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Spectral dependence of the correlation between the backscattering coefficient and the volume scattering function measured in the southern Baltic Sea

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Abstract

Direct measurements of the backscattering coefficient b_b require the determination of the Volume Scattering Function (VSF) and its integration over a backward hemisphere. In sea water they are difficult and are therefore carried out very rarely. That is why the backscattering coefficient is much more frequently obtained with so-called single angle scattering meters: these operate by measuring the VSF for a fixed angle region of the backward hemisphere. This article examines the spectral variability of the correlation between directly measured backscattering coefficients and VSFs. Also presented are the averaged slopes of VSF spectra, measured in southern Baltic waters over a wide range of scattering angles.

1. Introduction

The Volume Scattering Functions (VSF), a topic of interest to marine optics researchers for several decades, are still the least-known optical properties of sea water. The difficulties connected with their measurement (or rather with the design of the scattering function meter) begin with the large variability of measured values, which can reach as much as six orders of magnitude between small-angle forward scattering and scattering in backward directions. This results in the need for a high-sensitivity light receiver or a changeable amount of light illuminating the scattering volume. The next problem is to balance the capacity of the scattering volume. If the

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scattering volume is too small, then the small number of big particles flowing through the light beam causes the measured signal to be unstable. On the other hand, a large scattering volume capacity leads to decreasing angular resolution, or else requires a larger instrument (see Petzold 1972). Another problem is to obtain as wide a range of angles as possible. When light is scattered into small forward angles it is difficult to distinguish between the scattered light and the illuminating beam. That is why the so-called small angle problem can be solved by using a separate instrument. This was the way chosen by Petzold (1972), and nowadays this can be done on a modern instrument (see Slade & Boss 2006). On the other hand, when the light receiver moves close to 180° it shades the illuminating beam and limits the range of measurement. Because of these limitations a typical polar nephelometer can measure the VSF from 5° or 6° to about 170°. This is the range covering at least 50% of the scattered light. a review of many known constructions will be found in Jonasz & Fournier (2007).

The largest range of scattering angles was obtained with a prototypical version of the Multispectral Volume Scattering Meter (MVSM) (see Lee & Lewis 2003). Because this instrument uses a rotational prism of special shape, the unusual range from 0.5° to 179° with a 0.25° step was obtained. Unfortunately, because of the uniqueness of measurements made with the MVSM, the variability of VSFs is still poorly known. That is why even partial information about the scattering properties of sea water is very valuable.

There are a few optical properties of a medium that can be calculated from the VSF. The first is the scattering coefficient, which describes the fraction of light that changes direction per unit of length of its propagation. Operationally, it is the VSF integrated over all directions. But nowadays in sea water the scattering coefficient is usually obtained as the difference between the attenuation and absorption coefficients (measured by ac-9 or ac-s (WET Labs)). Another of these properties is the backscattering coefficient b_b, which is the VSF integrated over the backward hemisphere. Knowledge of b_b is very important because of its relation to remote sensing reflectance (Gordon et al. 1988). The above difficulties persuaded researchers to look for a simplified method of obtaining these values. The first such attempt was by Jerlov (1953), who tried to establish a link between the scattering coefficient b and scattering into the 45° angle. His dependence turned out to be erroneous, however, because at least 50% of the light is scattered into angles smaller than 5°. That is why the scattering coefficient cannot be approximated by the scattering function for a scattering angle as wide as 45. Later papers associated the scattering coefficient b with scattering into a much smaller angle of 4°. The first correlation based on measurements was presented by Mankovsky (1971). Morel (1974), who used the Mie model (an analytical solution of electromagnetic wave interaction with spherical particles), showed that the ratio $\beta_p(4°)/b_p$ changes only slightly with the refractive index and the particle size distribution. Recent measurements by Chami et al. (2005) show a linear correlation between the values of $\beta_p(4°)$ and the scattering coefficient b_p.

