding root-mean-square change between the measurements was 4% and 16%. There are, in other words, significant changes in the VSF over time, which we must bear in mind.

### Discussion

The intensity of the measured signal at angles larger than 90° is of the same order of magnitude as the level of the background noise. Better results would therefore have been obtained with a detector of higher sensitivity. Many of the previous measurements by others have been performed with a photomultiplier, which is more sensitive than the absolutely calibrated silicon photodiode optometer we chose to use.

Instead of using a white light source like the one we had at our disposal, one could use highly collimated, high-intensity, monochromatic laser light to obtain improved measurements. However, short-wavelength, high-power lasers are still expensive.

If one were to do measurements on a routine basis or measurements in the field, one would need a more portable sample container. Based on the same principles as those applied to design our sample container, one could make a smaller glass cylinder with thick glass walls instead of glycerol. Such a glass



**Fig. 7.** Radiances in relative units measured at 90° from three different types of phytoplankton. Constant values of 2, 1, and 0 are added to the radiances to make the lines distinguishable.

cylinder would be easier to carry and to clean, but would probably be more expensive to produce.

Simultaneous measurements on all angles would represent an improvement due to the fact that the VSF changes with time. By measuring at all angles simultaneously, one could speed up the measurement and thereby reduce this effect.

We have shown that our experimental setup for measurement of the VSF gives good agreement with theoretical results. Due to the accuracy, the angular sampling interval of 1°, and the extended angular range from 1° to 171°, we have revealed new and interesting features of the VSFs for the four types of phytoplankton species investigated.

These features might in the future be used as an extra parameter in phytoplankton recognition and classification characteristics, but this requires a thorough investigation of VSFs of a large number of different phytoplankton species. It is a difficult task to classify phytoplankton species with sizes comparable to that of the wavelength of light. Existing classification methods include analyses of absorption spectra, biochemical composition, DNA, and electron microscopic identification. The first two of these three methods give no unique classification, and the third and the fourth is time-consuming. It is, therefore, of great interest to investigate whether light-scattering measurements can be added as a new, relatively fast, and non-invasive method of classification.

If extended to include polarizers, phase modulators, and lock-in amplification, as described by Volten et al. (1998), the setup described here may also be applied to measure the full Mueller matrix. Although the scattered light leaves the cylinder at a small angle to the surface normal, this should have little influence on the results, since, at small angles of incidence, the transmission coefficients for vertically and horizontally polarized light are nearly equal. By measuring the full Mueller matrix, one can use the results in vectorized radiative transfer simulations, which give a more complete and correct description and may lead to new classification characteristics.

Future work with the same setup as described here should include measurements of the VSFs for more phytoplankton species, chosen systematically to include different parameters that might be expected to influence the VSF. It is also of interest to determine to what extent the VSF for a given phytoplankton species is reproducible and to what degree it depends on growth phase and the growing conditions, such as light, nutrition, temperature, and salinity.

In the current study, we have shown a new experimental setup for measuring the volume scattering function for marine particles. The measurements show us that the VSF has different shape for different types of algae. Further measurements on different types of algae can therefore make a valuable database.

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