As with the scattering coefficient b, links between the backscattering coefficient b_b and scattering functions β were sought. One of the first to address the problem was Oishi (1990), who used modelling methods to show that the scattering function for an angle of 120° gave the best linear correlation with b_b. Modelling was carried out with Mie algorithms for various refractive indices and different particle size distributions. In his paper, Oishi published some measurements that confirmed the results of calculations. The optical scheme of an instrument for determining the backscattering coefficient on the basis of $\beta(140°)$ measurements was presented by Maffione et al. (1991) and Maffione & Dana (1997). The designs of the latter authors were incorporated into commercially available instruments. In response to that latter paper Boss & Pegau (2001) supplied new arguments to justify Oishi's ideas. Like Maffione & Dana (1997) they used the non-dimensional quantity $\chi(\theta, \lambda)$, the definition of which includes the ratio of the backscattering coefficient b_b to the volume scattering function for various scattering angles:

$$\chi(\theta, \lambda) = \frac{b_b(\lambda)}{2\pi\beta(\theta, \lambda)}. \tag{1}$$

Boss & Pegau (2001) analysed the variability of $\chi(\theta)$ for clean sea water and for suspensions. They also used new measurements and stated that the most accurate approximation of the backscattering coefficient could be obtained with measured $\beta(117°)$. Other instruments were designed, enabling b_{bp} to be obtained on the basis of the measurement of light scattered into angles around 117°. Sullivan & Twardowski (2009) recently carried out research based on a very large number of measurements. They showed that the strongest correlation between backscattering coefficient and volume scattering function was obtained for scattering angles in the 110°–120° range. An interesting spectral analysis of the function $\chi(\theta, \lambda)$, based on measurements made with the previous version of a prototypical volume scattering meter for Black Sea water and selected phytoplankton cultures, was presented by Chami et al. (2006). They considered the particle-affected function χ for scattering angles 120° and 140°, concluding that $\chi_p(120°)$ was spectrally less dependent than $\chi_p(140°)$; the former is therefore recommended, especially during phytoplankton blooms.

The retrieval of backscattering coefficients from measured volume scattering functions is discussed below on the basis of VSFs measured in the southern Baltic. The aim of this article is to demonstrate the dependence of the function χ_p on wavelength, which has not been investigated before in Baltic Sea water.

2. Material and methods

The measurement data were collected during a cruise on the r/v 'Oceania' in May 2006. The Volume Scattering Functions (VSFs) of sea water (denoted by β for historical reasons) were measured at 42 locations in the southern Baltic. The data set consisted of various water types: turbid surface water taken near a river mouth, coastal water, open sea water and clean water from various depths. The prototype of MVSM designed and built at the Marine Hydrophysical Institute of the National Academy of Science in Sevastopol (Lee & Lewis 2003) was used for this purpose. The measurements, made at four wavelengths (443, 490, 555 and 620 nm), were previously presented in part by Freda et al. (2007) and were used to obtain an improved parameterization of the Fournier-Forand Phase Function (see Freda & Piskozub 2007). During the processing of the signal from the MVSM, the clean sea water contribution was subtracted (see Morel 1974). Thus, all the volume scattering functions, scattering and backscattering coefficients presented in this paper refer to particles suspended in sea water, hence the subscript p. The high angular resolution (0.25°) and the wide angular range of measured particle VSFs (from 0.5° to 179°) enabled accurate and direct calculations of the particle scattering coefficients b_p and the particle backscattering coefficients b_{bp}:

$$b_p = 2\pi \int_0^{\pi} \beta_p(\theta) \sin\theta d\theta, \tag{2}$$

$$b_{bp} = 2\pi \int_{\pi/2}^{\pi} \beta_p(\theta) \sin\theta d\theta. \tag{3}$$

The particle VSFs were extrapolated from 0.5° to 0° using a power-law dependency according to Mobley et al. (2002). Likewise, they were extrapolated from 179° to 180° with a constant value of $\beta_p(179°)$.

For the scattering spectra investigations, the particle VSFs were normalized by their values for $\lambda = 443$ nm and then linearized separately for each scattering angle:

$$\frac{\beta_p(\theta, \lambda)}{\beta_p(\theta, \lambda = 443\,\mathrm{nm})} = A_{443}(\theta)\lambda + B_{443}(\theta). \tag{4}$$

The $A_{443}(\theta)$ coefficients are the linear slopes of the VSF spectra normalized by their values for 443 nm. These coefficients were averaged separately for 5 locations near the Vistula river mouth, 21 stations in the Gulf of Gdańsk and 10 in the open Baltic Sea (measurements for water taken from greater depths were not included in the calculation of average values).

3. Results

The mean slopes $A_{443}(\theta)$ and their standard deviations for open Baltic Sea water, Gulf of Gdańsk water and Vistula river mouth water are shown in Figure 1. These slopes are generally negative and decrease with scattering angle. This means that the spectra of light scattered backwards decrease faster than in the case of forward scattering angles (which are much flatter). Nevertheless, there are some distinct differences between the angular characteristics of the mean slopes plotted for various kinds of water. The plot for turbid waters from the Vistula river mouth (Figure 1a) shows negative values of A_{443} throughout the range of scattering angles and a steep decreasing slope for most of the scattering angle range. This plot also shows good convergence (low standard deviation) for the majority of the scattering angles. Standard deviations are much higher for high scattering angles $\theta < 160°$, but this discrepancy is not observed with respect to open sea waters, and is not as distinct for Gulf of Gdańsk waters.

On the other hand, the open waters of the Baltic Sea (Figure 1b) have positive slopes $A_{443}(\theta)$ located in the central part of the scattering angle range. This simply means that for light scattered at right-angles to the illuminating beam, the scattered light spectra increases with wavelength. Moreover, the centre of the scattering angle range has the highest standard deviations. The rear part of the angle range decreases steeply and has low standard deviations. The waters of the Gulf of Gdańsk (Figure 1c) combine the features of the above two types of water. They have negative slopes $A_{443}(\theta)$ over the whole range of angles, but standard deviations are slightly higher for backward angles (like the river mouth waters) and in the central part of the range (as for open sea waters). These waters also differ from others with the deepest minimum observed for forward angles close to 10°.

The angular distributions of $\chi_p(\theta)$, averaged for all measurements made in the southern Baltic, are presented in Figure 2a. This shows that angles from 110° do 120° have the smallest differences between the four spectra of $\chi_p(\theta)$. In the same angular range one finds the smallest

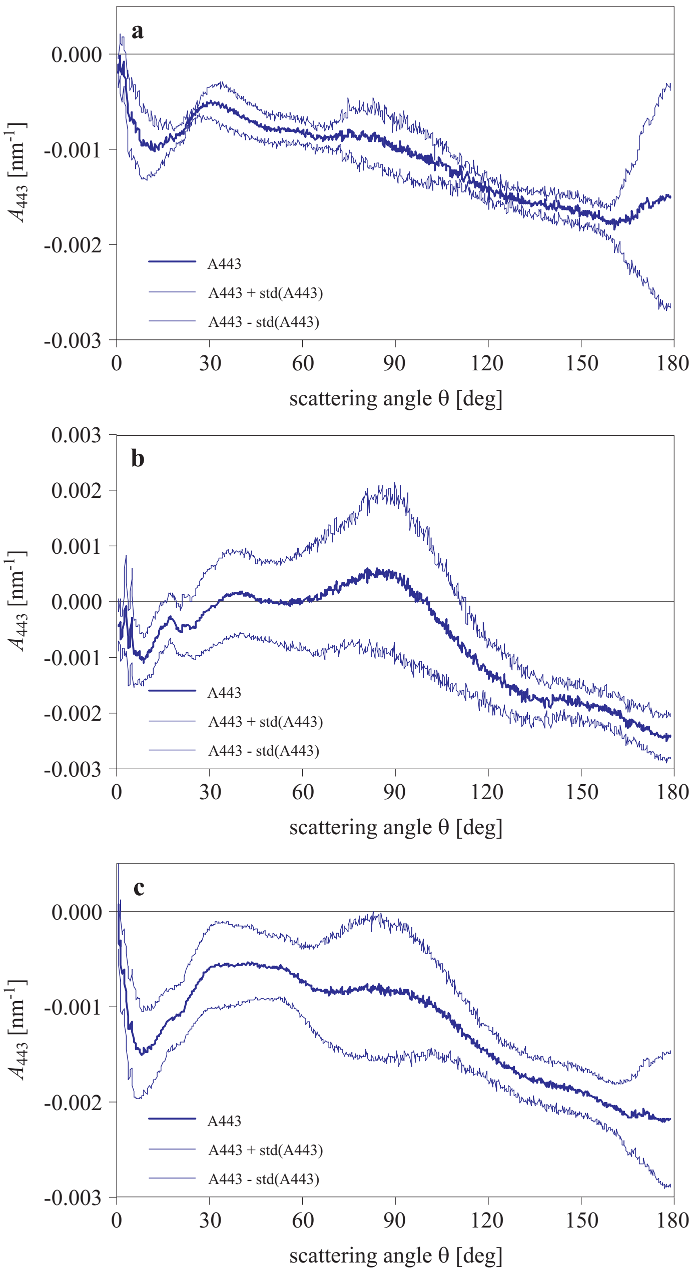

Figure 1. The angular variability of the linear slopes A_{443} of particle volume scattering function spectra averaged for 5 stations at the Vistula river mouth (a), averaged for 10 stations in the southern Baltic open sea water (b), averaged for 21 stations in the Gulf of Gdańsk (c)

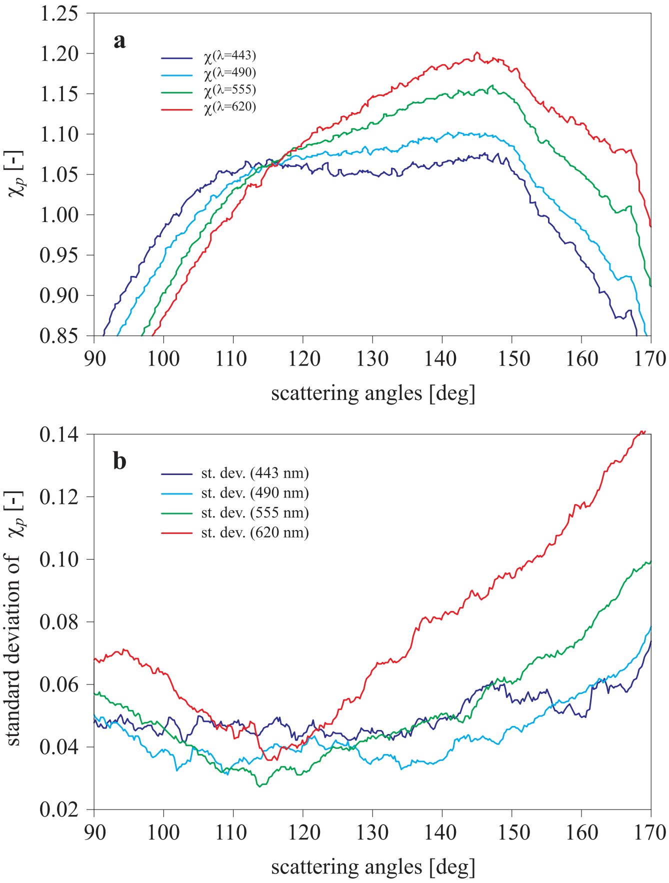

Figure 2. Functions $\chi_p(\theta)$ calculated for 42 series of particle VSFs measured in the southern Baltic. Average values of $\chi_p(\theta)$ for four wavelengths (a), standard deviations of $\chi_p(\theta)$ (b)

differences between the values of various functions $\chi_p(\theta)$ used for calculating the average (this is especially the case for longer wavelengths). This is shown in Figure 2b, which illustrates the standard deviations of 42 averaged functions of $\chi_p(\theta)$. The range from 110° to 120° is the only range where standard deviations are smaller than 0.05 for each wavelength examined. The standard deviations are higher for both smaller and larger scattering angles, especially at 555 nm and 620 nm.

In contrast, the plot of $\chi_p(\theta)$ shows a plateau around the angle 140°, and results are practically independent of scattering angles, especially in the case of shorter wavelengths. The instrument described by Maffione & Dana (1997) has a wide angle of view. The normalized weighting function (presented in that paper), which describes the impact on the measured signal coming from various scattering angles, takes a maximum value of 142° and the peak range (for half of its highest value) is from 130° to 150°. In this range of scattering angles the standard deviation of $\chi_p(\theta)$ for 443 nm and 490 nm is almost as low as ca 117° (see Figure 2b), but for 555 nm and 620 nm the standard deviation is clearly higher than for 117°.

4. Discussion

The angular variation in the slopes of the VSF spectra (Figure 1) belongs to the few of this type of data presented in the literature. This variation carries information about the composition of a scattering medium such as sea water. Finding links between the slopes of the spectra and the type of scattering particles would require a number of additional studies to be carried out. However, these graphs (Figure 1) provide insight into the

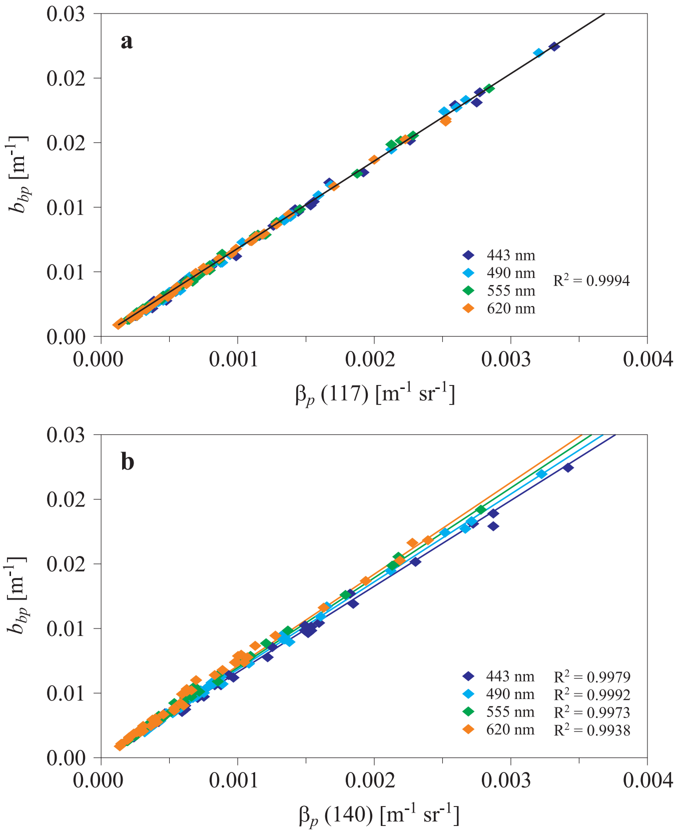

Figure 3. Correlation between the particle backscattering coefficient and the particle volume scattering function for scattering angle $\theta = 117°$ (a), for scattering angle $\theta = 140°$ (b), for 42 series measured in the southern Baltic

diversity of these spectra, showing that the spectral effects of light scattering in such quantities as the scattering coefficient and backscattering coefficient derived from scattering at different angles should not be neglected. This was the motivation for the considerations presented below.

Knowing the measured particle VSFs and their integrals (b_{bp} and b_p), one can then find a spectral relation between them. In Figure 3 measured values of b_{bp} were plotted against the particle VSF for 117° (Figure 3a) and against the particle VSF for 140° (Figure 3b). One can see that all the points in Figure 3a can be fitted with one linear equation (the best linear fit does not depend on wavelength λ) with a good correlation coefficient R^2, whereas in Figure 3b each wavelength requires a different linear fit (the ratio of b_{bp} to $\beta_p(140°)$ varies with wavelength). The linear regression lines as well as the correlation coefficients R^2 were put in the figure for each wavelength.

On the basis of all available measurements made in southern Baltic waters it was found that for a scattering angle $\theta = 117°$, function χ_p can be approximated by a single value of 1.07 for all the wavelengths examined. Boss & Pegau (2001) proposed a value of $\chi(117°) = 1.1$; these authors claim that this value is the same regardless of whether we consider the particle only (water removal approach) or both the particle and the water (total approach). According to the uncertainty of measured VSFs, which is about 5%, these values are in good agreement.

For a scattering angle $\theta_p = 140°$ the value of $\chi_p(\theta)$ changes from 1.06 to 1.19 in the range of wavelengths examined; $\chi_p(\theta)$ increases almost linearly with increasing λ. This relation can be described by a simple equation (with a high correlation coefficient $R^2 > 0.99$):

$$\chi_p(\theta = 140°) = 0.3 \frac{\lambda}{443} + 0.76. \tag{5}$$

The spectral variabilities of $\chi_p(\theta = 140°)$ and $\chi_p(\theta = 117°)$ are shown in Figure 4.

The standard deviations shown in Figure 2b indicate that for longer wavelengths the value of $\beta_p(117°)$ is better for obtaining the backscattering coefficient than $\beta_p(140°)$ because of its greater accuracy. This is consistent with the results of Sullivan & Twardowski (2009), who examined millions of VSFs obtained from MASCOT. Their measurements were carried out with a low angle resolution and for one wavelength only. My results (Figure 2b) show that for $\theta = 117°$ standard deviations of χ_p are 0.05 for all the wavelengths, while for $\theta = 140°$ the standard deviations are higher (for the longest wavelength of 620 nm the standard deviation is also the highest). This result seems to be consistent with those shown by Sullivan & Twardowski (2009) in their Figure 3b.

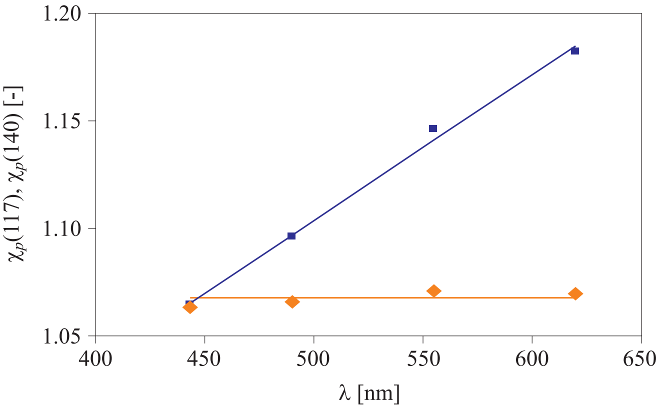

Figure 4. Spectral variability of $\chi_p(\theta = 140°)$ (blue squares) and $\chi_p(\theta = 117°)$ (red diamonds) obtained from 42 series of particle VSFs measured in the southern Baltic

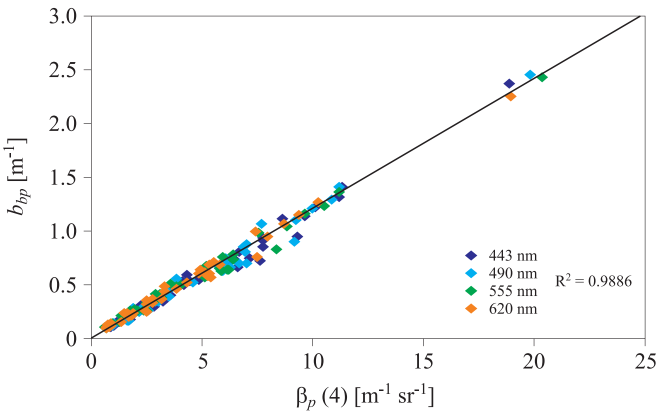

Figure 5. Correlation between the particle scattering coefficient b_p and $\beta_p(\theta = 4°)$ for 42 series of particle VSFs measured in the southern Baltic

The same method was used to find the relation between the total particle scattering coefficient b_p and particle VSFs measured at an angle of 4°. That relation has a slightly smaller correlation coefficient R^2 (see Figure 5). Moreover, the spectral dependence of the relation cannot be found, but from all the measurements of volume scattering functions the following dependence was found:

$$b_p = 0.121 \beta_p(\theta = 4°). \tag{6}$$

The accuracy of formula (6) was tested by comparison of its results with measured values of b_p (obtained by integration). Comparison of

168 sets (42 series, 4 wavelengths each) showed the highest relative difference between measured and calculated values to be 33 per cent. This result can be compared with the measurements presented by Mankovsky (1971), who found that the ratio of the particle scattering function to the particle scattering coefficient $\beta_p(4^\circ)/b_p$ was equal to 10.5 ± 2 sr. More recent measurements by Chami et al. (2005) demonstrate a similar linear correlation between $\beta_p(4^\circ)$ and the scattering coefficient b_p. On the basis of measurements prepared in Black Sea coastal waters they showed that $\beta_p(4^\circ) = 9.3 b_p + 0.014$. Both of these relationships give a slightly higher ratio of $\beta_p(4^\circ)/b_p$ than formula (6).

5. Conclusions

On the basis of available measurements made in the southern Baltic waters the following statement can be made: the spectral variation of scattered light in sea water depends on the angle of scattering; it also varies for different types of waters. The observed angular variation was the motivation for examining the spectral variability of the relationship between the backscattering coefficient and particle VSFs for angles 117° and 140°.

The measurements confirm the high correlation between the particle backscattering coefficient and the particle volume scattering functions for both angles 117° and 140°.

The particle backscattering coefficient $b_{bp}(\lambda)$ can be obtained from the particle VSF at 117° using a simple relationship – $b_{bp}(\lambda) = 1.07 \times 2\pi\beta_p(\lambda, 117^\circ)$. But if the particle VSF is known for 140°, then the spectral dependent formula $b_{bp}(\lambda) = (0.3\lambda/443 + 0,76)\, 2\pi\beta_p(\lambda, 140^\circ)$ should be used.

The correlation coefficient of the linear relationship between b_p and $\beta_p(4^\circ)$ is less than that for b_{bp}, and retrieval of b_p from measurements of $\beta_p(4^\circ)$ can lead to an uncertainty of over 30%.

The above conclusions are based on a set of measurements prepared during one single cruise in the southern Baltic Sea, which is why they probably should not be treated as having universal application.

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